ARMY ARCHITECTS

The Royal Engineers and the Development of Building Technology in the Nineteenth Century

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ABSTRACT

The thesis examines the contribution of the Corps of Royal Engineers to advances in the technology of building during the nineteenth century. It focusses on innovations in materials, forms, plans and services, and discusses the Corps' position and achievements relative to the private sector in Britain and her global empire. Perhaps best characterized as a social history of technology, this study demonstrates that, notwithstanding the significance of private sector individuals in British pioneering works, corporate contributions were also of considerable importance, particularly those of public offices, many of which were staffed by the Royal Engineers. Engineer officers held wide ranging and varied military and civil appointments at home and in the colonies. They were involved with nearly every aspect of novel building technology and they worked with a great variety of structural types.

The accomplishments of the Royal Engineers are viewed at three levels of achievement - the Corps; the civil office or military station; and the individual. At the Corps level, an important contribution was made to the diffusion of building technology through British imperial expansion, but the most significant achievement was in increasing knowledge of materials through experimentation. In civil office or military station, engineer officers' role as directors and superintendents of the Admiralty Works Department in charge of pioneering structures in the naval dockyards stands out as the most important. This was followed closely by Royal Engineers' work in the Science and Art Department where they joined new technology and Victorian architectural taste in building much of the cultural complex at South Kensington. Notable achievements were also made in the Inspectorate of Railways, the colonial stations of India and British North America and the Fortifications Department of the War Office. On the personal level, thirty engineer officers made important contributions and eight of this group are considered outstanding. Collectively, the Royal Engineers' contributions embrace virtually the entire spectrum of British achievement in building technology development which had a significant impact on architecture and society.

ABBREVIATIONS

ADM	*Admiralty Records Group*, Public Records Office, London
B	*The Builder*
Boase	Boase, F., *Modern English Biography*, First Published 1892, London, 1965.
BN	*Building News*
BSP	The Readex Microprint House of Commons *British Sessional Papers*
CEAJ	*The Civil Engineer and Architect's Journal*
CP	*Corps Papers and Memoirs on Military Subjects Compiled from Contributions of the Officers of the Royal Engineers and East India Company's Engineers*
DNB	*The Dictionary of National Biography*
MPH	*Maps and Plans Holdings*, Public Records Office, London
MPICE	*Minutes of the Proceedings of the Institution of Civil Engineers*
PP	*Papers on Subjects Connected with the Duties of the Corps of Royal Engineers*, known as the Professional Papers
PPNS	*Papers on Subjects Connected with the Duties of the Corps of Royal Engineers Contributed by Members of the Royal and East India Company's Engineers and Edited by a Committee of Royal Engineers*, short title *Professional Papers*, New Series
PPOS	*Professional Papers of the Corps of Royal Engineers - Royal Engineer Institute Occasional Papers*, known as Professional Papers,Occasional Series
PRO	The *Public Records Office*, London
TNS	*Transactions of the Newcomen Society*
WO	*War Office Records Group*, Public Records Office, London

INTRODUCTION

During the nineteenth century officers of the Corps of Royal Engineers in the British army were, amongst their many duties, architects as well as engineers. They were also regarded as 'scientific' men and because of their military position enjoyed high status as professionals in society. The present thesis examines the collective and individual contributions of the Royal Engineers to the development of building technology in the century, a phenomenon marked by progressive advances in structural theory and materials science and by the introduction of new materials, building types, plans and services as well as novel construction practices. These developments had a significant impact on architecture and society.

Britain, the first industrial nation and 'workshop of the world',pioneered many of the century's innovations in the technology of building. People who contributed to this came from a wide variety of occupations. Civil engineers played a prominent role. Thomas Telford, Robert Stephenson, Isambard Kingdom Brunel, Sir John Fowler, Sir Benjamin Baker and others advanced the art of bridge design. Sir Charles Fox pioneered wide span iron roofs and industrialized building. Sir John Hawkshaw and Rowland Mason Ordish further developed iron roofs. George Haden and Wilson Weatherby Phipson contributed to progress in heating and ventilation. Architects were important too. Sir Robert Smirke pioneered concrete foundations. Charles Fowler, Sydney Smirke, John Bunstone Bunning and John Baird designed important works in structural cast iron. Charles Barry jun. and Alfred Waterhouse helped establish terracotta in building. Manufacturers, ironfounders, industrialists and men of business were of great importance. William Strutt, Charles Bage and Sir William Fairbairn, entrepreneurs with engineering talent, introduced the iron frame, fireproof construction and other advances. Richard Turner, ironfounder, was a pioneer of the I beam and wide span wrought iron roofs. Morewood and Rogers, as well as Tupper and Carr, were early producers of corrugated galvanized iron. Richard Walker, Andrew Handyside and William McFarlane were pioneers of prefabrication. William Aspdin, Isaac Charles Johnson and J.B. White and Sons developed early Portland cement. Many came from other occupations. Sir Joseph Paxton, a gardner, designed the Crystal Palace. William Ranger, a builder, pioneered artificial stone and concrete structures. Dr. David Boswell Reid became the leading expert on heating and ventilation. And, as this thesis will demonstrate, some were military engineers.

The British also diffused and transferred advanced building technology around the world, to other nations and the empire. Sometimes this was achieved by the emigration of skilled architects and engineers to foreign lands, as in the case of Benjamin Henry Latrobe in America. In other cases, it was accomplished by building professionals undertaking projects in other countries or the colonies such as Charles Blacker Vignoles and R.M. Ordish, each of whom designed and built important suspension bridges abroad. Prefabrication, a technique and business inextricably bound up with colonialism, was especially important. British military engineers were stationed throughout the country's global empire and thereby participated in these processes to a considerable extent.

Nevertheless, scholarly study of British achievements, from the social history perspective, has focussed mainly on the 'heroes' of the private sector, especially civil engineers.[1] This bias has been reinforced by some architectural historians who have attempted to trace the roots of the 'modern movement' in part to the 'engineering architecture' of the nineteenth century, and to celebrate the 'functional tradition'.[2] It has also been supported by those scholars who have seen a schism between architect and engineer during the century and a separation between historicism and technological advances.[3] Moreover, little credit has been given to the collective contributions of engineering and architectural assistants in the offices of the 'great', many of whose names have been lost to history. Finally, there has been scant acknowledgement of the corporate contribution of public offices involved with design, construction and the building industry. The Royal Engineers played a central role in many of these both at home and in the colonies, and in so doing performed the role of many occupations in the private sector - architect, engineer, surveyor, building contractor, scientist, manufacturer, manager, educator and social reformer - often simultaneously.

The Corps of Royal Engineers differed from all other branches of the British army in having civil as well as military duties. From their wide ranging and varied appointments, Royal Engineers were particularly well positioned to be in the forefront of significant advances in building technology. In addition to their responsibilities for fortifications, barracks, military hospitals and other army works, they directed and supervised for the Admiralty construction in the naval dockyards. They were also Inspectors of Railways for the Board of Trade, and Surveyors-General of Prisons for the Home Office. Moreover, Royal Engineers served as architects for the Science and Art Department responsible for building much of the extensive cultural complex at South Kensington in London. And finally, they constituted colonial public works departments throughout Britain's global empire while serving at the same time the building needs of imperial defence. Royal Engineers were involved in virtually every aspect of the development of building technology - experiment and testing, manufacture of materials, education and technical writing as well as design, management, supervision and inspection of works. They also worked with a wide variety of building types - domestic, military, industrial, institutional and engineering structures.

This thesis will examine the position and contribution of the Royal Engineers relative to that of the private sector in the development of new building materials and structural forms as well as innovations in planning, servicing and other technical aspects of construction. It will be concerned primarily with the

social history of these developments. Particular attention will be given to the interplay of ideas and attitudes on the one hand, and available materials and methods on the other. Some of the themes running throughout the study will be: Royal Engineers' relationships with manufacturers, scientists, architects, civil engineers and foreign military engineers; the climate of support and incentive for experiment and innovation in their military and civilian projects; the interaction of their formal training and on-the-job experience; and the general influence of their theories, discoveries and works on nineteenth century building practice. Five main criteria will be used to assess contributions to the technology of building:
(1) inventor or innovator; (2) adaptive skill or agent of technology transfer; (3) architectural or engineering virtuosity in built works; (4) administrative, managerial, supervisory or regulatory talent; and
(5) teacher, technical writer, editor of building journal or publicist. No order of priority will be assigned to these; they sometimes overlap in an individual's career. Contributions will be evaluated at three levels - Corps, station or civil office, and individual.

The study is about two generations of engineer officers born 1780 to 1840. There are thirty individuals who comprise the core study group, although a number of others are mentioned as having some minor role in contributions to building technology development. While the study is concerned primarily with the Corps of Royal Engineers, engineer officers of the East India Company (Bengal, Madras, and Bombay) are included as well. The latter were amalgamated with the Royal Engineers in 1862 and had been educated at the Royal Engineer Establishment from 1817. Moreover, there was continuous contact between the Imperial and Indian Corps throughout the century, although they did not serve in each other's territory. British military engineers in India made some important contributions to building technology development in the colony and after retirement at home, and this study would not be complete without an assessment of their achievements. The study dates are from the end of the Napoleonic Wars (1815) when the Corps began its effective civilian role in lieu of major military employment to the end of the 1880's with the increasing adoption of steel and reinforced concrete - the two major 'new' materials of the twentieth century. Works studied are experiments with building materials as well as buildings, bridges and other structures which can be described as architecture. Other works such as docks, canals and railways are discussed only with respect to the development of new materials for building.

This is not a study of technology per se but a social history of technology. Purely technical matters are not evaluated in any detail, and where assessment is undertaken it is from the opinions of the engineer officers' contemporaries and not from the perspective of current building science or structural engineering knowledge and practice. It is also not a conventional architectural history in the fullest sense. No attempt is made to document systematically most of the buildings constructed by engineer officers, identifying their designers and patrons; nor are all the construction practices used by the Corps recorded. Neither is an effort made to describe and explain the pattern of style and stylistic change; nor are the customary aesthetic judgements offered that such an examination necessarily involves. The usual architectural descriptions have been made for well known buildings by the Corps in the works of other scholars, especially with respect to the buildings at South Kensington and in India. These descriptions are not repeated here except in bare outline to familiarize the reader or where relevant to a discussion of building technology. The clear emphasis in this thesis is on motive, means and opportunity for contributions to advances in materials, forms, plans and services, and on why buildings were built, what technology was employed, how and why and by whom. It is an attempt to relate architecture and building technology to the mainstream of the history of nineteenth century Britain and her empire.

Existing research on the subject of the present thesis is sparse and scattered. The various 'official' Corps histories provide some useful information but these are focussed primarily on military history and works, and rarely provide critical comment on buildings or building technology.[4] Some useful background information is provided by military historians.[5] Parris has outlined thoroughly the administrative context of Royal Engineers' work as inspectors of railways.[6] Hogg, Hughes and a few others have discussed the main points of British fortifications architecture but without much reference to building technology or to the Corps.[7] Evans and Tomlinson have discussed in considerable detail English prison architecture of the Victorian era, including the work of Royal Engineers, yet more remains to be said about the Corps' contributions, especially on building services engineering.[8] Physick, the Survey of London and others have described Royal Engineers' works at South Kensington in various levels of detail, including building technology, but more needs to be explained on technology, the careers of the engineer officers and their relationships with colleagues and collaborators.[9] Only two recent monographs deal specifically and directly with parts of the thesis subject - Hamilton-Baillie on the Corps and concrete, and Vincent on military construction techniques in the use of building materials in British North America.[10] Both scholars provide important information and insights but their interpretations can be modified in the light of evidence examined here.

The approach adopted for the present study was first to examine a wide variety of printed primary source material to identify major issues of building technology advances as defined by the engineer officers and their contemporaries, and then to pursue the details both there and in manuscript sources as required while placing these researches in an interpretive context by extensive reading in current architectural, engineering, military and social history of the period. Technical periodical literature was the major printed primary source. Most important was the Royal Engineer <u>Professional Papers</u> which was published more or less annually from 1837 until 1904. Also consulted were the Professional Papers of the Madras Engineers (1845-1856) and Professional Papers on Indian Engineering (1864-1886). Other periodicals examined include the Minutes of the Proceedings of the Institution of Civil Engineers, Engineering, The Engineer, Mechanic's Magazine, The Civil Engineer and Architect's Journal, The Builder and Building News. The British Parliamentary Papers were of considerable importance in research. Amongst the manuscript sources consulted, the most revealing were the reports, correspondence and drawings of the Admiralty and War Office located at the Public Records Office. Fortunately, biographical information on the Royal Engineers is abundant. The main sources used were the Dictionary of National Biography and obituaries of deceased engineer officers in the Minutes of the Proceedings of the Institution of Civil Engineers.

This thesis will provide for the first time a comprehensive evaluation of the Corps' contribution to the development of building technology in the nineteenth century within the context of architecture and society in Britain and her empire. It will enhance present understanding of British military engineers as well as those with whom they worked. Moreover, the study will increase knowledge of society's attitudes and achievements during the period concerning architecture and building technology. And broadly, it will provide further insight on the importance of advancing technology to the changing character and circumstances of the times.

The thesis chapters are organized as follows. First the background, training and duties of the Corps are examined. Proceeding from this we look next at some experiments with cements and concrete at the Royal Engineer Establishment, Chatham, (School of Military Engineering after 1869) which had a considerable formative influence on the Corps' attitudes and approaches to building science and to the materials tested or developed. This is followed by a discussion of the Royal Engineers' role as railway inspectors and their contribution to the development of novel bridge designs to meet the challenges of safety and transportation efficiency in the steam age. After this, an assessment is made of engineer officers' role in pioneering works in iron and Portland cement concrete in the naval dockyards as directors and superintendents of the Admiralty Works Department. Following on from this is a review of the applications of new building technology to fortifications, the Corps' principal duty as military engineers. Then we have a study of Royal Engineers' approaches to planning and servicing in prisons, barracks and military hospitals to achieve healthy dwellings. Next comes an examination of Royal Engineers' works of monumental public architecture at South Kensington while in the employ of the Science and Art Department, and an assessment of their achievements in joining innovative technology and Victorian taste. Many of the themes previously examined reappear in the penultimate chapter which focusses on the process of the diffusion of building technology through imperial expansion as seen in engineer officers' colonial works, and which evaluates the significance of their global building experience. The study closes with conclusions on the contributions of British military engineers to the developing technology of building in the nineteenth century.

1. THE CORPS: BACKGROUND, TRAINING AND DUTIES

An understanding of the background, training and duties of the Corps is essential to an analysis of the Royal Engineers' motives, means and opportunities in making contributions to advances in the technology of building. There are particularly important connections between social status and education and professional standing in comparison to civil engineers and architects. The remarkably wide and varied nature of the Corps' duties is also of considerable significance, especially its dual responsibility for military and civilian assignments. In these many roles the military discipline and corporate identity of the army interacted with the individual self determination and personal aspirations of the private sector. Engineer officers held a unique position.

Nature of the Corps

The roots of British military engineers can be traced to Norman times but it was not until 1716 that a Royal Regiment of Artillery and a Corps of Engineers were formed. By 1741 the Royal Military Academy had been founded at Woolwich to train them.[1] In 1759 the Corps of Engineers became a distinct body of commissioned officers but the earlier custom of first commissioning cadets to the Royal Artillery and then transferring them to the Engineers prevailed until 1761.[2] The Corps of Engineers became the Corps of Royal Engineers in 1787.[3] Military engineers were also employed by the East India Company from the mid-eighteenth century but not until 1798 was it permitted to place a number of cadets at the Royal Military Academy for its engineers and artillery, a body called the 'Company of Gentlemen Cadets'. In 1809 the Company established its own military college at Addiscombe.[4] It is important to distinguish the Royal Engineers from the Royal Sappers and Miners, the artisan soldiers who served under the command of the engineer officers. An equivalent group of men was also found in the East India Company military engineers. The Royal Sappers and Miners were sometimes of considerable assistance to the engineer officers in building work and in experiments with materials. They were amalgamated with the Royal Engineers in 1856.[5]

At the beginning of the nineteenth century it was only in France that engineering was clearly and definitely established as a learned profession. It had emerged there during the previous century first in the military and then in civil practice and under state supported scientific education. Indeed, the term 'engineer' had been used from the Middle Ages to denote someone engaged in the design of military engines and defence works. This use of the term persisted to the late eighteenth century and retained a military connotation in France and America well into the nineteenth. The title civil engineer developed to distinguish non-military engineers. In Britain engineering was a skilled craft not an intellectual pursuit and was the work of artisans. John Smeaton, who combined practical skill and scientific interests, is said to have been the person through whom the profession of civil engineering emerged in Britain in the late eighteenth century. The profession was still in its infancy with the establishment of the Institution of Civil Engineers in 1818. Accordingly, the Royal Engineers were not as advanced as their counterparts in France but were ahead of the private sector in Britain as an organized body of formally educated persons who pursued the practice of engineering.[6]

Together with the Royal Artillery, the Royal Engineers were known as the 'scientific corps'. In the pre-Crimean War period the two constituted a small proportion of the British army, usually less than 15%.[7] The Corps of Royal Engineers in 1800 number 94 and grew steadily to 262 at the height of the Napoleonic Wars in 1813. Following the termination of the war with France the Corps was severely cut back and by 1819 comprised only 193 officers. In the next few years it was increased slightly to 241 in 1825 but remained more or less the same for the next two decades rising only to 288 by 1846. From that point it rose to 336 in 1854.[8] The first two years of the Crimean War saw a notable rise in new commissions to the Corps - 20 in 1854 and 27 in 1855 respectively.[9] By the mid-1850's, therefore, the Corps numbered around 350 officers. Moreover, in the period 1809 to 1861 a total of about 500 engineer officers were posted to India after graduating from the East India Company's military college at Addiscombe.[10] The situation following the amalgamation of the Royal and Indian corps in 1862 is interesting. For the year 1870-71 the Royal Engineer establishment totalled 817 of which 395 were stationed in India, and of this latter number some 237 engineer officers were assigned to the Public Works Department.[11]

It is very revealing to compare the strength of the Corps to the numbers of civilian professional engineers in Britain. At mid-century there were about a thousand professional engineers, a number probably close to double that of the Royal and Indian corps combined. By 1870, however, professional engineers numbered 4,128, more than five times the Royal Engineer establishment, and two decades later they totalled 15,043. During the period 1850 to 1890 the number of institutions representing professional engineers also grew, from two to seventeen.[12] Perhaps more indicative is a comparison of the Royal Engineers and the members of the Institution of Civil Engineers. In 1830 the Institution's membership stood at 220 but by 1850 was around 700.[13] This shows that, while slightly smaller than the Corps at the earlier date, membership in the Institution was more than double the establishment of the Royal Engineers by the latter. Accordingly, it seems fair to conclude that civil engineers were roughly comparable in numbers to military engineers in Britain during the early part of the century but quickly surpassed them in the 1830's and 1840's, no doubt as a result of the railway boom, and the gap continued to widen as time progressed. Moreover, the relative size of the Corps' presence in Britain during the early decades of the century may be seen as appreciably smaller when it is considered that proportionately more engineer officers than British civil engineers were practising abroad.[14]

Unlike other British army officers, the Royal Engineers and the Royal Artillery did not purchase their commissions but entry to the corps was through nomination by the Master General of the Ordnance. This patronage system prevailed until 1857 when nomination was replaced by competitive entry exams.[15] All of the engineer officers who comprise the core group of 30 studied in the present thesis entered military service by nomination. Indeed, nomination (and purchase in the rest of the army officer corps) guaranteed that military leadership would be the preserve of the 'gentleman' thereby protecting the possessions and privileges of the ruling establishment.[16] The qualities of the 'gentleman' were never precisely defined but included gentle birth, ownership of land and if possible money too, some degree of education, a high sense of honour, courage and generosity.[17] The Duke of Wellington, Master Generalof the Ordnance, defined the desired recruits succinctly in 1833:"--- men who have some connections with the interests and fortunes of the Country."[18]

Recent historiography of the British army officer corps has demonstrated that officer recruits were overwhelmimngly from the propertied and professional classes and that the largest single group was the sons of military officers.[19] Razzel has shown that for army officers of the Indian service the large majority during the late eighteenth and early nineteenth century came from the middle class but that the proportion of the aristocracy and landed gentry increased over time, trebling from 1758 to 1834.[20] Scholars have based their conclusions on analyses of data on the occupation of recruits' fathers, a standard technique for determining social origins. A similar analysis was undertaken on the 30 engineer officers featured in the present study. The analytical model was adopted from one used recently by Crouzet to study the origins of Britain's first industrialists.[21] Results of the analysis are given in Appendix B and they confirm the findings of recent scholarship on the origins of British army officers. Research on the group of 30 engineer officers revealed father's occupation for 19, out of which 63% were from the upper class, 32% from the middle class, 5% from the lower middle class and none from the working class. The largest single contributory group was military officers which comprised 58%.

Officers' pay was extremely low. As established in 1806 it varied from 16s 3d per annum for an ensign to £365 for a lieutenant-colonel. These rates were less than half the pay of equivalent grade for civilian clerks in the War Office.[22] Pay was low precisely in order to ensure that only men of means entered the officer corps. Private means was not a luxury but an absolute necessity.[23] Moreover, the basis of promotion in the Royal Engineers was strict seniority and the rate of promotion notoriously slow compared to rates in purchase regiments.[24] There was therefore no financial or other incentive for promotion by meritorious works. An engineer officer could expect to enjoy a higher salary in civil duty but this was not lucrative either. The terms of Royal Engineers' secondment to civil service duties and rates of pay in these occupations will be further discussed in the last section of this chapter.

While the Royal Engineers followed the general pattern of British army officers with respect to social origins, they were not among the wealthier recruits. Anyone who was prepared to take the trouble to acquire the necessary technical knowledge was not likely to be rich enough to afford the purchase system, the prevailing method of getting on in the military profession.[25] Moreover, Royal Engineers were not expected to live quite so expensively as other officers and were not so socially distinguished as regimental army officers.[26] The East India Company engineer officers were even less likely to be wealthy recruits. They often sought India service because the costs of living were much cheaper there. Officers of the home army were sometimes snobbish towards their counterparts in Indian service and there was a distinct gulf between the two.[27] Nevertheless, engineer officers of the Royal and Indian corps studied here seem to have got on well together, at least on the professional level, and especially in their sharing of information in the Royal Engineer Professional Papers.

There is no systematic scholarly study of the social status and origins of civil engineers and architects with which to compare the position of the engineer officers. Nonetheless, evidence concerning social status may be found in the establishment and progress of their respective professional associations, in contemporary guides to careers, in census recognition and in the lives of prominent practitioners of the professions. By these measures civil engineers as a group were higher in standing than architects at mid-century. Apart from medicine or law they had the most claim to recognition amongst the 'new professions'. Both civil engineers and architects, however, were decidedly below military engineers in social status until the latter part of the century.[28] The two new professions were intensely interested in increasing their standing in society and adopted the behaviour of the 'gentleman' in pursuit of this objective.[29] On the matter of social origins, samples from civil engineers and architects respectively, who were the contemporaries of this study's 30 engineer officers, were analysed using adaptations of Crouzet's model.[30] The results are given in Appendices C and D. In the case of civil engineers, only a few were from the upper class (14%). The greatest number were from the middle class (49%) and the lower middle class (23%). Some 35% had fathers who were engaged in professions, business, craft or other occupation related to the building industry or engineering. For architects, only 3% were from the upper class. There were, however, 69% from the middle class and 17% from the lower middle class. Also, as many as 72% had fathers who were in the professions, business, trade or other occupation related to the building industry or architecture and this included 33% who were the sons of architects.

A few tentative conclusions arise from this discussion of the social status and origins of civil engineers and architects compared to engineer officers. It is probable that the Royal Engineers were less motivated than their civilian counterparts to gain status by way of public recognition of their works and contributions to advances in building technology. The army was an established and secure occupation for the well placed sections of society. Also, it would appear that civil engineers and architects coming as they did in considerable numbers from families in the building professions, business or trades may have had an advantage over the Royal Engineers in early exposure to the practical skills of design and construction. This was especially important in an age when the apprenticeship system prevailed as the route to qualification in both engineering and architecture, a phenomenon which will be discussed at length in another section. And lastly, given their high social standing the Royal Engineers might expect to be treated by their civilian counterparts as professional equals and possibly with some deference, making working relationships easier. Engineer officers were inclined to be more professionally allied to civil engineers than to architects. Nine of the thirty engineer officers featured in this study were members of the Institution of Civil Engineers but only one was a member of the Institute of British Architects.[31] A Royal Engineer was recruited by Thomas Telford as one of the early members of the Institution of Civil Engineers to help give the organization social respectability.[32] In the early 1860's, however, another was to be the centre of controversy over his prospective entry into the Institute of British Architects.[33] A number of the Royal Engineers won prizes for papers delivered to the Institution of Civil Engineers. Many joined other professional engineers' associations as these developed throughout the century and sometimes distinguished themselves in those organizations as well.[36]

Formal Education

The formal education of the engineer officer in the nineteenth century was a two stage process. One first entered the Royal Military Academy at Woolwich as a cadet and studied there for up to five years and upon graduation received a commission. Following this a junior engineer officer was sent to the Royal Engineer Establishment at Chatham (founded 1812, School of Military Engineering after 1869) where he completed his training in a course lasting about a year at the beginning of the century but later extended to eighteen months and then two years. The emphasis at the former was on theoretical knowledge and at the latter on practical skill. East India Company military engineers trained at the Royal Military Academy from 1798 to 1809 but then at their own military college at Addiscombe until it closed in 1861 in anticipation of the amalgamation of the Royal and Indian corps the next year. They also attended the Royal Engineer Establishment from 1817. Engineer officers in the service of the East

India Company also had the benefit of further formal training at the Engineer headquarters in India accompanied by a form of apprenticeship. A general description of these various educational opportunities will be given and an assessment made of their respective contributions to the knowledge and skill of engineer officers in engineering and architecture. Particular reference will be made to the Royal Engineers' own evaluation of the quality of their formal education as revealed in two important Parliamentary reports after mid-century.

The Royal Military Academy at Woolwich was for nearly two hundred years the cadet training institution for the majority of Royal Engineers and Royal Artillery. It was essentially a militarized public school until reforms of the late nineteenth century.[35] During the eighteenth century and first few decades of the nineteenth recruits were as young as thirteen or fourteen years of age but from 1835 admission age was fixed at not under fifteen or over seventeen.[36] Admission was by nomination by the Master General of the Ordnance (until 1857) and subject to an entrance examination which tested proficiency in writing English, mathematics, French,geography, history and the elements of drawing.[37] Recruits had therefore to have received suitable primary and some secondary education in schools or through private tuition before entry. An analysis of the early educational background of eighteen Royal Engineers featured in this study for whom information is available revealed that the vast majority had attended either a public school (22%) or a college, academy or other private school (55%).[38]

The course of studies was in two parts: a theoretical course for up to four years and a practical course normally lasting one year. With respect to subjects relevant to the technology of building, the theoretical course was heavy on mathematics and physics including arithmatic, algebra, logarithims, geometry, trigonometry, calculus, mechanics, hydrostatics, hydrodynamics and pneumatics. The method of teaching was to divide the cadets into classes or levels of competence and provide lectures and examinations both oral and written given by professors. Cadets kept notebooks which were examined too.[39] The theoretical course also included the study of fortification which comprised practical geometry, perspective in theory and practice and measured drawing. Cadets had to copy drawings, take views around Woolwich and other places and prepare plans, sections and elevations of an ordinary simple building, with conventional colouring, to show the different materials and with the technical names of different parts printed.[40] The practical course included lectures in chemistry, geology and metallurgy intended to equip engineer and artillery officers with useful knowledge on materials and structures of war but there was no specific training in engineering or architecture. Notebooks were kept and examined by a lecturer.[41]

The major benefit of the engineer officers' educational experience at the Royal Military Academy was exposure to some of the finest mathematicians and scientists of the day in Britain. Among these was Charles Hutton (1737-1823), Olinthus Gilbert Gregory (1774-1841), Michael Faraday (1791-1867), Sir Frederick Able (1827-1902) and Peter Barlow (1776-1862). Hutton was appointed professor of mathematics in 1773 and remained in the position until 1807. He was author of several publications including A Course of Mathematics for the Use of Cadets in the Royal Military Academy (1798-1801) which ran through many editions. On Hutton's recommendation, Gregory became mathematical master in 1802 and was appointed professor of mathematics in 1807, a position which he held until 1838. Gregory also authored several publications, most notably A Treatise on Mechanics (1806).[42] Faraday, who is best known for his work in electricity and his professorship at the Royal Institution (1833-1862), lectured at the Academy in chemistry from the 1820's to 1852. He was succeeded in the post by Able, chemist to the War Office, another distinguished Victorian man of science.[43] Barlow was appointed in 1801 as additional mathematical master under Hutton. His career at the Acaedmy lasted until 1847, making him the longest serving member of the educational staff. Barlow was an early member of the Institution of Civil Engineers (1820). Most influential was his publication in 1817 of an Essay on the Strength and Stress of Timber which went through five editions in his lifetime (last in 1851).[44] Also worthy of mention, although not a mathematician or a scientist, was Issac Landmann, who was a professor at the Royal Military Academy from 1777 to 1815. He was the author of A Course of the Five Orders of Civil Architecture with a Plan and Some Geometrical Elevations of Town Gates of Fortified Places (1785) and of Principles of Fortification Reduced into Questions and Answers for the Use of the Royal Military Academy at Woolwich (1796). The former work was partly based on Chamber's Civil Architecture .[45]

Until 1820 the teaching at the Royal Military Academy, except for some practical gunnery and possibly some fortification, was undertaken entirely by civilians.[46] By the 1830's a number of Royal Engineers acted as instructors at the Academy, the most important of whom with respect to the present study was Henry Young Darracott Scott. Appointed instructor in fieldworks in 1848, Scott took up in addition to his duties at the Academy the study of chemistry at King's College, London which laid the foundation for his later important contributions in limes and cements, a topic discussed in the next chapter.[47]

During the eighteenth century, passing out of the Royal Military Academy had been by way of public exams but these were allowed to lapse for seventeen years and were only re-established in 1811.[48] With the resumption of public examination for passing out, a new system was adopted whereby cadets were put through a competitive examination and then allowed to choose either the Engineers or the Artillery according to their rank in the examination results until half the number had chosen one corps, after which the remainder were allocated to the other.[49] Harries-Jenkins has criticised this system as not necessarily directing cadets to the occupation to which they were best suited and as a disincentive to develop further the theoretical knowledge gained at the Academy if one failed to get his choice.[50] Nevertheless, the overwhelming choice of top finishers in the exams was the Royal Engineers, indicating that it stood first in prestige and opportunity and also perhaps that the most theoretically qualified and able cadets comprised the Corps.[51]

Addiscombe was much the same as the Royal Military Academy with respect to training engineer officers, in this case for service in India. Entry was also by nomination and a qualifying examination. Age of admission was over 14 and under 18 originally but later was raised a year for the former. The course, however, was only two years in duration and consisted of mathematics, natural philosophy, drawing and surveying as well as chemistry and geology. There were competitive public examinations for passing out, the top cadets being sent to the engineers and artillery and the rest to the infantry.[52] A number of distinguished persons served as public examiners including Charles Hutton of the Royal Military Academy and Sir Charles William Pasley the distinguished first director of the Royal Engineer Establishment and a man who occupies an important place in this study.[53] The most distinguished teacher at Addiscombe was Jonathan Cape, a senior professor who served for 39 years (1822-1861). In 1838 Cape published mathematical tables and in the next year his two volume course in mathematics was adopted in preference to Hutton's earlier work.[54]

The Royal Engineer Establishment at Chatham owed its foundation and early development to Sir Charles Pasley (1780-1861). Pasley had experimented in 1811 with a course of instruction at Plymouth for the non-commissioned officers and men of a company of Royal Military Artificers under his command in order to improve their knowledge of fortification and fieldworks, concentrating especially on the nature of rough sketch, plan and section drawing. His chief objective was to better fit these soldiers to assist engineer officers in the field during the height of the Napoleonic Wars. The men instructed according to Pasley's system later proved to be of the greatest service in the last year of the Peninsular campaign and in Canada during the War of 1812-14.[55] On 23 April 1812, a Royal Warrant established Pasley's school permanently at Chatham making him the first director and opening instruction also to junior officers of the Royal Engineers as well as the non-commissioned officers and men of the military artificers now renamed the Royal Sappers and Miners.[56]

Pasley was born the son of a London merchant in Eskdalemuir, Dumfriesshire, Scotland. He was educated in the school of Andrew Little of Langholm and later at Selkirk. Pasley joined the Royal Military Academy in 1796 and graduated the next year receiving a commission in the Royal Artillery. In 1798 he was transferred to the Royal Engineers and posted to Portsmouth where he was employed in building Fort Monckton. During the period 1807-1808 he was engaged in the construction of martello towers on England's east coast. Pasley took part in the Napoleonic Wars and was severely wounded in the Walcheren expedition in 1809; this incapacitated him for further active duty but left him free to pursue his great interest in the education of military engineers. In 1810 he published an Essay on the Military Policy and Institutions of the British Empire which attracted great attention and went through four editions. More importantly, in the same year he and Sir John Fox Burgoyne formed a group called the 'Society for Producing Useful Military Knowledge' consisting of six Royal Engineers. The group aimed at encouraging theoretical and practical studies in military engineering but it did not survive the Napoleonic Wars. Pasley's experiment with improving the knowledge of Royal Military Artificers at Plymouth in 1811 was at his own expense, demonstrating his personal commitment to progress in military education. He was soon well recognized as a man of practical science and was elected a fellow of the Royal Society as early as 1816. Pasley was to serve as the director of the Royal Engineer Establishment until 1841.[57]

Pasley's system of education at the Royal Engineer Establishment was a teach-yourself method. It was initially mainly intended for instruction of the Royal Sappers and Miners. He had visited the schools and studied the systems of Joseph Lancaster and the Reverend Andrew Bell, the two individuals who dominated the primary education field in Britain from 1800 to 1830 and who had developed their methods with military connections.[58] Following the precedents of Lancaster and Bell, Pasley produced a three volume teach-yourself textbook and had non-commissioned officers lead the lessons. He explained that he had adopted this method because, in his judgement, the army would not have been willing to bear the cost of a professional teaching master.[59] The course of instruction comprised practical geometry, arithmetic, mensuration and plan drawing. The latter included preparing " a plan, section, and elevation of some simple, unornamented building according to scale."[60] Much of Pasley's teach yourself textbook was taken from Peter Nicholson's works on architecture but a good part of it was original.[61] The nature of Pasley's educational approach was described succinctly in his 1814 publication of the first volume of the Course of Instruction:

> "--- to lay down a Course of Instruction suited to the most untutored minds, and capable of being conducted by any man of good abilities, no matter how illiterate or ignorant in other respects; in short to establish a System of Instruction, which might be perpetuated like the drill of recruits, by the exertions of steady non-commissioned officers employed as teachers, without the necessity of calling in assistance of scientific masters of any kind ---"[62]

The essence of this approach was to be adopted in Pasley's method developed later for teaching practical architecture to the Royal Engineers.

It was not until 1825 that, by order of the Master General of the Ordnance, the Duke of Wellington, an architectural course was started at the Royal Engineer Establishment. This followed upon the transfer in 1822 of responsibility for the construction and maintenance of barracks from the Barrack Board of the War Office, an entirely civilian group, to the Royal Engineers under the Board of Ordnance.[63] In 1826 Pasley developed a lithographed teach-yourself textbook called Outline of a Course of Practical Architecture (reprinted and published in 1862). He acknowledged the help of "some of the most eminent civil engineers and builders of this country and persons in their employment" in the preparation of the textbook.[64] The course was essentially about traditional building in brick though not without information on the latest technology connected with it. Pasley stated in his preliminary observations that most buildings in England were brick and if one understood how to build in brick he could easily construct in stone. Accordingly, the purpose of the course in practical architecture was to explain all the details in the art of building in brick which could not otherwise be learned except by attending the execution of one or more buildings from beginning to end. Junior officers learned measurement in artificer's work, according to the practice in London, by attending measurements at the Royal Engineer Department in Chatham. Their design training consisted essentially of copying architectural drawings from books and manuscripts. After copying a sufficient number of drawings and attending the practice of measurement, engineer officers were expected to draw up an estimate of the expense of a given building from the drawings and specifications according to prices in the London price book for the current year.[65]

A civilian clerk of the works, Robert Howe, was appointed the first instructor in practical architecture. His job was mainly to prepare additional teach-yourself materials and guide the junior engineer officers in their exercises.[66] Sir Henry Drury Harness, a later director of the Royal Engineer Establishment, recalled in 1861 his days as a student under Howe in 1827 :

> "--- a Mr. Howe, a very able man and well fitted for the work prepared a course entirely in manuscript, and the drawings in manuscript, and under him we copied all those drawings; they were drawings in great detail, but of course were confined to English, or may I say London house building and so it is still. --- and under him we measured all those drawings regularly, and drew out those measurements into abstracts, and estimated for each of the buildings and each of the roofs."[67]

The architectural course was originally four months out of the engineer officers' year programme, the size of the classes was small and there were no passing out examinations at the Royal Engineer Establishment.[68] The emphasis was on intensive education by rote, a philosophy in which Pasley believed fervently. He felt that military men were especially suited to improvement by such methods:

> "--- although military men have less stimulus to individual improvement than civilians; their habits of discipline and obedience, and pride, and emulation which may so easily be excited amongst them, render them much more docile and improvable as a body, than any other class of men, provided their instruction is carried

> on under the eye of superiors zealous
> in the cause." 69

Pasley's book on practical architecture stood as the basis of the engineer officer's training in building construction until the 1860's. It offered a number of important features concerning advanced building technology of the early part of the century. Most importantly, it reviewed up-to-date limes and cements, a topic in which Pasley developed a considerable interest and expertise, as well as methods of constructing concrete foundations.[70] With respect to the latter, he featured the work of Sir Robert Smirke to whom Pasley seems to have been closely connected.[71] Also discussed were hollow pots and hollow bricks for fireproof floor construction, a variety of new heating and ventilation arrangements including Sylvester's cockle furnace, steam systems and hot air stoves, and hollow wall construction for economy, ventilation and anti-dampness.[72] Significantly, however, there was no reference whatsoever to structural iron for walls or roofs. It contained information on simple timber roof trusses based on Tredgold and Nicholson. Structural engineering technique was restricted to proportions of arches, piers, abutments and retaining walls. This teach-yourself textbook may have given engineer officers some grounding in the new advances in brick house building but except for its information on concrete foundations left them ill equipped to deal with major, innovative structures, especially wide spans and free standing construction in iron.

Not much changed in the content of the architectural course at the Royal Engineer Establishment before the 1850's, although one director after Pasley demanded greater diligence in the execution of drawings. Sir Frederick Smith warned in 1847: " A want of care and neatness in execution, will subject an Officer to have his Drawings rejected."[73] The new feature added at mid-century which had important implications for developing knowledge and skill in building technology was an optional course in experimental, applied chemistry given by Henry Scott. In 1852 an old cookhouse at the Establishment was converted to a chemical laboratory and the next year Captain Scott, who was at the time an instructor at the Royal Military Academy, was authorized to attend Chatham weekly to give instruction to the junior

Royal Engineers and the Royal Sappers and Miners in analytical chemistry. In 1855 Scott was appointed Superintendent of Surveying and Practical Astronomy at the Establishment and took charge of the chemical laboratory, continuing instruction and lectures in chemistry.[74] It was here that Scott was to discover a new cement and make major contributions to the knowledge and skill of the Corps in limes, cements and concrete.

Following much criticism and Parliamentary investigations into the educationof the Royal Engineers in the late 1850's, about which more will be said later, reforms were made in the architectural course and instruction in building technology. Chiefly responsible for the reforms was Henry Drury Harness (1804-1883) who was the director of the Royal Engineer Establishment, 1860-65. Commissioned in 1827, Harness first served at Bermuda where he had experience in designing barracks and other military buildings, including composite iron roofs. From 1834 to 1838 he was one of the instructors of fortification at the Royal Military Academy and in 1840 was appointed an instructor in surveying at the Royal Engineer Establishment. During his time at the Royal Military Academy he reformed the teaching of fortification and produced a textbook that was used for many years. In 1837 he became a member of the Institution of Civil Engineers. While at the Royal Military Academy in the late 1830's he helped Sir William Thomas Denison start the Royal Engineer Professional Papers. From 1846 to 1850 he was secretary to the Railway Commission. During the 1850's he edited a mathematics textbook for use at the Royal Military Academy, served on the Board of Public Works in Ireland and rebuilt fortifications at Malta as Commanding Royal Engineer in the territory. Harness was well qualified to undertake the reform of the Royal Engineer Establisment.[75]

Harness wanted to upgrade significantly the architectural course by appointing a well qualified officer to "instruct in the general principles of construction, and to take the officers through a course in which they shall prepare original designs, with specifications, estimates, and working drawings."[76] Nonetheless, he met opposition from Sir John Fox Burgoyne, Inspector General of Fortifications, Pasley's old colleague. Burgoyne wrote to Harness in 1860:

> "--- I have the impression that too much time should not be given to what is called the architectural course; for the practical purposes we require, it is scarcely susceptible of being learned by book and theory; the proportions of details of buildings and constructions, and to define proportion and put together several materials are essential items, and will be more readily acquired by closely witnessing the actual practice and operations, and studying by experience and effects how to gain strength with the smallest means, and therefore chiefly to be learned when employed on great works."[77]

Burgoyne's faith in learning by doing was the prevailing attitude in the Corps, as will be discussed at length below. Notwithstanding the cool reception which his superior gave to his suggestions, Harness pressed on and introduced a number of changes including practical instruction in the application of principles of mechanics to construction, provision of information on materials, lectures by experts in various fields of building and visits by engineer officers to engineering works and factories. He also extended the duration of the architectural course, which had declined to about 20 days by 1860, to 140 working days of the 18 month programme at the Establishment.[78] Harness' reforms were extended in the latter part of the century beginning with the appointment of Henry Wray as instructor of construction. Wray had been commissioned in 1848 and had spent six years in Western Australia (1852-58) in constructing convict establishments and other buildings.[79] Under Wray the syllabus included the quality and strength of materials, the science of engineering and building construction, sewerage, drainage, ventilation, gas and water supply as well as architectural design, measuring and estimating.[80] By 1875 the architectural course was 154 days out of a two year programme at the Establishment and the situation remained the same in 1887.[81]

After leaving Chatham a Royal Engineer was immediately placed on regular duty in some home or foreign station but from well before mid-century the engineer officer bound for India was not yet finished with his formal education. Upon arrival in India a young officer was sent to the headquarters of the Engineers for one or two years and in the Bengal Presidency he went through a regular course of study at the Engineer College which was established at the station where the Engineer headquarters was located. At the Engineer College the officer was to learn the Indian language and become familiarized with Indian customs. He was also put through a course in civil engineering. In all the presidencies, as vacancies occurred an officer was made an Assistant Engineer under an executive officer at the Engineer headquarters. There he would be called upon to make designs for small works, to draw up estimates, and to keep accounts. After this preliminary training he left headquarters to serve as assistant to some divisional Executive Engineer. On his appointment there he would be made responsible for carrying out, in all its details, absolutely by himself, some work under the Executive Engineer or some experienced subordinate. A young officer's training was exactly the same as that of the clerks of the works who served in the Subordinate Department, the 'practical men' who worked under the engineer officers in the Public Works Department. He learned the details of materials and their use in a variety of construction circumstances. As a young officer became more experienced and showed an aptitude for more important work, he was transferred to a greater responsibility and had two or three overseers from the Subordinate Department placed under him. Gradually his sphere of duty would become enlarged until he had a division assigned to him as an Executive Engineer.[82] In effect, an engineer officer in India served an apprenticeship as a necessary supplement to formal classroom training.

The most telling critique of the Royal Engineers' training before the 1860's comes from two Parliamentary investigations : the 1857 report of the Commissioners appointed to consider the best mode of re-organizing the system for training officers for the Scientific Corps ; and the 1862 report of the Barrack Works Committee. These reports evaluate the Royal Engineers' education for the period during which all of the 30 engineer officers featured in this thesis were in attendance at the Royal Military Academy, Addiscombe and the Royal Engineer

Establishment. A great deal of the critical evidence comes from some of these same engineer officers. The immediate stimulus for the 1857 Commission was press and Parliamentary criticism of the officer staff in the Crimean War.[83] In the case of the 1862 Committee, although the stated purpose was to recommend measures that should be adopted to simplify and improve the system of barrack construction and maintenance in order to give more direct responsibility to the persons employed with building works, the real issue was whether or not the Royal Engineers should be kept in charge in the face of public criticism of their work and education.[84]

During the late 1850's, The Builder was one focus of such criticism. The basis of a number of editorial complaints was that civilian clerks of the works in the Royal Engineer Department were doing the engineer officers' job but not getting credit or sufficient remuneration for it. There was a call for reform to raise the status and pay of the clerks of the works or better still to hire architects and civil engineers to undertake barrack works. Typical of the criticisms of the Royal Engineers' training and competence was an editorial of 26 July 1856. While acknowledging that "there are many most able officers in the department", The Builder claimed that military engineers were not properly trained for civil works:

> " The education at Woolwich does not make the young officer competent for this position; and when he leaves school, he is at once placed in command of what we are to suppose is a staff of experienced civilians, and gives at times, at any rate, as we happen to know, very nonsensical orders on matters of which he is positively ignorant. He is placed thus in a false position, and, with some few exceptions, remains in it. --- Unless we are misinformed, the military engineer officer, as a rule, is not qualified to perform civil engineering duties, or to prepare projects for such works, or even to organize and be head of such works. He has been fortunate in surrounding himself for the last thirty years with professional civilian assistants, under some indifferent and inappropriate title, to keep them from public view, who have performed the greater part of the works of the

> department, very indifferently in many cases, because working without hope of credit."[85]

There was much truth in The Builder's criticism as will be demonstrated in the section on the Royal Engineers' duties which concludes this chapter.

Also, in the very same year that the Barrack Works Committee reported, civil engineer George Burnell made an even more devastating criticism of the Royal Engineers not only in barrack construction but in fortifications too:

> " It is the fashion just now to employ officers of the Royal Engineers to superintend the works of architects and civil engineers; but the instances above given seem to prove the lamentable ignorance of the practical details of construction amongst the men who are assumed to be able to guide the State in its relations with private industry. A chair for the practical arts of building is in fact required at Woolwich, as it would be in any properly organized school of architecture; --- and, as the studies of military engineers are not usually such as to lead them to examine the minor details of building, it would be desirable to call in occasionally the services of the civil branches of the profession."[86]

Burnell was particularly critical of new barrack works at Aldershot and Colchester:

> "--- in this matter of barrack and camp construction the same observation may be made --- that the Royal Engineers are not efficiently instructed in the profession either of architecture or civil engineering."[87]

The criticisms from the technical press and building professions must have helped focus attention of the War Office and the Royal Engineers on the quality of the engineer officers' training.

By far the most revealing evidence concerning an evaluation of the state of Royal Engineer education before the mid-1860's is to be found in the report of the Commission on re-organizing the system of training for the Scientific Corps. In their investigations, the Commissioners first visited the Royal Military Academy and the Royal Engineer Establishment. They then drew up a questionnaire and sent it to a sample of Royal Engineer and Royal Artillery officers of various ranks and in different occupations and stages of their career. The Commissioners also visited and sent questionnaires to military schools in France, Austria, Prussia and Sardinia. Their general conclusion was that foreign schools were afforded greater importance by government, had better teaching standards, stricter discipline, more teachers, more money and a more complete system of education for engineer and artillery officers.[88]

With respect to training in architecture and civil engineering their most important recommendations concerned reform of the Royal Engineer Establishment. They called for provisional commissions after leaving the Royal Military Academy with passing out examinations after the Establishment course and final classification in order of merit for purposes of promotion and increased rates of pay, the extension of the study programme from 15 to 18 months and, most importantly, more opportunity for practical instruction and experience with major works.[89] The first recommendation appears not to have been implemented but the second one was taken up in the early 1860's. It was the last recommendation, however, which proved to be of pivotal significance with respect to the Royal Engineers' own assessment of the nature and quality of their training and it is worth quoting:

> "--- young Officers should have opportunities afforded to them, of being made practically acquainted with the working details of large public undertakings, and by their being made responsible for the works carried on under their orders, so as to induce them to take greater interest in their profession --- as it can scarcely be doubted that the more young Officers are obliged to depend on their own resources --- the greater probability of their proving efficient public officers."[90]

The basis of this recommendation was the conclusion that the Royal Engineers' formal education provided only a theoretical training and that practical skill had to be self taught and learned essentially on the job after leaving the Royal Engineer Establishment. But as the Commissioners explained, a young engineer officer did not have the chance to do this:

> "---he is not often placed in a situation where he is required to apply his theoretical

> knowledge practically, neither is he made responsible for works carried on under his orders; and thus he is not placed in a position to gain that practical knowledge, which his education and instruction at Woolwich and Chatham have failed to afford him. In some instances, he is placed in circumstances where he is obliged to think for himself, by being made responsible for the execution of important works; but even here complete responsibility is seldom given to him, as he is very liable to be directed to hand them over, in an incomplete state, to a successor, and thus young Officers cease to take an interest in the performance of their Professional duties."[91]

A total of twenty Royal Engineers replied to the questionnaire administered by the Commission. Their replies overwhelmingly support the conclusion that the engineer officers' theoretical education was more than adequate but that their practical training was deficient. Typical were the statements of three Royal Engineers who figure prominently in the present thesis - Sir John Lintorn Arabin Simmons, Henry Scott and Sir Douglas Strutt Galton. Simmons said of the engineer officers' training: "... this education is only theoretical; it remains therefore to teach them the practical utility of what they have learnt, and the application of science to practice."[92] Scott called for a six month course in civil engineering to be added to the programme at the Royal Engineer Establishment with visits to works in progress and practical design exercises. He maintained that engineer officers had quite enough theoretical training: "... I consider that, in the junior ranks at least, Engineer Officers do not so much need to extend their scientific acquirements of a theoretical nature, to enable them to perform their duties..."[93] The statements of Galton are particularly illuminating. He began by saying: "The theoretical education which an Officer has thus received is very much better than that received by the large majority of Civil Engineers, and if he were once placed in situations where he would be required to apply his knowledge practically, and where he would be responsible for the works he superintended and for the duties he performed - as is the case with Civil Engineers - he would gain that practical knowledge which his education does not afford him."[94] Galton continued by pointing out that because engineer officers were ill trained to deal with many practical matters they had often to learn on their own on the spot, not a desirable situation in his view:

> " Officers, when they have advanced in their profession, are generally placed in responsible positions, and are required to design and execute works calling for an amount of practical knowledge which their previous training has not necessarily given them an opportunity of acquiring. They are required in every variety of climate to deal with all sorts of different materials, they are frequently placed in isolated situations and unable to consult books, or to learn from the experience of others. Under these circumstances, therefore, it appears desirable that the education of an Engineer Officer should include the application of theoretical knowledge and instruction to the practical details of the principal parts of his profession."[95]

Finally, Galton gave his prescription for the best training method for engineer officers - the pupilage system of civil engineers:

> "--- practical knowledge gained in the construction of civil works would qualify men better than any other education for the varied duties of the Engineer Department in the field. --- students should be attached to stations at which works are in progress, either without commisssions or probably provisional commissions in the capacity of Assistant Engineers, where they should be employed in making drawings, specifications, and estimates, and in the minute and constant supervision of works, for the detailed execution of which they should be held as strictly responsible as the articled pupil of a Civil Engineer."[96]

The observations of these Royal Engineers were reiterated and developed further in engineer officer testimony before the Barrack Works Committee in 1861. It appears that officers trained during the early years of Pasley's architectural course left Chatham with reasonably good design skills but that later graduates were not so well prepared to assume construction duties. Henry Harness who was a student at the Royal Engineer Establishment in 1827 testified that: "--- an officer now is not fitted, when he leaves Chatham, to go out and make measurements or to make a design, and measure it; but I am quite certain that when I left Chatham I was perfectly able to sit down and make a design, and make all the measurements and estimates, and to ascertain the prices of different descriptions of work ---."[97] He further pointed out that while stationed in Bermuda (1828-1833) : "--- Col Nelson and I made many designs, and a very large number of estimates, including much cast and wrought iron work, and that was after coming straight from Chatham."[98]

The experience of brother officer Francis Fowke who was at Chatham fifteen years later was markedly different. Fowke is best known for his architectural works at South Kensington and is a major figure in the present study. In his testimony before the Committee, Fowke described how he had had to teach himself on the spot how to construct a barrack at Bermuda in the 1840's:

> " I was put to construct that barrack without any assistance, and I found that it was necessary to instruct myself, and I took every means of doing so, by first of all picking up as much as I could from books, and also from actual observation, construction always having been rather the bent of my inclination; ---"[99]

Fowke further explained that he learned by doing in all practical work and believed fellow officers skilled at construction had had the same experience:

> " I believe that to have been the beginning of all the instruction that I have had in practical work, the actual doing of the work without any assistance; and I believe you will find that that has been the experience of many other officers of the engineers who have been thrown on their own resources. I have frequently heard officers say in private conversation that that has been their experience; I refer to officers who are good constructors."[100]

Like Galton, Fowke favoured the apprenticeship system as the way to better engineer officer training. He suggested that each officer "be put in a state of apprenticeship under their superior officer" for at least two years before he was ready for ordinary duties.[101] Fowke added : "--- what I have just advocated would be adopting very much the same system in the Royal Engineers which has already been found to answer very well in civil practice, only that you have a very high class of material to deal with at the beginning."[102]

It will be remembered that engineer officers in India did go through a form of apprenticeship which the Royal Engineers were advocating for the Imperial corps. Bengal Engineer, Richard Strachey, who had been in India since 1834, extoled the merits of this system:

> " I think that you should aim at having a body of Royal Engineer officers who are capable of going into every detail: and I think that the way to arrive at that result is to give all the young Engineer officers the sort of training they have in India; that is to say, to make them go through the whole of the dirty work themselves, to give them the superintendence of some work or subdivision of duty, under an officer of experience, and to make them carry out the whole of the details of every sort themselves, without any subordinate to assist them."[103]

Pupilage or the apprenticeship system was the prevailing method of training civil engineers and architects throughout the nineteenth century notwithstanding the founding of the first chair of engineering at Glasgow University in 1840, the introduction of engineering courses at the London colleges in the same decade, the establishment of the Architectural Association in 1847 and later developments in institutional education. In Britain, learning by doing brought results as testified to by the nation's remarkable achievements in structural innovation in iron, in the development of artificial cements and other pioneering contributions to progress in the technology of building. The prejudice against change to the Continental systems of engineering education with their focus on theoretical science and mathematics as well as institutional instruction was hard to dislodge. The apprenticeship system served Britain well for the most part until the 1870's by which time it became increasingly obvious that extensive and rapid change in technology and the growing complexity of construction demanded greater investment in institutional training for engineers and architects and in technical education generally. Some effort had been made to improve the latter from the 1850's.

The engineering profession, however, did little to equip itself for the challenges of the future. British engineers spent much time aspiring to 'gentleman' status through the acquisition of wealth, property and titles. They were willing to learn from the theoretical work of others and to use science to practical ends but they largely ignored a new concept of engineering, one based on theoretical competence obtained in the academic discipline of a university. Similarly, the Victorian architectural profession was less involved in attempts to establish a means of formal institutional education for its members than in efforts to protect its interest and improve its social status. The Royal Engineers could claim an early advantage in theoretical training and their experience at the Royal Military Academy supplemented by that of the Royal Engineer Establishment was comparable to engineering education offered at Britain's universities at least until the 1870's. Nevertheless, what is more revealing, the Corps held on tenaciously to the idea that learning by doing was best and took as its model of success the achievements of the private sector.[104]

In-Career Training

The 1857 Commission on re-organizing the training of the Scientific Corps concluded that the Royal Engineers' opportunities for in-career learning were not adequate. The key problem was thought to be insufficient leave time to pursue improvement. Perhaps the most revealing testimony came from the current director of the Royal Engineer Establishment, Colonel Henry Sandham. He told the Commission:

> "I am of the opinion that after an officer has gone through his studies and duties, (theoretical and practical) at Woolwich and Chatham, facilities should be continued to him; he should have opportunities of travelling, and of visiting military and civil establishments and manufactories at home and abroad, afforded him; every inducement and every reasonable assistance should be given him to collect information. Hitherto an Officer has had great difficulties to contend with in his endeavours to improve himself; scarcely an Officer in the corps could obtain leave of absence from his duties even for such an object; this, and the

> expenses of travelling and of collecting information, have almost entirely prevented his seeking information beyond what a library could afford."[105]

Notwithstanding the report of the Commission, there is considerable evidence presented in this thesis which demonstrates that in-career training was supportive of the Royal Engineers' means to contribute to advances in the technology of building. Foreign travel to collect information was not a major feature but it did occur from time to time. Examples include Richard John Nelson's travel to Germany where he observed the practice of building laminated timber arch roofs and bridges by the Royal Prussian Engineers and others, Fowke's work at the Paris International Exhibition of 1855 where he observed state of the art techniques in building technology and experimented with new colonial woods, and Sir James Browne who travelled to Europe and especially America to study iron and steel bridge construction. The most important in-career learning opportunities, however, were working with private sector engineers, architects, manufacturers and others, and posting to a variety of colonial stations. In effect, this constituted a rough equivalent to the civil engineers' and architects' apprenticeship. Co-operation with the private sector will be explored throughout the thesis and the matter of colonial connections is examined in the penultimate chapter. Nonetheless, there were two other opportunities for in-career training that merit discussion - the engineer officers' own professional literature and the Corps library system. Both were considered by the Royal Engineers themselves to be of special importance. Two examples will illustrate this point. In his evidence to the 1857 Commission on re-organizing the training of the Scientific Corps, Colonel Sandham explained:

> " Great efforts have been made by Officers of the corps, and they have been at great expense in forming purely professional libraries at all the Engineer stations at home and abroad; as well as in printing and publishing Corps Papers on professional subjects, which have established the scientific reputation of the corps, and show that there is no want of energy on their part."[106]

A similar testimony was made in 1860 by Henry Harness in a memorandum on a report by Colonel Owen concerning the condition of the Corps service:

> " The publication of professional papers of the Corps, the compilation of the Aide Memoire, the foundation of the Corps libraries of professional works at our stations, have all sprung from ourselves, and are evidence of the special desire among us that our Corps shall preserve its character, and shall keep pace with progress of the age in its collective information."107

Indeed, the professional periodical literature, the Aide Memoire and the libraries of the Corps did reflect the extraordinary determination of the engineer officers to keep up with the times and improve their individual and corporate knowledge and skills.

Professional periodical literature was produced by both the Royal and Indian corps and from an early date. The Royal Engineer Professional Papers, founded by Denison with the help of Harness in 1837, compares favourably with civil engineering and architectural periodicals which emerged in the fourth decade of the nineteenth century and which had a considerable influence on the art and technique of building.108 In the first volume of the Professional Papers , Denison explained the purpose of the new journal:

> " The object of the present work is to collect, methodise and arrange, the large mass of professional information which is at present disseminated among the individuals of the corps of Engineers; and to combine it with that derived from other sources; thus enabling every officer to avail himself not only of the experience of his fellows, but also in some measure of that of all those whose occupations and duties are similar to his own."109

Denison saw the Professional Papers as one important means of overcoming the deficiencies of the engineer officers' formal education at Woolwich and Chatham:

> " It cannot be concealed, that when compared with similar institutions in other countries, these, as places of scientific instruction, are grievously defective, and it therefore behoves those who, after passing the ordeal of nominal examination, have received

> their commissions, not to delude themselves with the idea that they possess the elementary knowledge which their profession requires."[110]

Subscriptions to the Professional Papers after the first year of publication stood at 417. Of this number 110 or close to 25% were East India Company engineer officers.[111] From the outset, Denison emphasised that the new journal was an important opportunity to keep in touch with brother officers in India on professional matters: " I have received assurances of the intention of Officers of the E.I.C. Engineers to afford us their assistance and support; and from the nature of the duties upon which they are employed, we may expect to receive from them some valuable communications."[112] By 1847 subscriptions were held by 250 Royal Engineers, 112 East India Company Engineers (plus 50 copies to the East India Company as a government to be sent to their principal stations), 48 Royal Artillery and many from other corps. Copies were also sent by John Weale, the publisher, to almost every military library in the capitals of Europe and America.[113] The then editor, Sir Henry James, indicated the popularity of the Professional Papers and made a plea for the British government to purchase copies and deposit them permanently at various stations in the same way as with the East India Company to ensure the maximum availability and long term benefit from the periodical: " These volumes have been purchased by almost every Officer of the Corps, not for his personal gratification, but the better to enable him to discharge his various duties; but unless the information they contain is 'garnered up' by the Government at our stations, the fruits of our labour will be lost to those who succeed us."[114]

Reviews of the Professional Papers, although not without some criticism, were favourable. The review of the first volume by The Civil Engineer and Architect's Journal put the new publication in context yet was somewhat disappointed with the initial product:

> " The excellent example of the Institute of Civil Engineers, in publishing the first volume of their Transactions, has brought forth similar works from the Architects, and the Corps of Royal Engineers; the latter work is now before us, and contains many interesting papers, but not to the extent

> we were led to expect, from the well-known abilities of several scientific members of the Corps, which we fear may rather arise from punctiliousness in appearing before the public, than from want of talented means."[115]

By 1845, however, The Civil Engineer and Architect's Journal was outspoken in its praise for the Professional Papers: " This work prospers under its editor, Captain Denison, and the present volume contains many valuable and practical papers ---."[116] It continued later: " The civil engineer will find here a great many practical examples, to which he may refer with pleasure and advantage, and which he can find no where else."[117] The instructive values and other qualities of the Professional Papers were summed up nicely by Lieutenant Colonel Lacom in his reply to the questionnaire of the Commission on re-organizing the training of the Scientific Corps in 1857:

> " I venture to think the publication of professional papers, first begun by Sir William Denison, one of the most useful things in this direction which has occured in the corps in my time. Besides making the experience of each available to all, it creates a public opinion, enables Officers to appreciate each other, and brings them under the notice of the heads of the corps."[118]

Engineer officers in India were involved in producing two technical periodicals. The first was the Professional Papers of the Madras Engineers published 1845 to 1855. It was initiated by John Thomas Smith of the Madras Engineers. Smith made important contributions in the development of limes and cements and his career is discussed in chapter eight. While this short lived technical journal contained a number of important articles, its impact appears to have been rather parochial. The other venture was Professional Papers on Indian Engineering published in three series between 1864 and 1886 by Thomason College Press at Roorkee. The first editor was Major J. G. Medley of the Royal Engineers. Thomason College was founded in 1847 to train civilians as sub-assistant civil engineers, for the instruction of British non-commissioned officers and soldiers as overseers and to teach native Indians as surveyors. Engineer officers were not taught there but played an important role as teachers, and from the year of the college's establishment to 1891 all the Principals were Bengal or Royal Engineers.[119] Thomason College was the most celebrated of a number of civil engineering schools established in India, mainly to train personnel for work on irrigation canals, in which the Indian and Royal Corps played an important role as educators and administrators.[120] Circulation figures and reviews have not been found for the Professional Papers on Indian Engineering but its impact seems to have been considerably greater than the earlier effort by the Madras Engineers.

The Aide Memoire grew out of a suggestion for a Royal Engineer encyclopedia. It was produced originally (1853-1862) by a committee of engineer officers serving in Ireland at the time. They were G.G. Lewis, Harry Jones and Richard John Nelson. The last made important contributions in experiments with colonial woods while in Bermuda earlier in his career and this is discussed in chapter eight. Contributions were solicited from all officers in the Corps on military engineering subjects and related fields. Considerable information on construction was given. The editors' stated purpose was to provide a reminder and reference to military and collateral sciences already studied for the use of engineer officers in the field, the colonies and remote stations where reference books were seldom found. Revised editions of the Aide Memoire continued to be produced late in the century.[121]

In addition to the professional literature published by engineer officers, another important opportunity for in-career training was the Corps library system. Sir Charles Pasley started a professional library at the Royal Engineer Establishment in 1813. Libraries were soon established at other stations but enthusiasm later diminished and by 1845 only those at Chatham and Dublin remained. In that year the library question was referred to a committee of Royal Engineers which developed the idea of a central circulating library in London with out-station libraries which would be supported by subscription, the transportation cost between libraries to be borne by the government. The plan was formally approved in 1848. By 1850, in addition to a number of libraries in Britain, there were 16 established in the colonies, and in 1862 there were 19 foreign and 16 home ones, excluding India. After 1852 the Chatham and Dublin libraries ran their own affairs distinct from the central circulating system. By 1863 the total number of books, excluding pamphlets, was 6,000 in addition to which there were 4,000 and 1,800 respectively at the independent libraries of Chatham and Dublin.[122] The purpose of the library system was stated clearly:

> "---- to enable Officers, whether serving at home or on foreign stations, to pursue and refer to the best authorities on any of the multifarious duties which they, as Engineer Officers, are liable to be called upon to perform; such works being of necessity more numerous and more expensive than an officer can be expected to possess, or to carry with him."[123]

Undoubtedly, the Corps libraries were most useful in the colonies where alternative facilities were much less likely to be found. In British North America, for example, there were libraries at Halifax, Montreal, Quebec and Newfoundland during the 1860's. A list of books with the Royal Engineer Department in Canada in 1863 included, for example, Mahan's Civil Engineering (1846), Cresy's Encyclopedia of Civil Engineering (1847) and Mosely's Engineering and Architecture (1843).[124] It is probably impossible to determine exactly to what extent engineer officers used this library system and how much they benefited from it. Only one piece of evidence has been found and it gives a negative impression. In testifying before an 1838 Commission of Enquiry into Military Promotion, Major General Frederick Thackeray of the Royal Engineers in Ireland said: " We had a professional library under the roof of my own office and I found that I had no time to read any professional books, and I asked the gentleman who was the librarian whether the officers took out books, and he said that a few took out books but not professional books."[125] This of course was before the development of the circulating library system and cannot be taken as indicative of the effectiveness of the Corps libraries everywhere and throughout the century. Testimonials quoted earlier seem to suggest that the Corps library was of considerable benefit to the engineer officers.

Duties

During the nineteenth century the Corps developed a remarkably wide and varied range of skills based on professional, managerial and administrative appointments of markedly different character which any one individual could experience to a greater or lesser extent depending on his career path. Engineer officers had duties in construction, both military and civil, surveying and mapping, photography, telegraphy, electrical engineering, steam traction, aeronautics (balloons), artillery and torpedoes, military tactics and organization, and inspectorships, governorships and a host of other public service posts.[126] Some of the individuals who comprise the core group of 30 engineer officers studied here demonstrated a fair degree of mobility in their careers but others specialized in one or two assignments, particularly those on long term secondment to the civil service. Engineer officers worked in architecture and civil engineering in several different government departments and stations both at home and in the colonies including the War Office, the Admiralty, the Board of Trade, the Department of Education of the Privy Council, the Home Office and a number of colonial public works departments, most importantly in India.

Royal Engineers assigned to military and fortifications duty or to barrack construction and maintenance under the War Office were appointed to their station according to a roster which ensured each officer had a fair share of home and foreign service. An officer rarely spent much time at a particular station. There was a special unit in the War Office under the Inspector General of Fortifications which dealt with designs for defences as well as barracks and military hospitals, but the Royal Engineer departments at home and abroad at the various stations did much of the design and supervised construction. At home stations Royal Engineer officers in a district were usually allocated responsibility for a division with a clerk of the works to assist them. The engineer officers performed the duty of general supervision of works and produced original sketches for large buildings, but the design of small buildings, the detailed drawings of all buildings, the specifications and estimates were, as a rule, drawn up by clerks of the works and approved by the Royal Engineers. The criticisms of this system in the 1850's discussed earlier were therefore not without foundation. In the colonies the Royal Engineers had clerks of the works too, but evidence suggests that they were less dependent on them for design and construction expertise. They also had assistance from the men of the Royal Sappers and Miners. In India an engineer officer was primarily responsible for all design matters, and clerks of the works and other assistants were clearly in a subordinate role. Moreover, engineer officers in India were responsible for both civil and military construction of the state, and many were attached to the Public Works Department, a wholly civil body. Accordingly, it was an exceptional Royal Engineer who had the opportunity or the inclination to make important contributions to building technology while on military or barrack duty at home. He had a better chance while on colonial station, especially if assigned to a public works department, by virtue of his being often the only formally educated builder or scientifically trained person on the spot. In India the opportunity was considerable in this respect.[127]

It was in civil employment that engineer officers had the best chance to excel in contributions to the technology of building. Here they had greater responsibility, wider scope for their talents and more opportunities to work with gifted civilians. As the role of the state expanded in the nineteenth century, especially into areas demanding scientific and technological expertise, the Royal Engineers were often called upon to staff new or enlarged departments. Indeed, well into the century they were the only organized body of scientifically trained persons available to serve in such positions. In this respect historians have most often used the example of the recruitment of the Royal Engineers to serve as inspectors of science instruction in schools for the Science and Art Department, the main agency for the promotion of technical education which arose following the Great Exhibition of 1851.[128] The Science and Art Department was also the civil posting in which Fowke and Scott made their well known contributions to Victorian architecture. More indicative of the use of the Corps to staff new government activities in engineering and architecture was the secondment of Royal Engineers for the inspectorate of railways and as surveyors-general of prisons. And finally, the Admiralty called upon the Royal Engineers to direct and superintend a reorganized and much expanded Works Department for the naval dockyards, a civil office founded originally in the late eighteenth century.

The terms of the Royal Engineers' secondment to civil service employment varied in details from the late 1830's and early 1840's when they were called upon to serve the Admiralty, the Home Office and the Board of Trade, to the 1850's when they joined the new Science and Art Department to the 1870's when the government appointed a committee of enquiry to look into the matter. Essentially, however, they could be seconded upon the request of a civil department and at the pleasure of the War Office. The salary for the various civil postings usually exceeded military pay. Normally, engineer officers continued to draw their military pay and the civil department made up the difference between it and the salary for the civil posting. After ten years continuous employment in a civil posting an engineer officer had to return to military service or resign his commission or, with permission of the Secretary of State for War, go on the Reserve List with no guarantee of being recalled to military duty. One could, however, be recalled or asked to return to active military service before the expiry of the time limit.[129]

While remuneration for civil service department positions usually exceeded military pay, it was very modest. Engineer officers were paid less than what a civilian professional would be paid for an equivalent position. This was certainly true in the case of the railway inspectors and the directors and superintendents in the Admiralty Works Department.[130] In 1872 there were 48 Royal Engineers seconded to the civil service, 9 of whom were in civil engineering or architectural positions. The highest paid was Sir Edmund Frederick Du Cane as Surveyor-General of Prisons and Inspector of Military Prisons (£1,400) and the lowest was J.D. Bowly as temporary Assistant Architect to the Poor Law Board (£200).[131] The advantages to the public of the employment of the Royal Engineers in the civil service were succinctly described in 1857 by Inspector General of Fortifications, John Fox Burgoyne:

> " Officers are obtained of many desirable professional acquirements, and of qualifications which are thoroughly known, at rates of remuneration (where not under previous regulation) generally inferior to what would be considered reasonable for civilians of the same qualities; their previous military habits render them more managable as public Officers; they are totally independent of the class with which they are required to act, and perhaps control, and are consequently free from partialities that may exist in it; andtheir services in such extraneous employment can, without difficulty be dispensed with at any time."[132]

The quintessential Victorian civil servant, Sir Henry Cole, was an ardent advocate of the Royal Engineers and his collaboration with Fowke and Scott in the Science and Art Department is discussed in chapter seven. Cole was extremely critical of restrictions on the employment of engineer officers in civil employment and especially of the ten year rule for secondments. He had a vision of the Royal Engineers as potential 'super' civil servants: "Selected by open competition for ability, trained scientifically, subjected to military discipline, with an esprit de corps, and imbued with a sentiment of honour as public servants, the perfection of organization and administration might thus be attained through the instrumentality of officers of this Corps."[133] The Royal Engineers were perceived by many of those in authority as competent, disciplined, trustworthy, hard working and cost effective servants of the public in civil employment. These qualities were bound to enhance any aptitude an engineer officer possessed for making contributions to building technology development.

There was one other occupation of the Corps which has been mentioned already in connection with the Royal Engineers' formal education but it merits brief discussion here. This was posting as instructors and administrators at the Royal Miltary Academy and the Royal Engineer Establishment. In these roles Royal Engineers could have an important influence on the training of cadets and junior engineer officers. Pasley as director of the Royal Engineer Establishmnent during its critical formative period is of great importance in this regard. A memoir of Pasley which appeared in the Royal Engineer Professional Papers in 1863 described his contribution:

> " During the 29 1/2 years that he was head of the Royal Engineer Establishment, there was hardly any subject connected with his professions as a military man and an engineer - of instruction, construction, or destruction - that did not benefit by his attention - - - . The corps of Royal Engineers owes in fact its existence in its present condition, as well as its high state of efficiency,to his energy, his example and his exertions ---."134

Also of some note as director of the Royal Engineer Establishment is Henry Harness who instituted important reforms in the period 1860-65. Amongst the instructors,two were outstanding in their influence at the Royal Engineer Establishment - Pasley and Scott. It is to their achievements in developing and nurturing an experimental tradition at the Estabishment and in making personal contributions to the remarkable story of British developments in pioneering artificial cements that we next turn.

2. EXPERIMENTS AT THE ROYAL ENGINEER ESTABLISHMENT

The Royal Engineer Establishment had been founded as a deliberate attempt to improve the engineering effectiveness of the Corps. Sir Charles Pasley's personal aim was to make his branch of the Corps more scientific, and experimental science in building was an important part of this from the beginning. The approach was characteristic of the British empirical tradition, based on skills acquired on the job, which subordinated theory to practice.[1]

As early as 1816, Pasley undertook at the Establishment experiments on wooden models to determine the stability and most efficient form of retaining walls. Models were widely used in structural analysis and design in nineteenth-century Britain in contrast to the French preference for mathematics and the American 'trial and error' approach.[2] Pasley claimed to have confuted the then generally received theory of the pressure of earth on revetments or retaining walls. The results of his experiments were published the next year in his *Course of Instruction Originally Composed for Use of the Royal Engineer Department* and later in his *Course of Elementary Fortification* (1822).[3] A junior engineer officer at the Establishment was to resume Pasley's retaining wall experiments in the early 1840's.[4] Moreover, in 1845 an engineer officer of the Bengal Engineers made important use of models for the design of suspension bridges in India, a topic which will be discussed in the penultimate chapter. Pasley's model testing was a relatively early example of this characteristically British approach to building science and design and it set the style and tone for an experimental tradition at the Royal Engineer Establishment.

The most important contributions of this experimental tradition, however, were concerned not with structural engineering but with the manufacture and testing of synthetic cements. More generally, these contributions furthered understanding of old and new lime and cement mortars, plasters and stuccos, and also had an important impact on the attitudes of the Corps and others towards the uses of mass concrete and artificial stone. These achievements were almost entirely the work of two engineer officers - Charles Pasley and Henry Scott. Their endeavours were firmly rooted in the advances of their respective times, and though they differed substantially on key points, one was the logical successor to the other.

Pasley's work was undertaken in the 1820's and 1830's. It followed upon the development in the late eighteenth century and first two decades of the nineteenth of hydraulic limes and cements, initially natural and then artificial. These were stronger and more durable than ordinary lime mortar and were used principally as mortars for engineering works under water, in mortars and stuccos for building brickwork and, in the case of hydraulic lime, for mass concrete in foundations and in backing masonry retaining walls. Cements were developed primarily by the British and hydraulic limes by the French, although the two materials were used in both countries.[5] Pasley's contribution to British achievements in this field of building technology centred on the development and promotion of artificial cement, on the testing and advocacy of hoop iron reinforced cement mortar in structural brickwork, and in the publication of technical literature on limes, cement and concrete.

Scott's endeavours took place from mid-century until his death in 1883, encompassing a ten year career at the Royal Engineer Establishment where his most important contributions were made, as well as later work while in the employ of the Science and Art Department. His other building technology achievements in the latter position are discussed in Chapter 7. The period during which Scott made contributions was marked by the rise of Portland cement to hegemony, a phenomenon dominated by British achievement until the 1870's when leadership passed to Germany. It was also a time in which concrete was used increasingly in fireproof floor construction, and when some early experiments made with reinforced concrete anticipated the significant introduction of this revolutionary new technology in the last two decades of the century.[6] Scott's major accomplishments included the discovery and marketing of a new cement which was a rival to Portland cement as well as Martin's and Keene's cements for plaster and stucco work, and more importantly the invention of the selenitic process upon which his novel product was based. As an ancillary benefit of these endeavours he helped considerably to improve the knowledge and skill of the Royal Engineers in the use of lime, cement and concrete. After leaving the Establishment, Scott made some interesting though less significant contributions through his invention of a process for the manufacture of sewage cement and business ventures in its commercial application, as well as by his promotion of standardized test specifications for Portland cement.

Pasley and the Manufacture of Artificial Cement

Pasley began artificial cement experiments at the Establishment in 1826. In his own words, these were "induced" by Wellington's order of 1825 to develop a course in practical architecture for the Royal Engineers.[7] There is no evidence that he received a direct order to undertake this experimental work and therefore it seems fair to conclude that Pasley's investigations on the manufacture of artificial cement and related ventures were taken on his own initiative as part of teaching building construction at Chatham. It was not surprising that Pasley's bent for practical experimental enquiry should focus upon pursuing scientific explanations for the use of lime and cement, discovering new and better bonding agents and surface finishes for traditional masonry constructions, especially in brick, and making some explorations as well into the use of concrete as a cheap substitute material for brick and stone. When the Royal Engineers took over barrack construction and maintenance in the early 1820's, most building in England was in brick. Indeed, as discussed earlier, Pasley's <u>Outline of a Course in Practical Architecture</u> (1826) focussed on brick construction. Furthermore, the current fashion was for brick structures rendered to look like stone. It is significant that Pasley provided instructions in his teach-yourself textbook on practical architecture on how to disguise a heterogeneous structure with stucco, and that he referred to this technique's having been used in John Nash's terraces in Regent's Park.[8] Another underlying reason for Pasley's interest in limes, cements and concrete, though not articulated by him, was the military engineers' ongoing concern for improved fortifications. Their objective was to make these masonry structures ever more durable and resistant against the increasing fire power of artillery. This stimulated a search for stronger mortars. It also encouraged attempts to find cheaper solutions to traditional stone and brick construction in the face of niggardly Treasury allocations for land defences, thus inducing experiments with concrete.[9] And finally, it was of considerable significance that Chatham was located in the heart of the Medway country which, together with the Thames Basin, was responsible for three-quarters of England's cement production in the nineteenth century. The basic materials of chalk and clay were near at hand and North Kent was well placed for shipping in coal by sea and for transporting cement to London.[10] It was also an important advantage for Pasley to have manufacturers close by with whom he could exchange information on the techniques of cement making.

In the cementatious materials of modern times the first forward step was in the manufacture and use of hydraulic limes, both natural and artificial. John Smeaton (1724-1792) had pointed the way by experimenting with limes that would harden under water in his work on the Eddystone Lighthouse (1756-1759), and he had published the results of his experience in 1791.[11] A great number of other individuals worked to advance knowledge of hydraulic limes and cements in the late eighteenth and early nineteenth century. Amongst them the most pre-eminent was Louis J. Vicat (1786-1861), French engineer of the Ponts et Chaussées, who began investigations in 1812 and published his first results in 1818. These results were later extended and incorporated in a book in 1828, and this book was translated into English in 1837 by Captain John Thomas Smith of the Madras Engineers, about whom more will be said in Chapter 8.[12] Another important contributor, though not of the same calibre as Vicat, was J.F. John (1782-1847), a Professor of Chemistry at Berlin.[13]

Natural cement with hydraulic properties followed upon the development of limes for underwater use. In England the first such natural cement, later called 'Roman cement', was patented by James Parker in 1796. It was made by calcining nodules found in gravel deposits, but later cement stones dredged from the sea bottom near shore were used as raw material for natural Roman cements.[14] In 1822 James Frost, a London builder, obtained a patent in England for an artificial cement which he called 'British Cement'. Frost benefitted from Vicat's work, and he had visited a factory in Meudon near Paris where artificial Roman cement had been produced for use in building and civil engineering works since 1819.[15] Another British artificial cement was produced and patented by Joseph Aspdin (1778-1855) in 1824. He gave it the name 'Portland cement', but his priority in the discovery and development of the substance of true Portland cement has been questioned.[16] Pasley credited Smeaton as the source of basic principles for his experiments on artificial cements and said, with reference to Vicat, Dr. John and his English rival Frost, that he began "without knowing any thing of the previous labours of those two gentlemen on the Continent, or of Mr. Frost, the acknowledged imitator of Mr. Vicat in this country."[17] In 1852 Pasley claimed he had not heard of Joseph Aspdin's Portland cement until introduced to it by his son William Aspdin (1816-1864) at the Great Exhibition of 1851 where the product of Messrs. Robins, Aspdin and Company was displayed.[18]

Pasley's initial attempt to produce an

artificial cement in 1826 involved a mixture of brick and loam clay and chalk after Smeaton's methods. It was a failure, however, and he gave up in frustration.[19] Nevertheless, two years later he was persuaded to resume his experiments by his brother officer Sir William Reid (1791-1858), then a major in the Corps.[20] On the first renewed attempt, his assistant, a soldier of the Royal Sappers and Miners, accidently used the blue alluvial clay of the Medway and a measure of success was achieved. Pasley therefore continued his experiments over the next two years, examining natural hydraulic cements and searching for a synthetic substitute. At first he burnt his mixtures in small crucibles and then on a larger scale in a kiln. In 1830 he succeeded in producing his first satisfactory kiln-burned artificial cement and tried it with good results in structures at the Brompton Barracks, Chatham, including water tank linings, and in stucco for external wall surfaces. He also made from this cement artificial coping stones as well as ornamental vases and chimney pots.[21] Following upon this experience, in 1830 Pasley obtained permission from Major-General Sir Alexander Bryce, Inspector General of Fortifications, as well as from the Master General and Board of Ordnance, to print and distribute 100 copies of a twelve-page essay on his work and findings. It was distributed to all Royal Engineer stations at home and abroad and to all engineer stations of the East India Company. Pasley explained that he had published this essay "under the impression, that the inferences drawn from these experiments might be useful to Engineer Officers, especially in the Colonies..."[22] The essay did in fact prove to be a catalyst for experiment by engineer officers in the colonies and this story is taken up in Chapter 8.

Encouraged by these accomplishments, Pasley pressed on with his experiments over the next eight years. In 1836 he apparently produced his best results with Medway alluvial clay and chalk when working at his small Chatham manufactory which comprised a small iron kiln, a pugmill and a grinding mill. Pasley described the formula and advantage of his 'new material':

> "... it therefore appears that a mixture of 10 parts by weight of pure chalk perfectly dry, with 13 3/4 parts, also by weight of alluvial clay fresh from the Medway, will produce the strongest artificial cement that can be made by a combination of these two ingredients, and it has the advantage of not setting so quickly either as the artificial cement prepared by us in 1830, or the natural cement produced from pebbles of the Isle of Sheppy."[23]

In January 1837 Pasley gave an account of his artificial cement experiments to a meeting of the Institution of Civil Engineers of which he was a member.[24] The following year he published his master work entitled Observations on Limes, Calcarious Cements, Mortars, Stuccos and Concrete etc. in which his experiments on synthetic cement and related matters are fully described together with an historical account of the development of cementatious materials unequalled in the nineteenth century. A second edition appeared in 1847, but by then his researches had come to an end six years earlier when he left the Royal Engineer Establishment.[25]

In his experiments on the manufacture of artificial cement, Pasley obtained advice, information and assistance from an interesting variety of people. He credited the "zeal, intelligence and industry" of Private James Menzies of the Royal Sappers and Miners who assisted him, sometimes working alone, on the first successful experiments of 1828-30.[26] Pasley's 1836 experiments, from which he produced his best synthetic cement, were under the supervision of Robert Howe, clerk of the works and instructor in practical architecture at the Royal Engineer Establishment, and the work was performed by Lance Corporal John Down of the Royal Sappers and Miners assisted by three military boys.[27] In 1837 Pasley sent several samples of clay to Faraday at the Royal Institution, seeking an analysis of the specific gravity of the material. Faraday replied that he had time to analyse only two samples (pit clay and Medway clay) for which he provided the specific gravities but added: "This you required to know though I do not see what use it can be of to you..."[28] Faraday clearly did not contribute substantially to Pasley's development of an artificial cement but was the likely source for data on the specific gravities of clays given in Pasley's 1838 book. The first successful large-scale batch of artificial cement made by Pasley in 1830 was in a kiln belonging to a Mr. Nash, a coal merchant at Gillingham, the neighbouring town to the Chatham Establishment. Nash had himself tried many experiments on cements, according to Pasley.[29] For several years Pasley communicated with James Frost, the early producer of artificial 'British Cement', and in 1828 he visited Frost's works which had been established in Swanscombe Parish, Kent three years earlier.[30] Pasley said that in communicating with Frost he "always gave him full information" of his own proceedings but that "from a motive of delicacy" did not ask Frost about his proportions.[31] Moreover, Pasley claimed that he had advised Frost against washing the mixtures and against excessive drying, but to no avail; he was equally unsuccessful in persuading Messrs. Francis, White and Francis to abandon these practices after they purchased Frost's works in 1833. He also asserted that Frost had adopted his practice of using the blue alluvial clay of the Medway and his proportions of chalk and clay from the successful experiments of 1830.[32] Nevertheless, Frost later disputed some of these claims. He wrote to the Mechanic's Magazine in June 1841 from New York, about Pasley's 1838 book which he had just read:

> "... as he has made himself much more free than welcome with my name, and with my works, which he has in many cases grossly misrepresented, from not understanding them, I send you this letter as the first of two or three in which I intend to show the numerous mistakes the Colonel has made, and to do my best to place the whole subject in a better light."[33]

It appears that Frost and Pasley were not particularly friendly rivals and their relationship is an interesting case of how industrial secrets in the early artificial cement industry could become a delicate matter.

The basis of Pasley's claims for the qualities of his own artificial cement was a prodigious programme of testing. His objective was to establish 'scientifically' the superior strength in mortar of cement and hydraulic lime over ordinary lime, the equality of artificial cement with the best English natural cement, and the desirability of artificial cement (to his specification) over hydraulic limes (preferred by the French but also used in Britain). Pasley employed a variety of standard early methods for determining the tensile strength of mortar. Among these was the common practice of building out a number of bricks from a wall in the form of a 4 1/2 inch wide and 9 inch deep cantilever, the bricks being mortared in neat cement on the wide face and placed in position after the cement joint between the previous brick and its neighbour had set. Bricks were added at predetermined intervals, and to pass the test so many bricks had to be built per unit time (see Figure 1). Pasley used 15 bricks per hour in one test; in another he constructed a cantilever of 31 bricks, placing one brick per day.[34] He appears to have got the idea of testing by way of building bricks out from a wall from Captain Streatfred of the Royal Engineers at Chatham Lines, who first tested Pasley's cement in a series of experiments using this method in 1830, with Pasley in attendance on three occasions. Pasley also witnessed this test method at the cement works of Francis, White and Company, Vauxhall Bridge, Lambeth.[35] Another test method employed by Pasley, more reliable than the cantilever beam, was that of adhesion; this consisted of cementing two bricks together, and observing how much load was required to pull them apart. An apparatus was constructed consisting of a scaleboard, planks and weights, and a couple of pairs of iron nippers suspended from a gyn or from a tressel or tie beam. Stone bricks were cemented together in pairs and left ten days for the cement to set after which the joint of each pair of stone bricks was torn asunder by successive weights

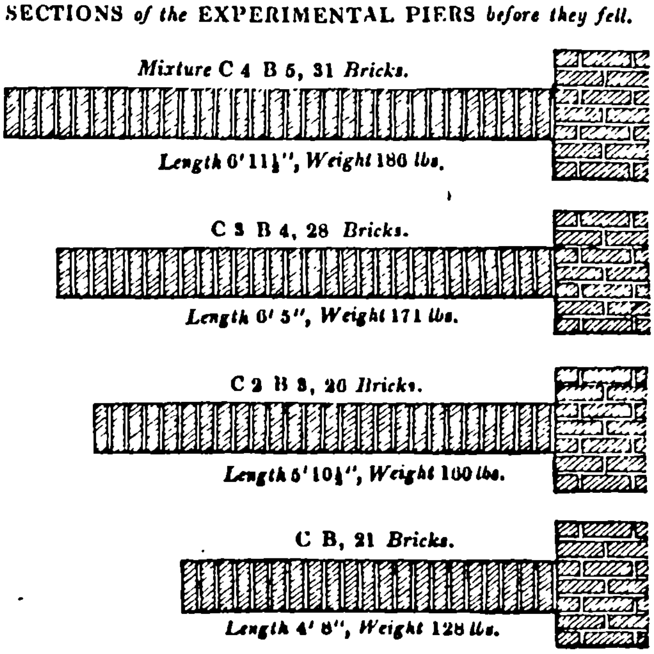


Figure 1 Pasley's Cantilever Beam Test

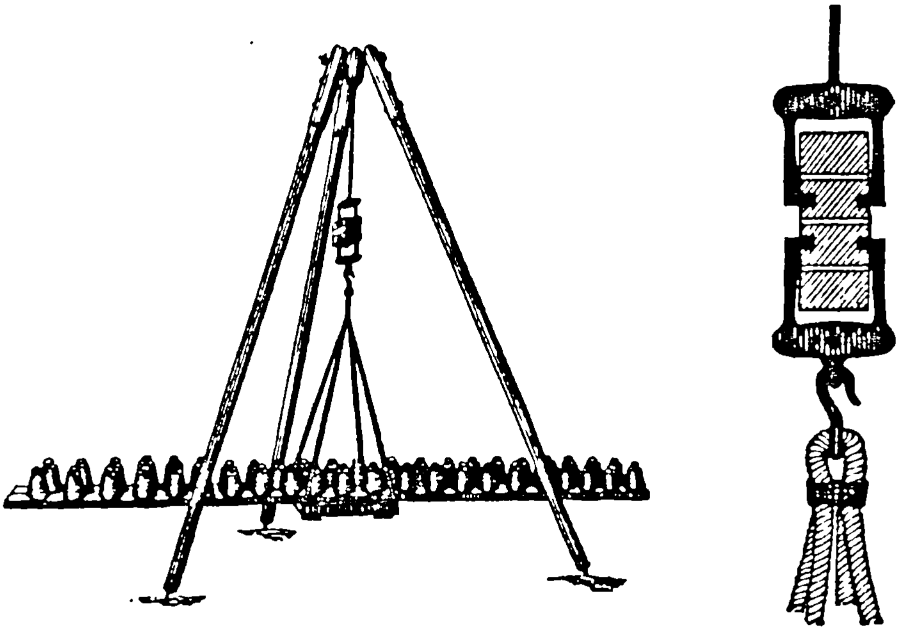


Figure 2 Pasley's Adhesion Test Apparatus

(see Figure 2). The maximum weight which could be borne by bricks joined with Harwich cement, a natural 'Roman cement', was used as the datum for comparison with Pasley's various mixtures of artificial cement.[36] Pasley also tested his new material by cementing together pairs of large Bramley-fall stones and tearing them apart. On one occasion the lower stone weighed nearly 2 1/2 tons. He suspended them from a beam by an eye bolt in the top stone and gradually added weight to a platform attached to the lower stone until the cement joint fractured and the mass broke down (see Figure 3). This rather spectacular series of experiments was intended to prove the strength of artificial cement in mortar for the largest type of stones used in civil engineering works, especially lighthouses.[37] And finally, Pasley built brick arches in cement and lime mortar respectively and, after a few months to let the joints harden, loaded them to destruction with successive courses of loose bricks (see Figure 4). The objective here was to show the superiority of cement in brick arch construction, particularly for tunnels.[38]

These early tests used by Pasley and others were far from 'scientific' in the modern sense. The more accurate and reliable system was to make a briquette of neat cement or mortar with a standard area at the neck or joint which was fractured under applied force to determine tensile strength. This test method was first introduced by the French engineers of the Ponts et Chaussées in their experiments on Portland cement 1848-1850.[39] The first systematic tests of cement on an extensive scale using the briquette method were made, beginning in 1858, under the direction of John Grant (1819-1888), engineer of the Metropolitan Board of Works, while he was working on the new main drainage project for London. The results of these experiments were published in 1866 and 1871. The briquette moulding apparatus and testing machine were made by Patrick Adie of Westminster and these were widely adopted and long considered as the standard in England.[40] Captain William Innes of the Royal Engineers adopted Grant's methods and Adie's

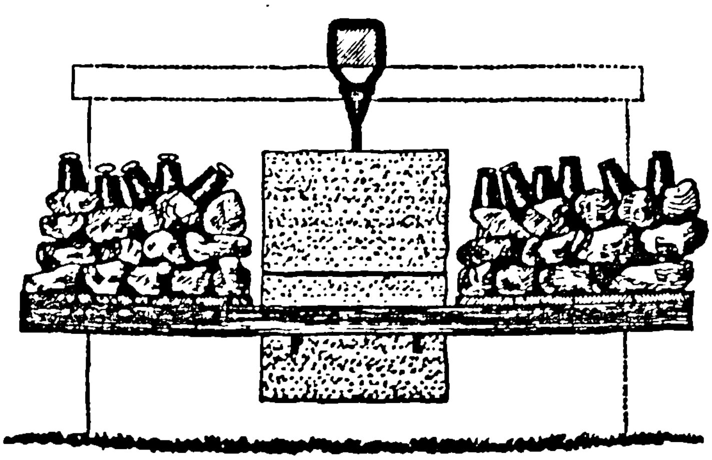


Figure 3 Pasley's Large Stone Adhesion Test

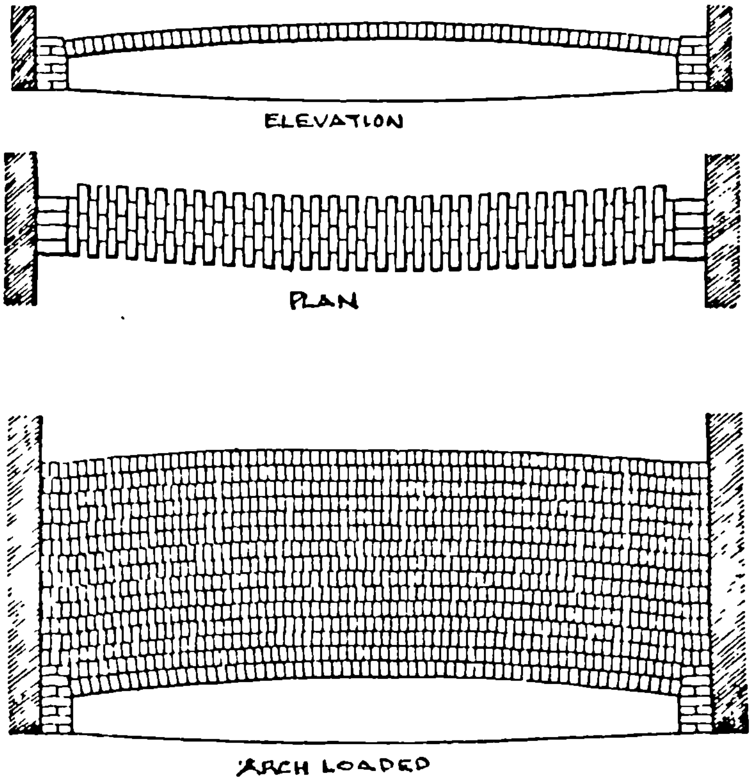


Figure 4 Pasley's Brick Arch Test

equipment for his experiments on Portland cement in 1870.[41]

Pasley did not undertake tests on the compressive strength of cement although he did perform crushing experiments on artificial stone or concrete, a matter which will be taken up in another section of this chapter. The first report on both tensile and compressive tests of cement was made in 1836 by E. Panzer of Germany. His compressive tests were made on short blocks which were crushed by a load applied through a lever arrangement.[42] Perhaps more surprisingly, Pasley did not test 'scientifically' the ability of his cements to harden, preferring simply to observe in a common sense fashion how long it took for the material to set. Apparently, Pasley did not know about (or if he did he chose not to adopt) the 'Vicat needle', an apparatus used to determine the time required for cement to acquire an initial set, which became a standard modern testing apparatus for cement. It was described in Vicat's 1818 publication and in Smith's translation of 1837. A variation of this type of device was also used by General Gilbert Totten (1788-1864) of the U.S. Corps of Engineers in his experiments on limes and cements at Fort Adams, Rhode Island, prior to 1830.[43]

Pasley was anxious to have credible witnesses to his tests on the strength of cement, a fact which illustrates how public confidence in science was still very much a matter of 'seeing is believing', at least as far as building technology was concerned. Perhaps the most spectacular experiment Pasley performed was in 1837 when he tore apart two huge Bramley-fall stones which had been joined together with his artificial cement mortar. The event was witnessed by several officers of the Royal Engineers, the Chairman of the East India Company, the naval superintendent of Chatham dockyard, "together with several members of the Philosophical and Literary Institution, and other Gentlemen, Tradesmen and Mechanics."[44] Pasley's performance was in the Victorian tradition of materials-testing publicity stunts. Contemporary examples featured the loading of reinforced brick beams and arches to destruction, the most well-known being events staged by manufacturers Francis and Sons in 1838 and J.B. White and Sons at the Great Exhibition of 1851.

Notwithstanding that by modern standards Pasley's testing methods may have been less than 'scientific', he was probably equal to the best of his contemporaries in the 1830's and certainly was regarded as a broad-minded man of science whose opinions could be relied upon. The Mechanic's Magazine said in 1837 that he was "well known for his liberality in all matters which tend to the advancement of science..."[45] Also, in 1819 Pasley had been a member of a committee to consider the Thames tunnel scheme by Sir Marc Isambard Brunel (1769-1849). When the works faltered in 1830, Pasley was asked to be a member of a panel of experts which would comment on a plan by Charles Blacker Vignoles to complete the tunnel, which he declined. It is interesting, however, to quote the words of confidence which were expressed by Sir Edward Codrington, Director of the Thames Tunnel Company, in making his request for Pasley's assistance. He wrote to Pasley in March 1830: "I have more faith in your judgement than in that of any other person and I believe I might say the same for my colleagues."[46] The panel of experts which Pasley was invited to join included Tierney Clarke, James Walker and Peter Barlow, all highly regarded members of the civil engineering community, the first two being active practitioners and the last a scholar and teacher.[47] It seems clear that Pasley was considered an equal of these distinguished professionals in the private sector.

In his many experiments Pasley undertook comparative tests on limes, hydraulic limes, puzzolana, and various sorts of cement both natural and artificial. Examples of the cements included samples of natural 'Roman cement' made by Messrs. Francis and Sons, Frost's artificial cement produced by Messrs. Bazley, White and Son, various Pasley artificial cement mixtures, and even some natural cement sent to him by a Royal Engineer officer in Kingston, Upper Canada (Ontario) about which more will be said in Chapter 8. Frost's artificial cement performed decidedly worst in these tests.[48] Pasley claimed from test results that his search for a synthetic cement had been a success: "... we consider our own artificial cement C4B5.5 to be at least equal to the best natural cements of England..."[49] The tests which confirmed this took place on 24 May 1837, the day Victoria became Queen, a coincidence which Pasley and his military assistants noted with pleasure.[50]

Scholars of the history of cement manufacture have classified Pasley's product as a good artificial Roman cement. He was too wedded to the idea current in the early decades of the nineteenth century that kiln temperatures should be kept low, and he threw away all particles which approached vitrification (clinkers). Pasley therefore did not grasp two of the essential aspects of producing Portland cement - high firing temperature and the grinding of clinkers.[51] Roman cement is the term generally used to describe a whole group of quick setting cements with clay contents greater than Portland and fired at a lower temperature, beginning with the natural variety produced by James Parker in 1796 and including synthetic varieties like Frost's and Pasley's. Practically the entire output of Roman cement was natural. It was used chiefly in brickwork, especially in civil engineering works, as a stucco on external walls of houses and on a small scale for precast concrete elements.[52] A.J. Francis has asserted that the Roman cement industry has been underplayed by historians and that as the principal product of the British cement industry for the first half of the nineteenth century it was responsible for a considerable number of important engineering works which could not have been built without it. Moreover, Francis contends that its discovery and large-scale use also led directly to the search for an artificial substitute, and that this in turn led to the development of modern Portland cement.[53]

Pasley recognized the great potential of artificial cement as early as the 1830's and encouraged manufacturers to produce it. He was frustrated, however, in his efforts to convince Messrs. Francis, White and Francis (later J.B. White and Sons, 1837), the firm that worked to Frost's patent, to adopt his own 'improvements'; and he was disappointed that this major cement manufacturer attached little importance to artificial cement, actually recommending its customers to use the natural Roman cements which the company also produced. Complaining of this situation in 1838, Pasley spoke prophetic words: "... the making of artificial cement will sooner or later become general in this country..."[54] By the mid-1840's there was some concern that the source of cement stones from which natural Roman cement was produced was near exhaustion, thus creating a greater incentive for the development of artificial cement. Pasley made this point in endorsing synthetic cement manufacture in the preface of the second edition of his book in 1847.[55] He did not patent his formula for artificial cement, although some manufacturers apparently used it in the 1840's.[56] In 1847 The Civil Engineer and Architect's Journal, in reviewing Pasley's book, felt that this formula "should be called Pasley's Cement, in contra-distinction to numerous cements which are in the market; none of which, however, appear to be superior, if equal, to the one recommended in this treatise, and which the General found to be the best after a long series of trials and experiments."[57] In a paper delivered to the Institution of Civil Engineers in 1852, Portland cement manufacturer George Frederick White paid tribute to Pasley and his influence on the development of synthetic cements:

> "... though it does not appear that he succeeded in producing a cement of greater adhesive, or resisting power, than the best Roman cement, his patient and laborious investigations have been of signal service, not only to manufacturers of cements, but to all who employ them in works of construction."[58]

Nevertheless, the influence which Pasley had on the development of early British Portland cement, the basis of the modern product of this name, was rather indirect in practical terms. In 1880, Isaac Charles

Johnson (1811-1911), the manager of Messrs. White's works at Swanscombe and developer of the firm's successful Portland cement from 1845, said in an article in the Building News that he was originally inclined to discard clinkers as useless because of Pasley's opinions, thus retarding his personal discovery of the process of Portland cement manufacture:

> "By mere accident, however, some of the burned stuff was clinkered, and, as I thought, useless, for I had heard Colonel Pasley say that he considered an artificial cement should feel quite warm after gauging, on putting your hand on it, and that in his experiments at Chatham, he threw away all clinkers formed in burning."[59]

Johnson and his employer J.B. White and Sons have been credited with introducing more consistent and rational procedures in the manufacture of true Portland cement.[60] Nevertheless, in 1852, more than a decade after Pasley had ceased his cement researches, he thought that 'Portland cement' was only a marketing name and that it was really no different from his own artificial cement.[62] Pasley reiterated his doubts five years later at a meeting of the Institution of Civil Engineers, when he asserted that Portland cement was not an improvement because its quality was uncertain as a result of the practice of burning part of the raw material to vitrification and then mixing it together with the rest.[63] Arguably, Pasley still did not appreciate the basic principles of making Portland cement by the time he died in 1861. Accordingly, Pasley's most important influence on the manufacture and use of cement was in the promotion of Roman cement, both natural and artificial, establishing its superiority over ordinary lime and supporting an English preference for its use as mortar, especially in civil engineering works, over hydraulic lime. Although Portland cement made Pasley's artificial cement obsolete by mid-century, the Royal Engineers continued to use natural Roman cement into the 1880's for marine works because its quick setting properties allowed work to be done between tides.[64]

Pasley and Reinforced Brickwork

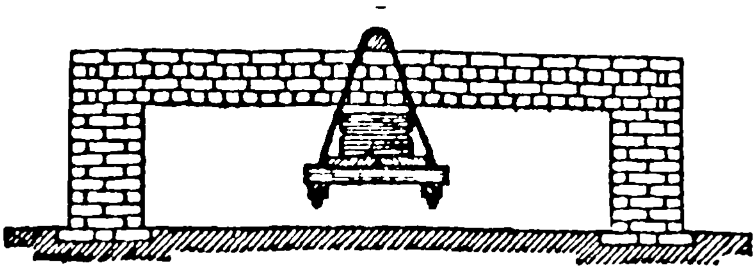
As an offshoot of his experiments on the strength of cement mortar, Pasley was involved with the testing and promotion of hoop iron reinforced cement bond brickwork. This was a type of construction used in Britain from the early nineteenth century as a substitute for bond and chain timbers in brick walls and for forming lintels over rectangular door and window openings. His experiments were not original; they were modelled on tests performed by engineer Marc Isambard Brunel and by cement manufacturer Messrs. Francis and Sons. Pasley nevertheless made an important contribution in substantiating the beneficial effect of the hoop iron reinforcement.

During the year 1831-1832 Brunel, in conjunction with trying to find cheaper and stronger ways to build brick arches for the Thames tunnel project, experimented on the cohesiveness of a variety of materials including hoop iron, which he embedded in cement mortar, drawing ties of the materials from the mortar by longitudinal force.[65] In 1832 he also built for experiment, in collaboration with Messrs. Francis, a large double cantilever semi-arch structure of hoop iron reinforced brickwork in the Thames tunnel works yard at Rotherhithe.[66] Three years later in December 1835 and January 1836 Brunel experimented further on various reinforcing materials, but mainly with hoop iron. As part of these investigations, he constructed a reinforced brick beam in neat Roman cement with hoop iron reinforcement in the lower five joints of the seventeen courses and with different numbers of lengths of iron per course (1 or 3).[67] Also in 1836, on the suggestion of Brunel, Messrs. Francis and Sons built a reinforced brick beam at their works in Nine Elms, Vauxhall. In this case cement mortar was used, not neat cement, but the hoop iron was placed in lower courses only as in Brunel's earlier beam. Pasley examined Messrs. Francis' beam in June 1837 and on 14 February 1838 it was tested to destruction as a well witnessed publicity stunt.[68]

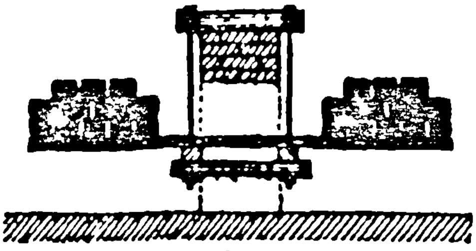
Following his reinforced brick beam experiment

Charles L. Francis told a meeting of the Institution of Civil Engineers on 27 February 1838 that he was of the opinion that the hoop iron had little to do with imparting strength to the structure.[69] At the next meeting of the Institution, 6 March 1838, Brunel replied to this assertion, saying he disagreed and that on the basis of his experiments everything was attributed to the hoop iron.[70] This emerging difference of opinion had apparently been seized on by Pasley as an opportunity to settle the matter, and at his request and by special permission of the Board of Ordnance he had begun his own reinforced brick beam experiments in the summer of 1837.[71] His brick beams were smaller than those of Brunel and Messrs. Francis; they were three in number, each 18 3/4 inches wide, 12 inches high, 13 feet 1 inch overall length and 10 feet long between bearings.[72] (See Figure 5) One was constructed with joints in neat cement alone, another with cement and hoop iron bond, and a third with lime mortar and hoop iron bond. The hoop iron was placed two in the top joint, two in the bottom and one in the middle, indicating that he was uncertain as to where best to place the reinforcement.[73] Results of loading to destruction were that the reinforced cement beam was strongest (9 times stronger than cement only beam), the reinforced lime mortar beam the next strongest, and the cement beam the weakest.[74] For Pasley this proved the great importance of hoop iron and the potential of reinforced cement bond brickwork:

> "... cement bond, consisting of 4 or 5 courses of brickwork laid in pure cement, if strengthened by longitudinal pieces of hoop iron in all the joints, may be used to supersede not only wooden lintels of doors and windows, but all timber bond generally in the walls of buildings... In using hoop iron bond in walls, the irons should extend if possible the whole length of each wall in one piece; but if a break be necessary, the adjoining ends need not be united together by the blacksmith, but turned down at right angles into one of the vertical joints of the walls by the bricklayers themselves."[75]



Elevation of an Experimental Brick Beam.



Section of an Experimental Brick Beam.

Figure 5 Pasley's Reinforced Brick Beam Experiment

Pasley also dabbled with testing the tensile strength of hoop iron by fixing the material in a vertical position and suspending weights from it. He nevertheless quickly broke off these experiments since his results nearly agreed with those of Peter Barlow and Thomas Tredgold whom he considered authorities on the matter.[76] Pasley was clearly not interested in abstract experiment divorced from practical purpose.

The Mechanic's Magazine credited Pasley with proving 'scientifically' the effectiveness in brickwork of hoop iron reinforced cement bond by a practical test of reinforced joints versus mortar only: "Mr. Brunel first tried some very interesting experiments, proving the extraordinary strength of brick work, laid in pure cement with hoop iron in the lower joints, but the same things had not been tried without hoop iron, which led to the experiments under Colonel Pasley."[77] Pasley and Brunel apparently followed each other's experiments with interest and debated some design details of reinforced brickwork. Brunel used reinforced brickwork in the Thames Tunnel. On a number of occasions Brunel personally informed Pasley that wooden laths properly treated for decay were as good for reinforcement as hoop iron which was susceptible to rust. Pasley did not agree that hoop iron was liable to rust once sealed in cement, but on the advice of Robert Howe, clerk of the works at the Royal Engineer Establishment, he recommended treating the iron with hot linseed oil.[78]

Pasley was an important advocate of reinforced brickwork and offered a specification for it, particularly in discussing this technique in his monumental book (1838, 2nd edition 1847). He saw it as a cheaper, fireproof and decay-resistant alternative in brick buildings to chain bond timbers in walls and to wooden lintels. Nevertheless, he was careful to credit Marc Brunel and to some extent Robert Smirke with introducing the technique.

> "The superiority of this sort of bond did not suggest itself until after Mr. Brunel had tried his memorable experiment of the brick beam, though

> I knew that this sort of bond had been previously used by Sir Robert Smirke, in several great buildings executed by his direction, but in which he did not use hoop iron, nor dispense entirely with chain bond or lintels, as I now propose. Sir Robert Smirke did however use hoop iron bond in some of his first buildings but I believe in combination with mortar only."[79]

It appears, however, that in the 1840's Pasley was considered the authority on the subject. In 1847 The Builder quoted an extract from Pasley's book (1847 edition) to demonstrate the strength of hoop iron reinforced cement bond and the advantages of the technique over timber which was susceptible to shrinkage, rot and fire.[80] The use of hoop iron as an uncalculated tie became quite common especially in the walls of terrace houses.[81] It was also used in foundations. An example was in the new Judges' Chambers in Chancery Lane, London which was under construction in 1837. Here Pasley's specification was followed exactly.[82] Hoop iron reinforced cement bond in brickwork was used in three important projects undertaken by Royal Engineers featured in this study. Sir Joshua Jebb used it in the outer walls and in ceilings of cells in Pentonville Prison (1840-42); Douglas Galton employed the technique in the walls and some floors of the Herbert Hospital (1861-1865) at Woolwich; and Sir Arthur Clarke specified hoop iron bond for tidal basin retaining walls and docks in the Portsmouth dockyard extension (1864-1873).[83] Reinforced brickwork, however, did not catch on as a major structural material since cast iron and later rivetted wrought iron were far too strong as rivals.[84]

Hamilton-Baillie has suggested that Pasley and his contemporary brick beam experimenters came very near to inventing reinforced concrete some sixty years before the use of the material became generally accepted.[85] There may be some truth in this with respect to Marc Brunel, because his main purpose was to find a superior form of brickwork for the Thames Tunnel and he actually used reinforced brickwork in its construction. Brunel also knew where best to place the hoop iron reinforcement - in the lower courses. This was not the case with Charles Francis, the cement manufacturer, since he thought hoop iron did not add strength to a brick beam or arch. It was probably not true for Pasley either since he was primarily interested in sorting out conflicting opinions on the effectiveness of hoop iron and was also uncertain about where to place the reinforcement. A.J. Francis has speculated that William B. Wilkinson (1819-1902) may have got the idea for his reinforced concrete floors patent (1854) from the brick beam experiments of Brunel and Pasley which had been so well publicized in the technical press and in the second edition of Pasley's book (1847).[86] However, there is no evidence to substantiate this hypothesis. Accordingly, without stretching a point, it cannot be said that Pasley either anticipated reinforced concrete in the modern sense or influenced others to do so. As a postscript, true reinforced brickwork using hoop iron was not patented until 1892 in Germany and the next year in Britain, more than thirty years after Pasley's death.[87]

Pasley and Other Royal Engineers on Early Concrete

In the rediscovery of concrete, France led the way with beton, first in foundations from the mid-eighteenth century and later in buildings by the 1830's. Apart from some earlier experiments, the pioneer in concrete foundations in England was the architect Sir Robert Smirke, beginning in the second decade of the nineteenth century. The use of concrete blocks (artificial stone) for foundations as well as for walls was pioneered by William Ranger, a builder, George Leadwell Taylor, Civil Architect to the Admiralty (1824-1837) and Thomas Cooper, an architect. Ranger used both artificial stone and mass concrete in constructing the walls of buildings as well as marine works.[88]

The Royal Engineers were involved in controversy surrounding the introduction of concrete and artificial stone in early nineteenth century England. Their position was an ambivalent one. On the one hand they publicized and promoted the use of concrete in foundations and as a backing for masonry construction, but on the other they condemned the use of the 'new material' in building superstructures and in civil engineering marine works. A.J. Francis has blamed Pasley in part for delaying the more general introduction of structural concrete by as much as two or three decades.[89] Nevertheless, a close examination of the evidence suggests this is unfair. The views of Pasley and other Royal Engineers on early concrete were not atypical of those expressed and practised by many British architects and civil engineers before mid-century. Furthermore, it can be argued that the Royal Engineers had reasonable grounds for their views when assessed in the context of their times and not in the perspective of modern building science.

It will be remembered that Pasley featured Smirke's foundation work with concrete, which the latter called grouted gravel, in his Outline of a Course of Practical Architecture (1826), the teach-yourself textbook for engineer officers at the Royal Engineer Establishment. In his 1838 publication, Observations on Limes, Calcareous Cements etc., Pasley offered a detailed description and evaluation of the respective methods of underpinning the walls of buildings with concrete foundations recently executed by Smirke for the new Custom House in London and by George L. Taylor in collaboration with William Ranger for a storehouse at Chatham naval dockyard. Pasley was decidedly more impressed with Smirke's technique.[90] The concretes used in both cases were made of lime, not cement, as was common practice at the time.

Pasley was also very much aware of Ranger's work with artificial stone and mass concrete in wharf walls from his own observations of projects by Taylor and Ranger at Chatham naval dockyard and from reports of fellow officers William Reid at Brighton and William Denison at Woolwich.[91] He also knew about an experimental concrete casemate constructed by Ranger under the supervision of Sir George Judd Harding of the Royal Engineers at Woolwich, a project described in detail in

Chapter 5.[92] Pasley decided to undertake experiments on Ranger's concrete at the Royal Engineer Establishment. He began in 1836 by trying to determine how any given lime was fit for making concrete or artificial stone on Ranger's principle, which was a patent lime concrete made with boiling water to speed up the set.[93] His curiosity led him to expand this enquiry beyond the then conventional method of making concrete with lime.

Pasley's tests were made on small prisms of concrete which he produced in wooden moulds 4 inches long, 2 inches wide and 2 inches deep. These samples of artificial stone or concrete were made from various limes, hydraulic limes and cements, using different aggregates in varying proportions and using both boiling and cold water. Pasley found that hydraulic lime was better than chalk lime for concrete, and that boiling water helped lime set faster but did not make it stronger in the end. Moreover, he concluded that cement should not be used for concrete because his tests showed that the adhesion of cement mortar was reduced by a greater amount than was lime mortar by the inclusion of sand.[94] Herein lay Pasley's negative role in the development of structural concrete, for he did not proceed to test properly the strength of cement concrete. His condemnation of it may have been a serious setback to its acceptance not only by military but also by civil engineers.[95] All the same, Pasley did perform flexural tests on his prisms of lime and hydraulic lime artificial stone, as well as on similar prisms of natural stones, bricks and chalk for comparison. From these experiments he concluded that artificial stone made according to Ranger's system was much inferior to all natural building stones and even to sound well burned bricks.[96]

While Pasley was engaged in these experiments, his brother officer William Denison also took up investigations of concrete in his capacity as Superintending Engineer in the Admiralty Works Department at Woolwich naval dockyard (1837-1845). Denison, who had worked under Pasley at Chatham as Instructor in Surveying (1833-1835), was no stranger to experiment. He won the

Telford Premium from the Institution of Civil Engineers (1838) for his paper on strength testing of Canadian timber while stationed on the Rideau Canal project (1827-1831). He was also a key promoter of scientific enquiry in the Corps as founder and editor of the Royal Engineer Professional Papers. While at Woolwich dockyard in 1837, Denison experimented with making concrete blocks using slightly hydraulic lime and tested them to see if they would break down under chemical action of water. He also consulted Faraday on this matter. In the same year he began strength tests on some of the concrete blocks made by Ranger for Woolwich docks, but he discontinued his work because Pasley was at that time involved at Chatham in related concrete experiments. Denison sent these blocks to Pasley who tried them as beams and applied crushing tests. In comparison to similar tests on Yorkshire stone as well as on tiles and cement with hoop iron bond, Ranger's artificial stone proved the weakest - 13 times weaker than the strongest Yorkshire stone.[97]

Denison had witnessed the performance of Ranger's concrete both in blocks and in mass for the construction of wharf walls at Woolwich. This experience led him to condemn the use of exposed concrete for wharf walls because the surface exfoliated under frost conditions and was easily damaged by the mechanical action of ships impacting it. Nevertheless, he thought that concrete was of unquestioned value in foundations and in other situations where it was protected from frost or mechanical action.[98] By the mid-1840's Denison was to modify his view marginally in making an important proposal for a major breakwater at Dover, a story which is taken up in Chapter 4.

Supported by Denison's experience and by his own observations and experiments at Chatham, Pasley had little hesitation in expressing his opinion of Ranger's concrete and artificial stone: "... it should be confined to the foundations of buildings chiefly, in addition to which it may however also be used occasionally, but with judgement, for the backing of wharf walls, and for the formation of retaining walls..."[99] Aside from these reservations, Pasley was decidedly in support of the 'new material': "Upon the whole, it may be allowed that the use of concrete and artificial stone, if kept within proper bounds, that is so as not to attempt to supersede stone and brickwork entirely, is a very great improvement."[100] It seems clear that aside from his experimental experience, Pasley's distrust of concrete in superstructures was based not so much on its use in buildings but mostly on the poor performance of Ranger's material in wharf walls. The only other structure he discussed at any length was Harding's experimental concrete casemate at Woolwich. Here he did not condemn the new material but argued that in the face of artillery fire brick casemates laid in cement mortar and coated with pure cement would be stronger. He also said brick casements, unlike concrete, would not be damp.[101]

Some of Pasley's contemporaries were much more optimistic about the potential of Ranger's product in the mid-1830's. For example, The Civil Engineer and Architect's Journal commented in a review of Lieutenant Colonel Reid's article on concrete structures at Brighton, which had appeared in the first volume of the Royal Engineer Professional Papers:

> "... we feel convinced that it might be introduced for every variety of building with great economy... Mr. Barry has very successfully introduced it in the new front of the College of Surgeons, Lincoln-Inn-Fields, also the front of a house in Pall-Mall. Mr. Ranger has built a small church with concrete, also several docks, wharfs and numerous other works, and in the sea-wall at Brighton, with great success as appears by the Report before us."[102]

In the early 1860's Henry Scott told a group of fellow officers in a lecture on concrete at the Royal Engineer Establishment: "The writer who has most discredited its general employment was our own Sir Charles Pasley, whose opinion must carry great weight wherever his name is known: but I hope to shew (sic) that on this point he was mistaken."[103] With the benefit of hindsight, this may have been true; but Pasley and Denison were not alone in their views on concrete in the early nineteenth century. Sir Robert Smirke, who was arguably the most practical architect and best constructor of the times, used concrete only for substructures.[104] Indeed, Pasley seems to have been guided by Smirke's practice. He commented in his 1838 book: "... concrete was of very inferior importance, except when used in mass for foundations or for backing, to which Sir Robert Smirke, who first introduced the use of it in this country, very judiciously confined it."[105] Furthermore, there were other authorities who restricted concrete to substructures. One was Dennis H. Mahan, professor of military and civil engineering at West Point, whose _An Elementary Course of Civil Engineering_ (1837) was a standard textbook for the U.S. Corps of Engineers. Peter Barlow edited a British edition of this book which was published in 1845.[106] Similarly, George Burnell in his _Rudimentary Treatise on Limes, Cements, Mortars, Concretes, Mastics, Plastering etc_. (1850) said that concrete was "principally used for the purpose of distributing the weight of a large heavy construction over the greatest surface possible; or for the backing of coursed masonry, in cases where walls are required of great thickness."[107] Burnell also said that Ranger's artificial stone did not seem to work in practice but that he saw no reason why a successful product could not be developed.[108] Accordingly, though Pasley and Denison were conservative in their view of concrete in superstructures they were not alone in this, and on balance they deserve credit for being early promoters of concrete for substructures. That was itself an important advance, even if not entirely an innovation of the early nineteenth century.

Pasley's Contribution to Technical Literature

Notwithstanding the importance of Pasley's contributions to the development of artificial cement in the early nineteenth century, another of his significant achievements was helping to place the making of mortars and stuccos employed in the contemporary building industry on a more 'scientific' basis. In this his contribution was as much about rationalizing the old as promoting the new. Pasley said that the main purpose of his celebrated 1838 book was to provide an explanation of the means of experiment and observation whereby any intelligent person could decide for himself what mortars and cements were the best and most economical for various circumstances.[109] He was particularly concerned to promote a well-informed building industry: "... unless a man of business be also a man of research, he cannot know what has been done in foreign countries, or even in distant parts of his own."[110] Pasley himself had read the greater part of existing literature on limes and cements, both English and foreign. He paid great tribute to Smeaton and said that amongst the French engineers whom he had met, Vicat and General C.L. Treussart (1779-1834) were the most distinguished writers.[111] In the appendix to his 1838 book Pasley gave a critique of most of the earlier writers whose works he had consulted. One is struck by his thoroughness. Pasley himself had experimented on an incredible variety of limes, hydraulic limes, puzzolana, trass and cements, both natural and artificial, using different aggregates, proportions and preparation processes. He described these experiments in great detail in his book, and from his findings he recommended appropriate manufacture methods and specifications for use. Pasley was also concerned about the apparent problem of the adulteration of the product by manufacturers, and so he gave information on tests and other helpful hints to readers on how to judge quality in limes and cements.[112]

Pasley's chief rival appears to have been Vicat, especially through Smith's translation. Pasley had a noticeable chauvinistic attitude towards Vicat and for that matter to Frenchmen generally. He never missed an opportunity to claim that his cement had proved superior to hydraulic lime. He once asserted that the adoption of artificial cement in France demonstrated that Vicat's theory had been "practically refuted", and on that occasion he was swiftly rebuked by George F. White, a prominent cement manufacturer, who replied that Vicat's theory remained sound and that his work was as valuable a contribution to science at Pasley's.[113] In another instance, James Frost castigated Pasley's condescending tone in a remark the latter made in his 1838 book about a patent mastic cement being an ingenious composition "though invented by a Frenchman".[114]

Pasley's 1838 book was widely quoted in the technical press and attracted much attention, particularly from those engaged in manufacturing cement and lime and in associated occupations. It was so popular that it was very soon out of print and thereafter was much sought after. This induced Pasley to publish a second edition in 1847.[115] The original edition had been strongly recommended by The Civil Engineer and Architect's Journal and in its review of the second the journal commented: "Both the engineer and architect are under great obligations to General Pasley for the very elucid (sic) manner he has set forth in his treatise the results of many years' laborious researches and experiments on limes, mortars and cements."[116] In its review of both editions, The Builder said: "Since the publication of the work, artificial cements have been made and used extensively, so as to justify the opinion General Pasley had advanced in this respect... We recommend the work to the study of all engaged in construction to whom it may still be unknown."[117]

Nevertheless, a review of technical literature of the later nineteenth century reveals that Pasley's publications were not as influential on contemporary experts as were those of Vicat and other foreigners. Civil engineer George Burnell, in his Rudimentary Treatise on Limes, Cements etc. (1850), thought the best sources for his subject were foreign because the English disliked theory and were reluctant to examine old habits. He thought the French treated the subject more scientifically, and attributed most credit for progress in the science of lime to Vicat. Burnell viewed Pasley and others as merely confirming Vicat's theory.[118] In 1862 engineer officer Henry Scott considered the principal sources on limes and hydraulic limes were Vicat, Colonel Raucourt de Charleville (a Frenchman practising in Russia) and General Treussart.[119]

Furthermore, late in the century Lieutenant Colonel H.C. Seddon's Aide Memoire for the Use of Officers of the Royal Engineers (1883) contained no reference whatsoever to Pasley's publications.[120] The Americans seem to have been little influenced if at all by Pasley. Mahan in his Elementary Course of Civil Engineering (1837, 2nd edition 1845) gave credit for his understanding of lime and mortar to Vicat, Raucourt de Charleville, Treussart and Colonel Totten of the U.S. Corps of Engineers.[121] General Quincy Adams Gillmore (1825-1888), perhaps the foremost American authority on limes, cements and concrete after mid-century, often referred in his Practical Treatise on Limes, Hydraulic Cements and Mortars (1863) to Vicat, other French writers and to Colonel Totten, but never to Pasley.[122] On the other hand, civil engineer and test laboratory owner Henry Faija, in the third edition of his Portland Cement for Users (1890) referred in an appendix to Pasley's test data on the adhesiveness of Roman cement, then nearly sixty years old, to show the comparative strength of Portland cement.[123]

Accordingly, on balance it would appear that the influence of Pasley's publications, at least as reflected in reviews and in the works of later technical writers, was most important before mid-century, though he was referred to occasionally until the end of the century. It is probably impossible to determine to what degree his books practically influenced architects, engineers, builders, craftsmen and others in the construction industry. Except as carried by brother Royal Engineers abroad, Pasley's influence appears to have been parochial compared to Vicat and other Frenchmen whose publications had a more global impact.

Scott and the Discovery of Selenitic Cement

Henry Scott was the principal successor to Pasley in the experimental tradition at the Royal Engineer Establishment. Born at Plymouth in 1822, Scott was educated privately. His father was an extensive quarry owner so it is interesting to speculate that Scott may have developed an early interest in building materials and had contact with the lime manufacture industry as a boy. He entered the Royal Military Academy at the age of sixteen, and was a brilliant scholar who graduated top of the class two years later in 1840, an exceptionally short time. After receiving his commission he studied at the Royal Engineer Establishment from 1841 to 1842, immediately after Pasley's departure, so he did not benefit from his older brother officer's instruction. As explained earlier, Scott was appointed an instructor at the Royal Military Academy in 1848 and it was there that he began experimenting with limes and cements. He started by trying to make a cement from some specimens of shale sent to him from Gibraltar where he had been stationed earlier (1843-48). Scott had noticed the quick decompositon of shale in some escarps which he constructed at Gibraltar. While engaged in these experiments Scott was visited by William Reid, then Commanding Royal Engineer at Woolwich, the engineer officer who had encouraged Pasley to resume his investigations on limes and cements in 1828. It was Reid who procured the approval of the Inspector General of Fortifications for Scott to use his experiments as an opportunity to teach junior officers of the Royal Engineers and non-commissioned officers of the Royal Sappers and Miners methods of testing limes and cements, and secured Scott's appointment as an instructor at the Royal Engineer Establishment in 1855, a position which he would hold for ten years. Scott pursued his experiments initially on clay and limestones from near the Royal Engineer stations of Plymouth and Devonport, his childhood home. A happy accident was to lead him to an important discovery.[124]

According to his own account, Scott's invention of selenitic cement began in 1854 with his noticing by chance an unusual chemical reaction on a piece of lime he was calcining in the coal fire of the dining room fireplace in the officers' quarters at Chatham. This coincidental observation of the effect of sulphurous coal fumes on calcination led him to be the first to ascertain the action of sulphur compounds and sulphuric acid on quicklime. Scott showed specimens of the calcined material to Michael Faraday, Dr. William Allen Miller and Frederick Able, Chemist to the War Department. These experts were unable to explain satisfactorily the phenomenon which Scott had observed, and the theory they originally advanced was later superseded by that of a German chemist, F. Schott (c. 1870). On Faraday's advice Scott took out a patent (1854) for a cement, even though at that point he had not realized that sulphur was the key causitive agent. His second patent did recognize the vital role of sulphur, but attempts by Lee, Son and Smith of Halling to manufacture the patented cement proved impracticable as a commercial venture because of the large consumption of coal in the kiln and the variable results in the product. Scott's third patent (1856) for a method of subjecting heated calcined lime lumps to the fumes of burning sulphur was successfully taken up by Lee, Son and Smith at their works near Rochester and later at the company's subsidiary operation in Upper Grand Street, Blackfriars, London. William Lee was the principal and founder of Lee, Son and Smith, the most prominent of the Medway cement manufacturers in the nineteenth century. Established in 1846, by the time it took up Scott's patent, Lee's company had commenced making Portland cement in addition to lime and Keene's cement. Scott's 1856 patent was also worked by Rickman and Company of Lewes.[125]

In 1864 Scott left the Establishment and the next year succeeded deceased brother officer Fowke as architect to the Science and Art Department. During 1870 he obtained a fresh patent on his cement, and in 1871 he formed the Patent Selenitic Company Limited to work it. By this time Scott had discovered that results could be obtained best by adding sulphuric acid to water used in preparing mortar, or by the addition of Plaster of Paris or powdered gypsum to lime. His patent specification called for 5% ground Plaster of Paris mixed with calcined hydraulic lime ground to a powder. Shareholders in the company included Gilbert R. Redgrave, architectural assistant to Scott in the Science and Art Department, and Charles Nelson and Company who also made the patent cement under license. Many other firms were licensed to make Scott's cement too. The Patent Selenitic Company survived until 1885, two years after Scott's death.[126]

Strength tests on Scott's cement were first carried out at Chatham in 1857 by Corporal Grey under the direction of Captain Schaw and later by Scott with the assistance of Lieutenant Moncrieff of the East India Company engineers. These experiments used Pasley's method of testing the adhesive strength of cement by pulling apart with suspended weights pairs of stone bricks which had been cemented together. Comparative tests were done as well on Portland cement, on varieties of natural cement and on hydraulic lime. A second series of experiments was conducted by Scott at the Establishment in the same year in which he performed flexural tests on small prisms of cement mortar using methods described in Pasley's book (1838) and in the works of General Treussart. The results of these experiments showed that Scott's cement was inferior to Portland cement, but offered many advantages in pointing ordinary brickwork and was better than Lias lime (hydraulic) for marine works, especially wharf walls. Experimental strength ratings determined at the Establishment were confirmed by tests at Chatham naval dockyard under Colonel Godfrey Thomas Greene, Director of Works for the Admiralty, and by those of a Mr. Linn at Paddington for civil engineer John Fowler. Scott's cement was also tested at South Kensington by Francis Fowke in 1858 and this is discussed further in Chapter 7. The products of Scott's Patent Selenitic Company Limited were tested in 1872 at the laboratory of David Kirkaldy (1820-1897) the distinguished leader in nineteenth century materials testing facilities in Britain. Tests were also conducted by A.W. Colling, clerk of the works, for George Edmund Street in conjunction with the building of the New Law Courts (1874-1882) in London.[127]

The primary uses of Scott's cement were for stucco and plaster but it was also used for mortar and in concrete as a substitute for hydraulic lime. There were two qualities (A and B). Grade B was for dry work, chiefly stucco. Grade A could be used for hydraulic purposes. It was employed in stucco and plaster, for pointing brickwork, and in concrete. Neither of the grades was quick setting, and quality A was so slow that it was unsuitable for tide work or underpinning where a fast set was required.[128] The selenitic process allowed limes of feebly hydraulic character to carry more sand. It produced a tougher mortar and a good plastering material and because it did not slake, retained its original warm buff colour.[129] It was reportedly 30% cheaper than Portland cement and comparable in hardness as plaster.[130] Scott claimed, moreover, that his cement was 20% of the cost of Plaster of Paris or Martin's and Keene's cements for plaster work, and that it was harder and non-absorbent; as it set more quickly it allowed finishing work to proceed faster.[131] Some manufacturers claimed that Scott's cement was superior for plaster because it did not conduct sound, and architects found it good for sgraffito work and for stamping decorative patterns on stucco.[132]

Scott's cement was used as hydraulic mortar in government marine works at Dover and Hythe. It was employed as mortar for an escarp wall at Tilbury Fort by Captain Orde and in the construction of magazines and sheds at Sheerness dockyard by Lieuteneant Colonel Montagu. The material was used as stucco by Captain Thomas Inglis at Woolwich and as a plaster by Captain Schaw in the new officers' mess at Brompton Barracks, Chatham. Mr. Macdonnell, a civil engineer working under Colonel Greene, employed Scott's cement at Chatham naval dockyard. These were all before 1861. Scott's plaster had also been used about 1857 for some cottages near Maidstone. From 1858 Scott's cement was tested and used by Fowke at the South Kensington Museum, and Scott gave his brother officer great credit for the successful application of the new material. Fowke and Scott were to make varied and extensive use of the material while each was employed in the Science and Art Department, and a full description of this work is provided in Chapter 7. Scott's cement was used in concrete revetments (1865) at Newhaven Fort by Lieutenant J.C. Ardagh; this was the earliest major use of concrete by the Royal Engineers for fortification superstructures in Britain, and a full description is given in Chapter 5. Later uses of Scott's cement were in the War Office, Whitehall, in Westminster Cathedral, in Keble College, Oxford and in the new university at Liverpool.[133]

It would appear that, unlike Pasley's quest for an artificial cement, Scott had not set out to discover a new cement but was led to it as a result of his inventive curiosity, scientific aptitude and interest in experiment. He was only thirty-two when the discovery process began. After leaving Chatham he was clearly motivated by the commercial prospects of his invention. Scott had fifteen children, and that accounts in some measure for his desire to earn money apart from his modest salary as architect to the Science and Art Department. In his later career he was much like General Quincy Adams Gillmore of the U.S. Corps of Engineers in the degree to which he was involved in commercial ventures. In this respect he differed markedly from Pasley who had not even bothered to patent his artificial Roman cement.[134] There is some evidence that some representatives of the private sector did not approve of military engineers being involved in commercial pursuits. In 1861 civil engineer George Burnell made what may have been a veiled attack on Scott:

> "Some of the officers of the Royal Engineers, enjoying considerable influence in the constructive departments of the service, have not hesitated to become interested in patent inventions employed in the works constructed by those departments. Of course, if an officer discover, in the course of his independent researches, something which is likely to be publicly and generally useful, there can be no reason why he should not make the most advantageous use of his discovery for his own purposes. But as an officer receiving full pay from the nation is

> supposed to devote the whole of his intellect to the service of the nation, there is something indelicate and unprofessional in such a man's working a patent whilst he retains his appointment."[135]

Notwithstanding Burnell's suggestion that certain unnamed Royal Engineers were guilty of impropriety in working a patent there is no evidence that Scott used his position to favour the sale of his patent product to government departments. In January 1871 Scott wrote a letter to the Science and Art Department, where he was then employed, advertising his patent cement which was being marketed by his Selenitic Company Limited. He explained that he wished for no financial gain from the Department for his patent cement and that, as a matter of policy, he declined any royalty from its use at the South Kensington Museum or any public building where he was superintending the works.[136]

It appears, however, that 'Scott's Cement' was reasonably well taken up by the government, judging from the description given above of its employment on various projects. The War Office, Admiralty and the Science and Art Department figured most prominently. This new material was also used to some extent by the private sector. Nevertheless, the precise success of Scott's Patent Selenitic Company Limited has not been determined. Although selenitic cement fell into disuse in the twentieth century, Scott was responsible for the proposal to add gypsum (calcium sulphate) to Portland cement to retard setting, a process still used in the modern cement industry.[137] Scott's invention of a new cement and particularly the selenitic process were significant contributions to advances in the technology of building.

In addition to these achievements, Scott's experiments and lectures at the Royal Engineer Establishment had a definite, though difficult to measure, benefit in improving the Corps' knowledge and skill with limes, cements and concrete. Most of this was directed towards constructing better masonry in fortifications. Before 1862 Scott had undertaken a series of experiments on hydraulic and ordinary limes with the assistance of Sergeant Hartley. They tested the fracturing weight of brickwork mortar joints both by flexural tests and by crushing loads. He also used data from strength experiments on hydraulic limes and cements conducted at the Establishment by Captain Schaw assisted by Lieutenant Moncrieff and Corporal Grey. His major objective was to prove the superiority of hydraulic lime over pure lime and later to compare hydraulic lime with cements, both Portland cement and his own patent product. Essentially, Scott was updating Pasley's earlier work. However, from his test results he disagreed with Pasley on an issue of major consequence. Scott demonstrated that higher proportions of sand weakened both lime and cement mortars, whereas Pasley had claimed that sand weakened cement to a greater degree than it did limes. This conclusion led Scott to insist on strictly 'scientific' specifications for proportions of sand used in both lime and cement mortars for fortifications. It also helped to remove the reluctance to use cement in concrete, caused by Pasley's earlier influential writings in this respect.[138] Scott viewed science as a triumph over craft rule-of-thumb in building, and he urged junior officers of the Royal Engineers to follow scientific principles in mortar-making to ensure that their works would prove lasting monuments to their skill in construction:

> "Notwithstanding, however, all the obstacles in the way of better practice, I look forward to the day in which we shall feel quite independent, as respects mortar making, of the workman's traditions. We have, indeed, already taken a long step towards it. Though brought up in the notion that mortar making was a mystery which required a long practical apprenticeship to master, we Miliary Engineers now gladly call in the assistance of the chemist, and consider his opinion a very useful check on that of the practical builder."[139]

Concerning concrete, from 1862 Scott joined Fowke as the Corps' chief advocate of the material for superstructures in works of fortification on the basis of both strength and cheapness. He went to considerable lengths to demonstrate that Pasley's views on concrete were wrong, not only showing that the effect of sand in weakening cement more than lime no longer applied to cements such as Portland and his own product, but also pointing out that Pasley used quick-setting cements which were not appropriate for strong concrete. Scott quoted General Treussart, Colonel Rancourt de Charleville and other French authorities on the matter of a good formula for concrete and pointed to the recent successful works in mass concrete by Francois Coignet, the foremost pioneer of the use of the material in building superstructures.[140] Scott's advocacy of concrete was to have important ramifications for the Corps' work with fortifications in the 1860's, and this topic is taken up in Chapter 5.

Scott's Other Contributions to Cement Manufacturing

After leaving the Royal Engineer Establishment, Scott continued his inventive genius beyond selenitic cement. Altogether he obtained some fifty-nine patents for cements, lime and kilns. His improvements in firing pottery and other kilns were extensively introduced throughout the Staffordshire Potteries, and his inventions caused great saving in the cost of burning lime and cement.[141] Amongst the contributions of this indefatigable inventor, perhaps the most interesting was his development of a process for the making of cement from sewage sludge. He patented this process in 1868 and formed Scott's Sewage Company Limited two years later to work it. Directors of the company included the Duke of Sutherland, Sir Henry Cole, and Warren de la Rue, the well known printer and practical genius in applied chemistry and mechanics.[142] Gilbert Redgrave was a partner and company secretary.[143] Henry Cole was managing director of the company and an energetic promoter of the scheme. For three years Cole lived in Birmingham and Manchester with the object of convincing the municipal corporations to adopt Scott's patent process for turning sewage either into a portable pulverized manure or a cement.[144] The character of the company's directorship and management is an indication of Scott's high social standing and professional reputation.

Scott's invention of a process for treating sewage and producing a cement from sewage sludge is an interesting case of the interaction of Victorian concern for sanitation and the search for advances in building technology.[145] His invention was an offshoot of the lime process of sewage treatment. Slaked lime and clay were introduced into the main sewers of a town some distance from the sewage precipitating tanks. This had the effect of checking the emission of noxious gases which found their way into streets and houses and of scouring filthy decomposing matter from the main drain. The sludge from the precipitating tanks was collected, dried and burnt in down-draught kilns of special construction to Scott's specifications.[146] Scott explained that apart from being an economical way of cleansing and disposing of sewage water, his patent process had advantages in cement manufacture over ordinary methods:

> "First, as I have already stated, the materials used undergo a considerable increase from the lime and clay originally present in and removed by the precipitants from the sewage water; second, the agitation in a long length of sewer produces better admixture than can be effected by ordinary mechanical appliances; and third, the sewage yields a large amount of fuel, which is sufficient, or nearly so, to effect the calcination of the deposit."[147]

Both hydraulic limes and cements could be produced by Scott's process as well as a material which approximated to the composition of Portland cement. Selenitic cement could be produced too and Scott recommended it. The process was first tried at Ealing and later at Birmingham, Burnley and several other towns. Scott's sewage cement and sewage treatment process were endorsed by a host of experts including Frederick Abel, Mr. Hawksley, President of the Institution of Civil

Engineers, Dr. Voelcker of the Society of Arts, Dr. Odling, Professor of Chemistry at the Royal Institution, and Dr. Edward Frankland, a professor of chemistry and one of the Commissioners for the Inquiry on the Pollution of Rivers who recommended Scott's process to the Parliamentary Select Committee on the Birmingham Sewage Bill. Scott's sewage cement was used to advantage by Messrs. Lucas Brothers, one of the largest builders in the country and the main contractors for Scott's Royal Albert Hall, and sales of the product were reasonably good at Burnley.[148]

Nevertheless, Scott's new material was not a commercial success.[149] Scott himself had warned a meeting of the Royal Institute of British Architects in 1872 that "he could not encourage the expectation that the cement would be much cheaper than others now in use, in as much as when new materials were introduced the public had generally to pay for the novelty."[150] At the turn of the twentieth century Gilbert Redgrave, recalling the failed venture of which he was a part said: "We believe that the valuable invention was somewhat in advance of its time, but with the present state of our knowledge of cement manufacture, it could be carried out with complete success..."[151] It was a tribute to Scott's inventive genius that this former colleague and expert on cement manufacture should have seen him as a man who worked at the frontiers of knowledge in building technology.

Indeed, only three years before his death at the age of sixty-one Scott, in collaboration with Gilbert Redgrave, made another contribution to the development of advances in cement manufacturing. This was a paper delivered to the Institution of Civil Engineers on the manufacture and testing of Portland cement, for which the two received the Institution's prestigous Telford Premium.[152] The Royal Engineers had only begun to take up the use of Portland cement on a significant scale for mortar and later concrete in the 1860's.[153] In 1870 Captain William Innes (1841-1875) had experimented with Portland cement, using Grant's methods to determine the best proportions for strong mortars in the material. As part of his investigations, Innes became involved in a developing debate in the engineering profession on standards for cement testing. He favoured a specific gravity test over the then conventional weight test based on pounds per Imperial bushel.[154] Another advocate of standardized testing was Lieutenant H.C. Seddon. In a lecture to the Royal Institute of British Architects in 1872, Seddon made a plea for the Institute to collaborate with the Institution of Civil Engineers in promoting the development of Kirkaldy's laboratory as a private sector national materials testing centre.[155] At the time Seddon was head of the design branch of the Barrack Department in the War Office and a lecturer on building trades at the School of Military Engineering, Chatham.[156] Scott's paper in 1880 was therefore in the tradition of a developing concern in the Corps for standardized testing of cements.

The Germans were the first to adopt national test standards for Portland cement in 1878. Britain, next to the Americans, was the last of the major industrial countries to adopt these measures notwithstanding that it had been the pioneer of the new material. This came in 1904. British engineers and architects during the late nineteenth century were in the habit of issuing their own specifications for tests according to their personal test methods or individual requirements. This often caused much friction between the building professions and manufacturers.[157] In 1880, the year Scott and Redgrave presented their paper, William Gostling, cement manufacturer, explained that there was a great diversity of opinion on the three main tests which had developed up to that time - fineness, weight, and tensile strength. He claimed there was a total of thirteen different varieties of test for 21 specifications.[158]

Scott and Redgrave offered test standards for the fineness or sieve test, for a weight test and a tensile strength test. Leading cement manufacturer, George F. White, thought their recommendations were "amply sufficient to secure the best quality of cement without needlessly harassing the manufacturer and interfering with his legitimate profit."[159] Nevertheless,

G. Gravitz, a German Portland cement manufacturer, told the meeting of the Institution of Civil Engineers at which Scott and Redgrave had read their paper that the standards suggested by the two gentlemen were less exacting than those in force in Germany, Austria, Sweden and Russia.[160] Grant's test standards were also stricter.[161] Scott was particularly concerned over the 28 day strength test, which both he and Grant had adopted from German practice, because of delays it would cause in many construction situations.[162] Scott and Redgrave were naturally sympathetic to manufacturers, being themselves in the cement business. Nevertheless, at least in the judgement of the Institution of Civil Engineers, they had made an important contribution to the developing debate on the question of national test standards for Portland cement. Considering that the first such standard in the world had been established in Germany only two years before, their paper was certainly timely and significant.

Henry Scott had developed an extraordinary expertise in limes and cements based on experiments during his ten year career at the Royal Engineer Establishment. This expertise was to flourish after he succeeded Fowke as architect to the Science and Art Department and may indeed have been an important factor in his appointment. Pasley had been the founder of the experimental tradition at the Establishment and his strength testing experience was well known and respected. After his departure from Chatham, Pasley was to take up a position vastly different from his earlier career but at least in some respects suitable for his skills in materials testing - Inspector-General of Railways. The Royal Engineers were selected to staff this new department of government in 1840 and the story of their achievements there in the development of building technology is taken up in the following chapter.

3. RAILWAY INSPECTORS AND SAFE BRIDGES

In structural history, bridges have been on the leading edge of technological advances: in materials, forms and methods of construction. The coming of the railway in the early nineteenth century presented new challenges for bridge builders. It also presented the state with an unprecedented problem in regulating railway development, particularly in ensuring the safety of the travelling public. Safe bridges was an especially critical concern. Faced with this novel situation, the government turned to the Royal Engineers to staff the inspectorate of railways, an office established within the Board of Trade by the Railway Regulation Act of 1840. In that year, Lieutenant Colonel Sir Frederic Smith was appointed Inspector-General of Railways and thereafter railway inspection became the responsibility of officers of the Corps, serving or retired.[1]

The railway inspectorate was not an isolated phenomenon in government. Forced by the failure of local authorities to deal with striking new social problems following upon industrialization, Britain established, from 1833 to 1854, an extraordinary number of central agencies whose total functions added up to an administrative revolution. It marked the origins of the British welfare state.[2] The powers granted to these agencies were largely designed to regulate social not economic matters, and the dominant philosophy was the belief that exposing abuses and giving advice together with the employment of 'scientific' experts in carrying out these tasks would be effective in ameliorating problems. Persuasion rather than coercion was the approach.[3] Engineers or other building professionals were amongst the experts selected as Her Majesty's Inspectors. In addition to their appointment as railway inspectors, the Royal Engineers also staffed the inspectorate of prisons and individual engineer officers were seconded to serve as inspectors in other government departments; for example, one worked for the General Board of Health.[4] The Corps was thus an instrument of the state in new civil offices directed towards achieving social policy objectives, in part by way of engineering and architecture.

The Royal Engineers' role as railway inspectors was to be an object of controversy during the nineteenth century. On balance, the evidence suggests that the engineer officers' corporate contribution was largely responsible for the success of this new public office, notwithstanding its statutory limitations. Moreover, an assessment of the Royal Engineers' influence on the development of novel materials and structural forms in railway bridges indicates that their achievements were noteworthy. They made contributions to bridge design in three important ways. The inspectors acted as a salutory check on railway engineers and companies, helping to keep a good balance of economy, transportation efficiency and safety. Engineer officers could also challenge their civilian counterparts by provoking discussion on design concepts or details, sometimes offering important ideas of their own, and thereby promoting a greater and more thorough consideration of alternatives. Finally, they were largely responsible for the establishment of Board of Trade standards for safe design through accumulative on-the-job experience, public enquiries, research and experiment. As Pugsley has argued, while such prescriptions may tend to relate to out-of-date or at least uninspiring structures, they can at their best provide the means of using the experience of pioneers or other leading designers so that the ordinary practitioner can work for the public good without running undue risks of catastrophic failure or producing structures that are markedly inefficient.[5]

Statutory Powers, the Question of Safety and Competence

Railway inspectors' powers were extremely limited. The Board of Trade had no authority to require companies to submit plans of new works before they were built nor had its officers power to inspect or superintend works in progress. Inspectors therefore were not in the position to express an opinion on the design of a work before it was constructed nor upon the workmanship or the materials while it was in progress. All the inspectors could do was to visit the work when notice was given by the company that it was complete and then and there formulate an opinion as the circumstances allowed of its completeness. In the government's view, to do otherwise would put responsibility on the state and not on the railway company where the duty belonged for safety in bridges and other works.[6]

In the debate over the Railway Bill of 1840 in the House of Commons, there was criticism that even the most able and conscientious inspector could not certify from a single visit that a railway was safe. Moreover, the Board of Trade had no power originally to postpone the opening of a line but obtained this in 1842. Where an opening was postponed, the company had no right to appeal to the courts, but informal appeal existed by way of parties of sufficient influence and standing appealing to the President of the Board to repudiate his inspector's report and revoke the order. This did happen on occasion. The Board could postpone an opening for only a month at a time and on receipt of an inspector's report. Postponement requirements had little practical effect.[7] Powers of persuasion vastly outweighed legal ones for the railway inspectors.

The number of inspectors was extremely few. Originally there was only the office of Inspector-General, first held by Smith, who was succeeded by Pasley (1841-1846). In 1844 Captain Joshua Coddington was appointed Assistant Inspector to Pasley. The number of inspectors remained at two until 1856 when it was increased by one; in 1867 the number stood at four. Engineer officers also normally served for only about five years or less in the inspectorate.[8] Inspectors sometimes worked under considerable pressure but this seems to have been a result of the irregularity of the duties. Had there been enough inspectors to meet all the calls in the busiest times there would probably have been underemployment in the slack times. Nevertheless, there were too few inspectors to permit monthly inspections of more than one or two lines at any given period. Their effectiveness came not from cases in isolation but in relation to general principles derived from experience.[9]

Available evidence suggests that the Royal Engineers appointed to the railway inspectorate, as a rule, had little previous practical experience in bridge construction, especially in iron, apart from military works such as pontoon and other floating bridges or catenary rope suspension spans.[10] Officers of the Corps were schooled in the art of military bridge construction as a necessary part of their training at the Royal Engineer Establishment. The chief text was General Sir Howard Douglas', An Essay on the Principles and Construction of Military Bridges and the Passage of Rivers in Military Operations (1816). This book also contained material on road bridges of wooden trestles and piles, common forms early adapted for railway construction.[11] Nevertheless, the railway inspectorate was clearly a case where an engineer officer had to learn on the job about bridge construction.

A definition of 'safety' is critical to an evaluation of the Royal Engineers' role as railway inspectors. Pugsley has defined the term in the modern sense in an especially clear and concise manner:

> "... a structure is safe if it withstands the loads that come upon it during its working life, that it continues to serve the functions for which it was designed, and does so to the satisfaction of its owners and users without causing damage or undue disquiet to the general public."[12]

In the present case, the matter of public confidence was especially important. The measurement of safe loading conditions was an uncertain business in the nineteenth century. Moreover, the collapse of a single bridge could and did cause widespread public concern over the safety of new technology and the popular press and others frequently symbolized the railway accident as lurking death.[13] (See Figure 6) The Dee Bridge disaster is a celebrated case of this phenomenon and it is discussed at length later in this chapter. Given the often fragile nature of public

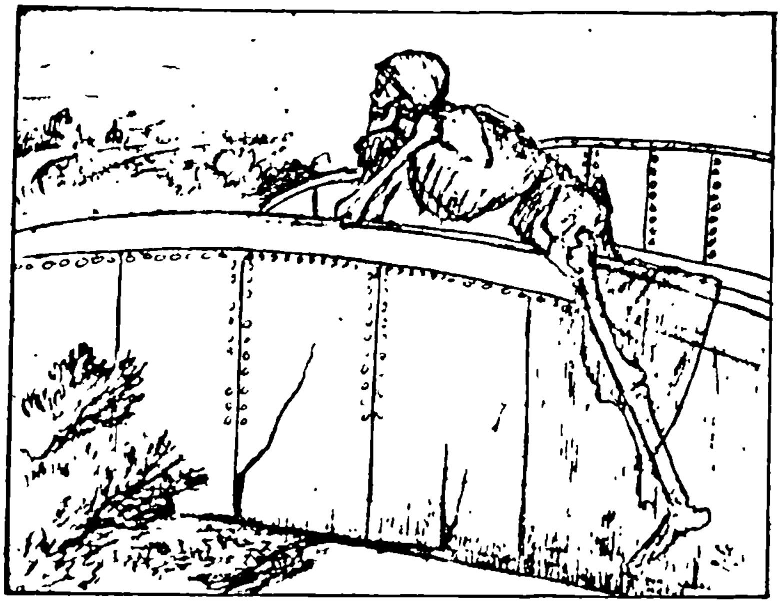


Figure 6 Sir John Tenniel's Drawing of the Railway Bridge as Lurking Death

confidence in novel railway bridge designs, it was important that the government help to assauge any fears that should arise if technological progress was not to be impeded by people's unwillingness to travel on lines with up-to-date structures.

Recognizing the Royal Engineers' limited experience in the construction of public bridges, especially for railways, the engineer officers of the inspectorate were inclined perhaps to be overly cautious on the matter of safety. This tendency was likely to be reinforced if not intensified by the circumstances under which their inspections were performed. While the statutory regulations did not hold them responsible for guaranteeing the safety of bridge structures, they would be placed in a difficult position in the public eye should a catastrophe occur shortly after their inspection report had recommended opening a line.

The question of the Royal Engineers' competence to inspect railways was a matter of public debate, especially amongst civil engineers. Nevertheless, negative opinion nearly always focussed more on the interference of the government and the bureaucratic system within which the inspectors worked than on the general competence of the Corps or that of individual engineer officers. The sharpest criticism came in the first decade of the inspectorate's operations and thereafter there was an increasing tendency to acknowledge the benefits which accrued from inspection not only for the public but also for the railway engineers and the companies.

An early instance of a hostile comment occurred in 1845 on a disputed case over the Whitehaven Junction Railway. Lord Lonsdale, accompanied by his engineer George Stephenson, complained angrily to the President of the Board of Trade: "What could the Royal Engineers possibly know about railways"[14] More thoughtful was the criticism of Isambard Kingdom Brunel. In 1840 he told a Parliamentary select committee investigating the question of government inspection of railways that he was opposed to the idea and seven years later lectured the Royal

Commission on the Application of Iron to Railway Structures that inspection retarded progress by taking as the rule, the prejudices or errors of today and applying them to design problems of tomorrow. Brunel considered free competition and public opinion the only effective means of ensuring engineering progress.[15] His view was shared by many others.

The most celebrated instance of criticism of the railway inspectorate was in 1850 over the Torksey Bridge affair, a subject which is discussed in detail later in this chapter. In the debate over the delayed opening of the bridge, a number of distinguished members of the engineering community including C.H. Wild and John Scott Russell condemned the inspection system and said that it was wrong to charge the Royal Engineers with the responsibility for inspecting railway structures because they lacked practical experience and knowledge in this field.[16] The Secretary of the Institution of Civil Engineers, Charles Manby, caught the substance of these criticisms when he said that the Royal Engineers "... possessed undoubted skill for their own peculiar military duties, but were placed in a false position when they were entrusted with the execution and control of civil works, of which their previous pursuits precluded their obtaining a practical knowledge."[17] It is significant that this was the only controversy of its kind in the discussions of the Institution of Civil Engineers during the nineteenth century and also that the affair was still being referred to in 1886.[18]

One of the most interesting criticisms of the railway inspectorate was by the civil engineer and technical writer Francis Roubiliac Conder (1815-1889) in his Personal Recollections of English Engineers (1868).[19] The anecdotal evidence which he used to support his criticisms concerned the activities of Inspector-General of Railways, Charles Pasley. Aside from Smith, whose career in the inspectorate was brief and rather uneventful, Pasley was the first Royal Engineer to be faced with the difficult task of learning a controversial new job virtually without precedent. Pasley kept a diary during his career as Inspector-General of Railways and it demonstrates that he attempted to overcome his ignorance by great industry and conscientiousness.[20] Nevertheless, his initial lack of knowledge was an easy target for criticism. Like Brunel and others before him, Conder roundly condemned statutory inspection and pointed to the Royal Engineers' lack of practical knowledge of railways, albeit with sympathy for their difficult position. Conder's summary of his criticisms is worth quoting:

> "But to pass Acts of Parliament, containing certain scientific statements unintelligible to most of the legislators; to profess to inspect, in the interest of the public safety; and then to send an Engineer officer, practically unacquainted with the subject, to take a walk, or drive over the line, was a method which combined several evils. It lessened the sense of responsibility, where alone that sense was available for public security; it took the onus from the Companies, while it assumed no responsibility on the part of the Government; it placed the officers of a scientific corps in a false positon, and tended to break down their high sense of duty by ordering them to take part in a sham."[21]

On the matter of bridges, and iron girder spans specifically, Conder made an important point. Essentially, he contended that engineer officer inspectors had to rely on the calculations and statements of the railway engineer responsible for a bridge being inspected:

> "It was a curious duty in which to employ officers, who were accustomed to receive orders of the utmost precision. For the most serious question of the time, the strength of girder bridges, the only available information was to be found in the tables and formulae prepared by the very men whose work was to be investigated. Slow processes of test, such as are possible in the foundry and fitting-shop, were inapplicable to bridges in situ. Careful daily watching, or the rude test of actual experience, could alone give certainty as to the faithful execution of any portion of the works of a long line of communication, in accordance with the drawings."[21]

To some extent this criticism was valid but, as will be discussed later in this chapter, the Royal Engineers attempted to overcome their statutory limitations through increasing emphasis in inspections on proof testing new bridges, eventually with reference to Board of Trade strength standards largely of their own making by way of experiment and other research.

Perhaps the foremost defender of the Royal Engineer railway inspectors was Sir John Hawkshaw (1811-1891), undoubtedly one of the greatest engineers of the nineteenth century. Hawkshaw was president of the Institution of Civil Engineers (1862-1863) and of the British Association (1875). His early career was dominated by railway engineering, including bridges, but he later expanded his practice into waterworks, town drainage, harbours and related concerns. He is especially noted for his designs for the wide span iron roofs of Charing Cross and Cannon Street railway stations in London. He also designed the foundations of the Spithead Forts (1861-1868) and this will be discussed in Chapter 5.[22]

At a meeting of the Institution of Civil Engineers in 1862, G.P. Bidder had complained that the evidence of railway inspectors before coroners' juries and other public enquiries concerning railway accidents was given too much weight considering their inexperience and short length of service. Hawkshaw came to their defence:

> "With regard to the Inspectors of the Board of Trade, with whom he had frequently been brought into contact, he begged to say, that, although he could not always agree with them in opinion, he believed, that they discharged their duties with candour and singleness of purpose. They had difficult tasks to undertake, as they had to commence their duties without any previous knowledge in the conduct of railways; and it was to be regretted that after remaining in office just long enough to acquire a certain amount of information and experience on the subject, they were superseded by others. That, no doubt, accounted for some discrepancies between Civil Engineers and these officers;

> but he had always experienced from them gentlemanly courtesy, and, although they had sometimes differed from him in opinion, he never had occasion to call in question their integrity, or their honour."[23]

Four years later, in a meeting at the Institution of Civil Engineers on the question of Board of Trade standards for iron railway structures, Hawkshaw explained that the Royal Engineers had a difficult job and that compared to civil engineers they were more likely to be reasonable in debating contentious matters in a design:

> "... he thought it was somewhat hard upon the officers of the Royal Engineers, that they should be called upon to be precisely definite in their views as to weights and loads, and modes of construction, when they heard how Civil Engineers varied on those subjects. He undertook to say, if four or five Engineers were sent to investigate the strains on those bridges, and to act upon their own opinions, they would probably be found more troublesome than officers of the Royal Engineers, who, he felt bound to say, had sometimes very arduous duties thrown upon them. They were called on suddenly to say whether a railway, upon which there were large works, was safe for the public, and they had to pronounce promptly upon the questions; and he thought, as far as his experience went, they were usually amenable to reason."[24]

Another civil engineer at the meeting added a measure of praise for the railway inspectors and recognized their benefit:

> "Mr. Berkley thought the supervision of the Officers of the Board of Trade was valuable. However much Engineers desired to do what was right, the bringing them into contact with gentlemen who, though they might not have all the practical experience of the Engineer in the construction of railways, desired to see that the structures were designed so as to be perfectly safe, and who had special and extensive experience relating to accidents on railways, was an advantage."[25]

This acknowledgement of the salutory effect of the railway inspectors' primary concern for safety was indeed an important indicator of a growing acceptance by the civil engineering profession of the competence and contribution of the Royal Engineers who staffed the inspectorate. In 1872, A.M. Rendel said, in response to an allegation by G.P. Bidder that the recent failure of bridges in the Punjab was mainly the fault of the India Public Works Department, that Bidder's complaint sounded much like the attacks sometimes made in Britain against the railway inspectors of the Board of Trade which "he should think had now been heard for the last time."[26]

The judgement of historians on the role of the railway inspectors has been favourable. Porter, author of an 'official' history of the Corps in 1889, said of the duties of the Royal Engineers in the inspectorate:

> "That they have been, as a rule, well performed is admitted by all. Indeed, it is the rarest thing possible to read a complaint, or even to hear doubt thrown upon the manner in which these officers have fulfilled their functions."[27]

Nearly ninety years later, Simmons expressed a similarly positive opinion, putting the matter in the perspective of the Victorian beginnings of the welfare state:

> "Like their fellows in factories and mines, these Inspectors were engaged in a subtle and difficult exercise. Over the years they performed their part in it well. The country owed them a great debt. So did the whole railway service, the companies and their employees alike."[28]

It is difficult to disagree with these two assessments. The railway inspectors clearly demonstrated competence and made important contributions concerning the design of safe railway bridges, as the following case studies illustrate.

New Design in Old Material: The Laminated Timber Arch

It is instructive to examine briefly the Royal Engineer railway inspectors' response to the laminated timber arch in railway bridges. Although this structural technique was developed earlier on the Continent, at the time the inspectorate was first established the laminated timber arch bridge was a relative novelty in Britain, having been introduced 1837-1839 by John and Benjamin Green on the Newcastle and North Shields Railway. Booth has recorded 34 of this type built in England and Scotland 1837-1850. Joseph Locke used more than any other engineer. Robert Stephenson never used them and rarely timber for that matter. I.K. Brunel developed his own timber bridge system and used only one laminated arch. The type had advantages of quick erection and cheap first cost but maintenance could be costly and life short. It seems the main problem was decay due to poor bonding techniques and the lack of good preservatives. Strength and stiffness under load were critical to life span. These bridges tended to oscillate, opening up joints and allowing water penetration. Flexibility was also a cause of public concern for the safety of the bridge type. By mid-century they had been eclipsed by the introduction of structural wrought iron.[29]

Dinting Vale Viaduct by Locke and Alfred Stainstreet Jee was one of the more interesting of the early laminated timber arch bridges. Begun in 1843, it had five timber arches of 125 foot span built of Memel fir treated by Margary's wood preservative process. There were four ribs in each arch composed of planks 3 inches thick fastened together by oak trenails. The ribs were stiffened by diagonal cross braces screwed upright by wrought iron rods (see Figure 7).[30] Pasley inspected the viaduct 6 August 1844. He recorded in his diary: "Set out at 9:48 accompanied by Mr. Jee - See the Dinting Viaduct - very good."[31] The bridge was opened for traffic two days later. In 1846 at a meeting of the Institution of Civil Engineers Pasley explained further about the viaduct that he "was much pleased with the design and solidity of its construction."[32] He also commented that this was a good example of a general rule he had observed in his inspections that accidents to bridges were attributed not so much to defects of design as to carelessness on the part of those who superintended the execution of the works or from the use of improper materials, undue haste or

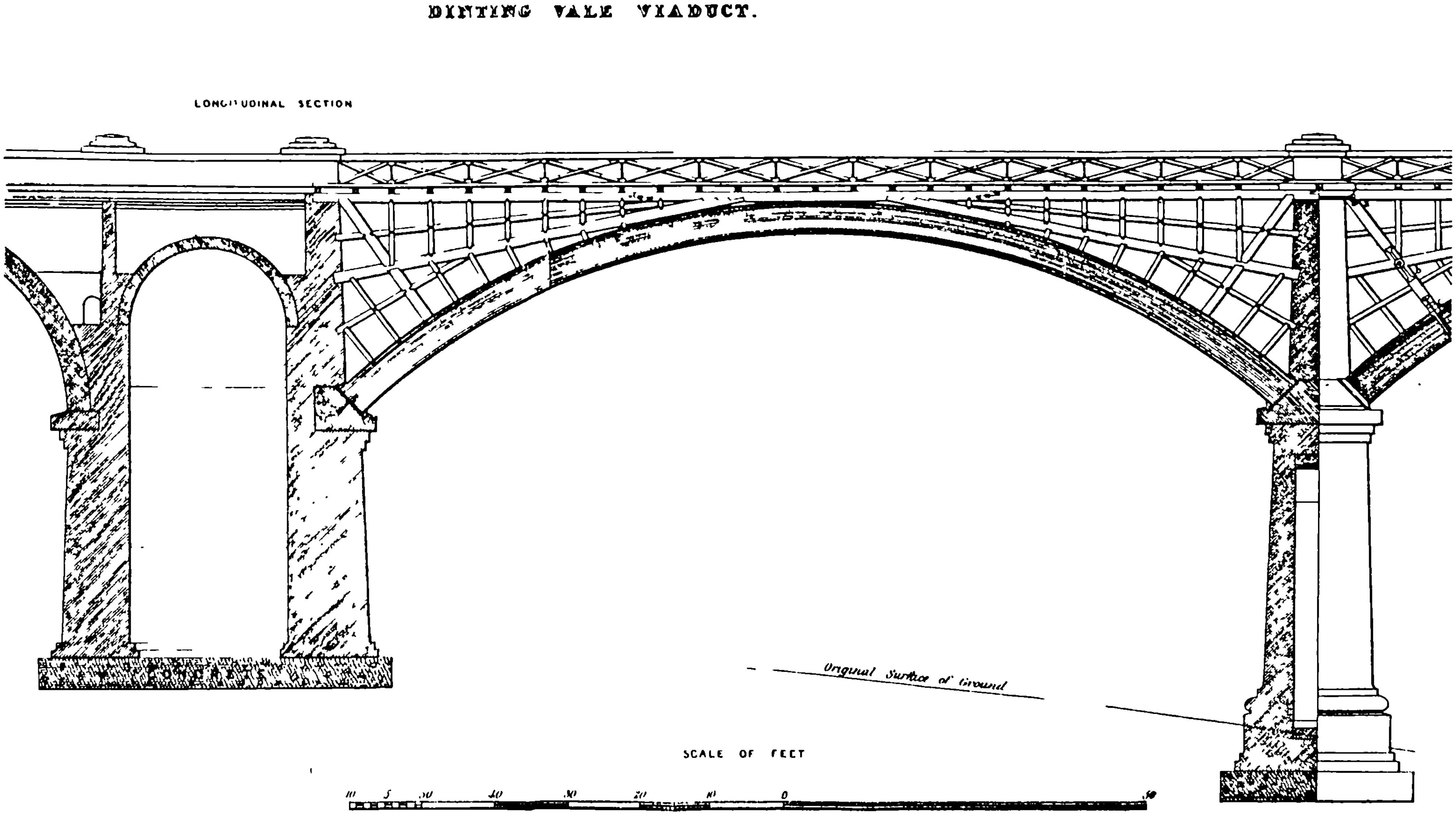


Figure 7 Dinting Vale Viaduct : Timber Arch

building in bad weather. He was particularly anxious to insist on the use of good cement over lime mortar in which case "the risk of failure would be greatly diminished."[33] Pasley seemed to demonstrate confidence in the design abilities of civil engineers but was not so convinced of the conscientiousness of their subordinates or railway contractors. He also showed that he accepted rather unquestioningly the effectiveness of the laminated timber arch design. Pasley was concerned more with mortars in traditional masonry bridge construction, a subject on which he was an expert. Indeed, Pasley continued to express uncritical confidence in the laminated timber arch. After inspecting Robert Nicholson's Tynemouth Bridge, he wrote in his report 7 October 1846 that the method of construction "has hitherto given satisfaction, for no doubt can be entertained of its strength, if the depth of these arched ribs of bent planks be justly proportioned to the span."[34] In this Pasley revealed a key attitude which affected his judgement as a railway inspector. If he had seen it work before, he thought it was likely to work in the case under inspection provided it was scaled up or down to meet the span requirement.

Inspectors after Pasley were more 'scientific' in their approach to inspections, especially following the Dee Bridge disaster (1847). They subjected bridges to proof load tests. In his inspection of Vignoles' laminated timber arch viaduct over the River Lune in June 1848, Captain George Wynne was particularly concerned about stiffness. This structure was built on a curve and consisted of a series of laminated bows, spanning openings averaging 60 feet and springing from timber piles and stone abutments. Wynne passed a slowly moving train of six wagons, loaded with 50 tons of rails, several times over the bridge. He noticed only 3/4 of an inch deflection and explained that while looking under the bridge during passage he could not perceive any lateral or swaying motion.[35] Notwithstanding the fact that Vignoles' bridge proved sufficiently stiff, Wynne reported that he did not direct the train to pass at any considerable velocity as on such a curve it would be highly dangerous. Accordingly, he recommended a 4 miles per hour speed limit as the condition of opening the bridge to traffic.[36]

Speed limits were imposed in some cases for bridges constructed of laminated timber arches because of their tendency to be too flexible. In his report of 17 February 1849 on the bridge over the River Tay into the town of Perth designed by Locke, inspector Simmons reported:

> "I consider it safe at moderate speeds; but in as much as there is a great deal of movement in the timber laminated arches extending in one that I tried to a rise of half an inch, and a fall of one inch and a half, or a movement altogether of two inches in the passing of an engine, I should strongly recommend that some method be tried by which the structure may be stiffened, as this constant movement must materially tend to the destruction of the bridge."[37]

This 444 yard bridge was constructed of timber segmental laminated arches of 50 foot span resting on timber piles. Later in the same year inspector Sir Robert Laffan investigated it further and identified the flexibility problem as the wooden pile supports and imposed an 8 miles per hour speed limit.[38]

The inspectors' concerns for stiffness in laminated timber arches, following Pasley's somewhat unquestioning acceptance of the new type, probably helped to some degree in encouraging railway engineers to improve their designs within the limits of existing technology and therefore to achieve the maximum life and safe operation of these structures. The inspectorate also helped to allay public fears about the flexibility of the design type. In September 1850, in response to complaints about the oscillation of Green's Ouseburn Viaduct (1839), Captain Laffan inspected the structure and pronounced it perfectly sound, attributing the feeling of insecurity to the light rails.[39] Nevertheless, the major challenge for the Royal Engineer railway inspectors was not these novel structures in timber but more revolutionary designs in iron.

Cast Iron and the Dee Bridge Disaster

Cast iron developed as a structural material in the late eighteenth century as a compression substitute for stone in arch bridges; but in the 1790's and early nineteenth century it came to be used in girder form for mill buildings and short span bridges and its brittle nature and weakness in tension led to a number of accidents. The risk with cast iron was not one of instability (as in rigid masonry structures) but catastrophic failure under load, usually some load beyond that of the weight of the structure itself. Designers therefore sought substantial margins of safety.[40] With railway bridges, one attempt to overcome the length limits and brittleness of cast iron beams was the trussed (or assisted) girder. External wrought iron bars were used both to join and reinforce the castings. Designers later sloped up the ends of the tie bars, anchoring them above the beam section, apparently thinking that the tension in the sloping ties would hold up the centres of the beams and counteract the applied load as in a suspension bridge; therefore they made their composite beams shallower at mid-span than they would have done with simple castings. These trussed cast iron beams were used by many engineers over a relatively long period of time. The first recorded use was by Vignoles in 1831. Although beams of this type had failed in railway bridges and were replaced without incident, the first fatal failure which occurred in the Dee Bridge, 24 May 1847, was a landmark in the history of nineteenth century building technology.[41]

Robert Stephenson designed the Dee Bridge with trussed girders consisting of three castings, each bolted together at the joints making a length of 109 feet. The clear span was 98 feet. (See Figure 8) Pasley inspected the bridge on 20 October 1846 and reported it safe. He made no remark on it in his diary other than that he had inspected it. He had left the inspectorate by the time the accident occurred. Pasley heard of the disaster on 25 May 1847. Two days later he remarked in his diary that the accident seemed "unaccountable" because the bridge had

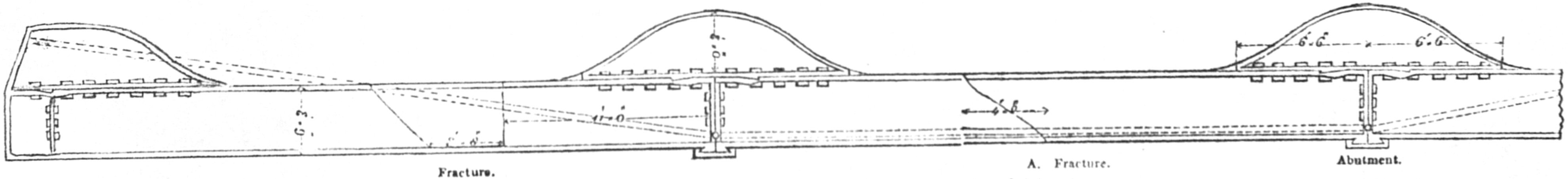


Fig. 1. Elevation of Dee Bridge Girder 109 feet long and 98 feet in clear of the Bearings.

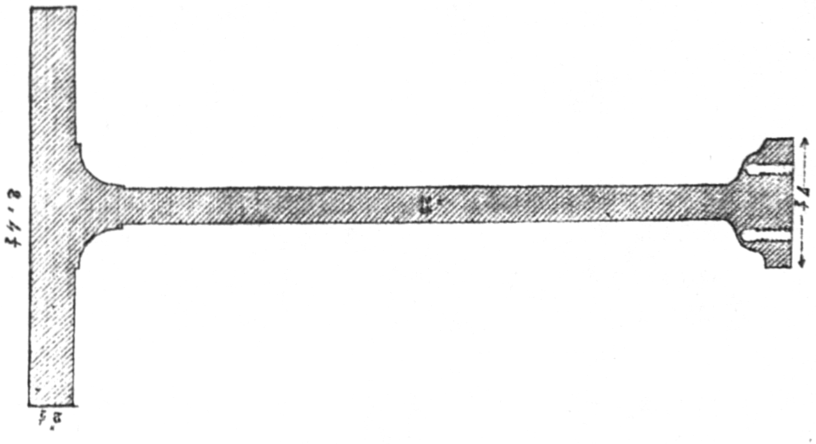


Fig. 2. Section at Fracture A. Depth 3 ft. 9 in.

Figure 8 Dee Bridge Girder

appeared "adequate of strength" and also noted that he had seen Robert Stephenson who it seems was anxious to discuss the failure with Pasley.[42] At the coroner's inquest in June, Pasley explained that he had compared the plans with the executed work and examined it in the detail he thought necessary. He went on to say that he had reached his conclusion about the safety of the Dee Bridge by comparing it with a similar trussed girder design for the bridge over the River Ouse at York for the York and Scarborough Railway; as the bridge at York and other similar bridges had stood, he thought that the Dee would because its girder depth was proportionately deeper than the others of shorter span.[43] Conder (1868) later poured scorn on this explanation as proof that the one day inspection process was a sham, but called it a good military reason.[44] Pasley told the jury that he had always been of the opinion that the wrought iron tension rods would do little good since the two metals in such a girder behaved so differently in thermal expansion and contraction.[45] He said he had repeatedly mentioned his opinion to engineers and that he much preferred well proportioned simple castings used in the well accepted way to the trussed girder.[46] He also told the jury that he had not been informed about a girder which had cracked through the bottom flange on the Dee Bridge and which Stephenson had replaced without incident.[47] The cracked girder incident and the later bridge failure induced Pasley in retrospect to consider the girder type unsafe.[48]

Pasley's evidence was given under a good deal of pressure and to a considerable degree he was careful to interpret his actions to exonerate himself in the fatalities. By one account he was so agitated that when he was called to testify he could hardly speak and what he said was inaudible to the body of the court.[49] Evidence suggests that he was not as concerned about the flaws of the trussed girder type prior to the accident as he suggested in his testimony. For one thing, he had expressed astonishment in his diary on hearing of the catastrophe. Perhaps more revealing was an incident which occurred only a month before the fall of the Dee Bridge.

Pasley had then participated at a meeting of the Institution of Civil Engineers in a discussion about the failure of a trussed cast iron beam in a mill at Manchester. Sir William Fairbairn attributed failure to the trusses which had tended to weaken the casting which was not of the best form. Stephenson, Bidder, Vignoles and Andrew Handyside, who had used the type, defended the trussed girder and agreed that failure was due to improperly positioned truss rods and erroneous calculation of the strength of the beam. Pasley disagreed with all of them. He said that he had read reports about earlier building collapses at Oldham and Northfleet which some had put down to poorly designed cast iron beams. Pasley felt all these accidents were caused not primarily by the failure of cast iron beams, trussed or simple, but by the use of common lime mortar instead of good cement in the walls supporting the beams. Pasley seemed inclined to attribute the buildings' collapse to the failure of a material he knew well from his years of experiment at Chatham rather than a material he had much less experience with. It would appear also that he was less likely to doubt the safety of cast iron beams, simple or trussed, than the civil engineers who employed them. In the case of the Dee Bridge, Pasley had probably taken Stephenson's word for the soundness of the structure as confirmation of his own rule-of-thumb that if it worked before it would work again. On balance it would be unfair to blame Pasley for the Dee Bridge accident or for that matter Stephenson. Nevertheless, it seems clear that Pasley contributed nothing to the improvement of badly designed trussed girders in the way Stephenson did later with his span over the River Arno or T.L. Gooch did with his bridge on the Trent Valley Railway.[51]

While Pasley's involvement with the Dee Bridge disaster was unproductive, that of his successor in the inspectorate was not. Captain Simmons had been ordered to inspect the accident two days after it happened. He first examined the bridge 27 May 1847, accompanied by Stephenson who gave his view on the cause of the accident, namely that the girder had been hit sideways by the engine or a carriage leaving the track. Simmons observed the way in which the girder had been broken as a preliminary step in diagnosis and undertook some experiments on the standing part of the bridge, taking measurements of deflections assisted by Mr. Owen, Inspector of Metals for the Admiralty, and officers of the railway companies involved. Following this, the distinguished civil engineer James Walker was appointed to assist Simmons and to make a joint report with him to the Railway Commission and the coroner. The appointment of Walker seems to have been an attempt to add credibility to the opinion of the 26 year old Simmons who had only recently joined the inspectorate. Walker (1781-1862) had been President of the Institution of Civil Engineers (1834-1845). He had built bridges but was mainly a docks and harbours engineer. Walker and Simmons attended the inquest 2 June 1847. Simmons had undertaken further experiments on deflection from stationary and moving loads, and on the effect of twisting in the girder which was a feature of the design. The results were used to support their report. Essentially, Simmons and Walker found that the tension bars were next to useless and that the cast iron girders were not of sufficient strength on their own. The accident was caused in their view by the failure of the cast iron girder owing to the gradual weakening produced by the continued application of a load near the breaking weight, the adding of ballast stone to the deck immediately before the accident, and the passage of the fatal train whose increased momentum over the bridge added to the effect of its weight, putting a breaking strain on the girder. They said they had arrived at this conclusion after due consideration of the dissenting opinions of Stephenson, Locke, Vignoles and Gooch that the girder was of sufficient strength, and that they held their view most decidedly.[52] (See Figure 8)

In its verdict, the coroner's jury agreed unanimously with Simmons' and Walker's report that the girder was not of sufficient strength to bear the weight of fast moving trains going over it. Pasley, incidently, had agreed with the report too in his testimony but it is not entirely clear whether he had seen it or not before giving his opinion. The corner's jury further expressed the opinion that cast iron girders, even though trussed with wrought iron rods, were unsafe for fast moving trains and recommended a government enquiry into the safety of cast iron bridges. This recommendation was passed on to the Railway Commission.[53]

On 29 June 1847 the Railway Commissioners recommended a Royal Commission to the government and said they had decided to do so after considering Simmons' and Walker's report. The only qualified engineer on the Railway Commission was Royal Engineer Captain Henry Rowland Brandreth. He was formerly Director of Architecture and Engineering Works for the Admiralty (1838-1846). Brandreth was no novice with iron structures. In his early career he had built prefabricated cast iron barracks and hospitals in the West Indies (see Chapter 8) and while at the Admiralty had played a central role in pioneering wide span iron roofs in the dockyards (see Chapter 4). Parris has shown that the Commission regularly referred technical matters to Brandreth who sat on occasion independently of his colleagues to hear engineering evidence and reported his findings to them. It is therefore not unreasonable to suggest that Brandreth played an important role in reviewing Simmons' and Walker's report and in recommending a Royal Commission. Brandreth died suddenly in February 1848.[54]

Accordingly, while the recommendation of the Dee Bridge disaster coroner's jury undoubtedly influenced the government to call a Royal Commission (appointed 27 August 1847), a good deal of credit must go to the Railway Commission and especially the Royal Engineer officers who were involved - Simmons, Brandreth and Harness (the secretary to the Railway Commission). The Royal Engineers were the only ones on the Commission and its staff who were qualified to understand the technical matters at hand apart from the political issue of public concerns. Indeed, the formulation of the statement of the engineering problem facing the nation could only have come from a good understanding of the technical issues. This statement became the basis of the terms of reference for the Royal Commission and identified the challenge: that contemporary knowledge of the strength of materials in the face of increasingly heavy loads and great speeds was inadequate; that the experiments necessary to solve the problem were beyond the resources of individuals; and that the solution could not be left to the accumulation of accident data - it was needed at once.[55]

The Royal Commission on the Application of Iron to Railway Structures

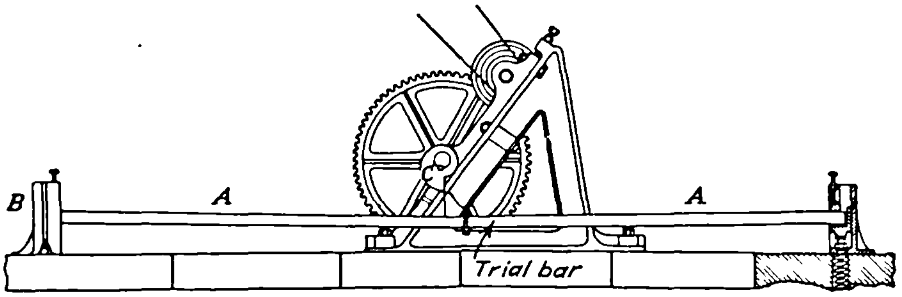
In the report of the Royal Commission on the Application of Iron to Railway Structures (1849), the Commissioners expressed the hope that their efforts would "enable the engineer and mechanic to apply the metal with more confidence".[56] The metal to which they referred was cast iron. Although the report contained information about wrought iron, the Commissioners declined to express an opinion on the innovative wrought iron tubular girders then being introduced. Nevertheless, it was cast iron that had failed in the Dee Bridge and that was the metal the public feared and in which confidence had to be restored.

The Commissioners stated in their report that they had information supplied to them on the proportions and forms then employed for cast iron structures based on experiments on iron bars but none had considered dynamic loads. Accordingly, the Commissioners undertook their own experiments on the effects of percussion and vibration, and on moving loads. Eaton Hodgkinson undertook some experiments on the former (at Lambeth) and offered the results of his extensive experiments for the Menai and Conway Bridges, but key experiments on both areas of concern were carried out by two Royal Engineers - Sir Henry James and Sir Douglas Strutt Galton. The former was a Commissioner; the latter was the Secretary of the Commission. James was at the time Superintendent of Works at Portsmouth naval dockyard, where the engineer officers' experiments were carried out. He had been appointed to the position with the Admiralty in 1846 and had some experience with construction in iron in the dockyard (see Chapter 4). Prior to his Admiralty appointment, James had been ten years in the Ordnance Survey to which he was to return in 1850, becoming one of its most distinguished Directors-General. Galton, who in 1847 was Secretary to the Railway Commission, also had been with the Ordnance Survey (1846). In his seven years in the Corps he had undertaken no notable work with iron but had distinguished himself at the Royal Military Academy, apparently scoring the highest marks on record, taking first in every subject. Galton's most important work was done later in barracks and hospitals and in the developing field of sanitary engineering (see Chapter 6). James appears to have been most involved with the experiments.[57]

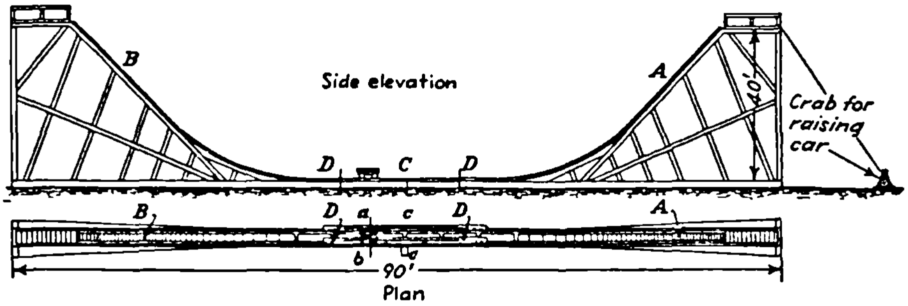
As a preliminary investigation for the Commission, James did some tests on the effects of static loads on rectangular cast iron bars to ascertain breaking weight compared to rules established by mathematical calculation from several writers on the subject. In this he made the important discovery that the larger the castings, the greater the falling off from their computed strength due to soft centres. He concluded that test bars should be the same thickness as castings intended for use. This was an important finding and ended up as a recommendation in the Royal Commission report.[58] The conventional method of testing with small bars (normally one inch square cast iron bars of various lengths) had been developed to determine the strength of castings given the great variation in quality from different foundries. Fairbairn had used them too for experiments on the effects of time and temperature on the strength of cast iron (1837-1842).[59] James appears to have had some priority in realizing from bar testing that small specimens could not really be representative of iron in large castings which were subject to flaws and blowholes, and that the only safe calculation of strength would come from using test units equal in thickness to the thickest part of the proposed casting.[60]

Tests by the two Royal Engineers concerning the effects of percussion and vibration (which they called reiterated depression) were carried out on an apparatus consisting of revolving cams to deflect a cast iron bar and then release it suddenly. From these experiments James and Galton concluded that the bars would not bear the repeated application of 1/3 of their breaking weight without damage. This was an important contribution to the understanding of fatigue in cast iron.[61] They also tested a wrought iron box girder but no effect was observed.[62] The conventional margin of safety for cast iron was that the greatest load should not exceed 1/4 of the breaking weight. As a result of these experiments on fatigue, the Commissioners recommended this factor be increased to 1/6.[63] (See Figure 9)

James and Galton next proceeded to undertake tests on the effects of dynamic loads on structural iron. They began by experiments with slowly moving loads but observed no appreciable effects in this case.[64] Accordingly, they moved on to experiments on fast moving loads. These were undertaken with another Commissioner, Reverend Robert Willis, Jacksonian Professor of Natural Philosophy at Cambridge. The apparatus was built at Portsmouth naval dockyard by James and tests were carried out wholly by James and Galton.[65] Charlton has said that this was perhaps the most significant research of the century into dynamics of structures.[66] Willis credited the Royal Engineers' results as new and important, demonstrating for the first time the greater deflections produced by moving loads.[67] The apparatus was designed to be as real as possible. It consisted of a 90 foot railway track supported by a special scaffold, and the moving load was a carriage with two axles. (See Figure 9) Results of their 400 tests on cast iron bars of various sizes were alarming. Dynamical deflections were sometimes up to three times those of statical at higher speeds. The Commissioners undertook further tests on actual bridges at Ewell and Godstone for comparison and the effects were found infinitely less. Willis also made



Fatigue Testing Machine



Railway Track Used for Dynamic Tests of Beams

Figure 9 James' and Galton's Experiments for the Royal Commission on the Application of Iron to Railway Structures further experiments using his own apparatus at Cambridge and consulted his mathematician colleague George Stokes concerning the problem with James' and Galton's results. No conclusive explanation was found by the Commission but it thought that while in large bridges dynamic effect could be considered negligible, it would be a factor in short and weak structures traversed with excessive speed.[68] The Commission made the recommendation to calculate for increased deflection from moving loads on bridges of less than 40 feet.[69]

The Royal Engineers made some important contributions to the understanding and use of structural cast iron by way of their participation on the Royal Commission. It is interesting and ironic, however, that while the Commission report cautioned engineers on the use of the trussed cast iron beam, it accepted the technique as a safe solution to bridge design notwithstanding the fact that it had no experimental data on the type except for James' very preliminary and incomplete tests on reinforced castings.[70] The girder form that had caused the 'panic' with the Dee Bridge disaster had been assessed almost exclusively on the evidence given by practising engineers to the Commission.[71] Also, apart from publishing some of Hodgkinson's experiments on wrought iron, the Commission said nothing very significant about this key material of mid-century. The legacy of the Royal Commission report was to have some important consequences for the Royal Engineers' role as railway inspectors.

Development of the Wrought Iron Bridge

By 1850 cast iron had been eclipsed by wrought iron as the modern structural material and this transformation heralded unprecedented advances in understanding of materials and their use. This progress was nearly all made in England and initially almost wholly in the field of railway bridges.[72] Sutherland has called the building of the Britannia Bridge (1845-1850) over the Menai Straits perhaps the greatest step forward in structural understanding and practice in the last two hundred years.[73] This massive continuous box girder of rectangular section with cellular flanges, designed by Robert Stephenson with the assistance of William Fairbairn and Eaton Hodgkinson, was an ingenious solution to a bridging problem for which there was no known method of meeting the requirement.[74] It is instructive to review the part played by the Royal Engineer railway inspectors, particularly Pasley, in the evolution of this landmark design. Also revealing is their role in the development of other contemporary wrought iron bridges, especially the controversy over the Torksey Bridge in which Simmons was the central character.

Stephenson's first proposal for the Menai Bridge was for two cast iron arches. He called on Pasley on 10 February 1845 to explain his idea but Pasley objected to it on the grounds that it would obstruct navigation and would be impracticable because difficult to construct.[75] A report for the Admiralty in March 1845 by Sir John Rennie, James Rendel and Captain Vidal of the navy also objected to Stephenson's proposal because it would not give shipping full vertical clearance over the whole span.[76] Two days after his initial visit, Stephenson called on Pasley again to answer his objections to the cast iron arches proposal. On this occasion Pasley noted in his diary: "I am convinced, now good."[77] Nevertheless, sometime later that month, probably aware that the Admiralty was going to reject the cast iron arches design, Pasley suggested to Stephenson that he try another approach. He recommended to Stephenson that he erect a suspension bridge to provide a platform to construct a "lattice or truss bridge such as they have done in America, and such as Sir John McNeill (sic) has lately made in the Royal Canal at Dublin; either a latticed or a trussed bridge, partly of timber and partly of iron, or entirely wrought iron."[78] Pasley thought that once the trussed span had been constructed the suspension chains could be removed because the truss would be strong enough to carry trains on its own, but insisted that the chains should be kept on to provide "superabundant" strength and to facilitate repair of decayed parts of the truss in the future without causing injury to the stability of the bridge.[79]

It is not known what information Pasley had about American lattice or truss bridges. A number of parallel top and bottom chord trusses were used widely in America in the early 1840's. Ithiel Town (1784-1844) had patented a lattice plank system in 1820 and this was adapted for railroad bridges in the 1830's. Some other pre-1845 patented trusses used on American railroads, either wholly in timber or composites of wood and wrought iron, were those of Stephen Harriman Long (1784-1864), William Howe (1803-1852) and Thomas Willis Pratt (1812-1875). None of these bridges, however, achieved the over 400 foot clear span required at Menai.[80] With respect to British bridges, Pasley only discussed the lattice girder. He had inspected in November 1843 a light wrought iron lattice road bridge of 84 foot span over the line of the Dublin and Drogheda Railway at Raheny, designed by John Benjamin MacNeill (c1793-1880). Pasley wrote in his diary concerning this bridge that it bore 22 tons in MacNeill's load test.[81] In 1844 Pasley explained at a meeting of the Institution of Civil Engineers that he had approved the bridge because "it appeared to be on a good principle, and was well constructed."[82] As quoted above, he referred specifically in conversation with Stephenson to MacNeill's wrought iron lattice railway bridge at Dublin over the Royal Canal. This 140 foot span, three truss structure, built 1843-1845, was to develop serious stability problems by 1856.[83] Pasley said nothing about the timber lattice bridges then extant designed by William Scarth Moorsom (1804-1863) for the Birmingham and Gloucester Railway, the maximum span being 160 feet.[84]

The idea of a lattice or truss bridge for Menai was clearly pushing existing technology beyond its limits. Moreover, the lattice girder never became popular for British railway bridges.[85] Nevertheless, Pasley demonstrated that he could make a contribution to the examination of design alternatives by sharing with the railway engineer his knowledge based largely on previous inspections. Other railway inspectors were to demonstrate this characteristic ability to contribute through accumulated experience.

As Stephenson had expected, the Admiralty's objection rendered ineligible his cast iron arches proposal.[86] However, Pasley's suggestion of the lattice or truss concept was not well received by Stephenson who seems to have associated the use of this structural form with timber, at least as indicated in his testimony a few years later to the Royal Commission on the Application of Iron to Railway Structures. Stephenson told the Commission he had never used the lattice.[87] Early in April 1845, Stephenson called on Pasley again, this time to present a revolutionary new idea. It was for a wrought iron tubular girder bridge, albeit using suspension chains for erection. In Stephenson's account of the meeting Pasley concurred with the soundness of the idea but insisted that the suspension chains used for erection be left on after completion. Stephenson felt that it would be difficult to use a flexible chain to strengthen a rigid platform. His opinion was based on personal observations of Samuel Brown's unsuccessful railway suspension bridge at Stockton constructed in 1830 which Stephenson replaced by a cast iron span in 1842.[88] Evidently Pasley was more hopeful with respect to the possibilities of railway suspension bridges. Indeed, he had expressed an early interest in the question of stiffening platforms of suspension spans so as to render them more serviceable and safe; this was in his paper to the Institution of Civil Engineers in 1838 on the failure of Brown's suspension road bridge at Montrose.[89] Pasley indicated that his curiosity had drawn him to inspect Brown's bridge which had been badly damaged in a severe gale "having always been of the opinion that from the example of failures some of the most instructive lessons in practical architecture or engineering are to be found."[90] At the time Pasley was Director of the Royal Engineer Establishment but this statement revealed an attitude which would be an asset in his later career as a railway inspector.

Stephenson did not challenge Pasley vigorously on the issue of keeping the suspension chains in place, claiming in his recollection of their meeting that he felt the matter would sort itself out in the progress of the work.[91] However, Fairbairn in his account of the building of the Britannia Bridge contends that initially Stephenson wanted to keep on the chains because of doubts arising from his lack of direct experimental knowledge of wrought iron tube strength. He further argued that Stephenson's doubts were allayed by witnessing one or two experiments on the model tube at Fairbairn's works but that he had not charged his mind on the chains matter until October 1846. Fairbairn took full credit for being the only one who had confidence from the outset in the strength of the tubes working on their own. Hodgkinson also advocated keeping the chains as auxiliaries.[92]

Nevertheless, Stephenson's acquiescence with Pasley's view on the issue of chains was arguably more a matter of pragmatism than doubt. On 5 May 1845 the necessary legislation for the bridge came before a House of Commons committee. It seems that the committee considered Pasley's evidence of particular importance. Stephenson, knowing he needed Pasley's support, decided to leave the impression with the committee that the chains might be left on as auxiliaries to the tube if necessary while expressing unequivocally the opinion that the tube was strong enough on its own. This was probably a wise decision since in his evidence Pasley continued to insist on the chains being kept. What is interesting though is that Pasley's testimony may have convinced the committee that the chains could indeed be dispensed with. Pasley confidently endorsed the tube design but was nervous on the chains issue. He often repeated himself and when asked if he had the power to disallow the bridge if the chains were taken off, said he did not know. When pressed further for a simple yes or no answer on whether the bridge would work safely without chains, he finally allowed that it was a difficult question to answer until the bridge was actually built - this was the answer Stephenson wanted.[93]

Late in 1845 and early the next year Stephenson and his team worked on the design and testing of chains intended as scaffolding which would also support the tubes in the event of a failure in erection. However, between July 1846 and May 1847 the idea emerged of erecting the tubes by floating them into position and lifting them on hydraulic jacks. Consequently, the suspension chain erection method was abandoned.[94] Even so, as completed, the Britannia Bridge's masonry piers, through which the tubes pass, appear overly tall. Enduring evidence is thus presented of the original intention to use piers as towers for erecting the bridge with suspension chains. These might even have been left in place as a measure of extra strength for the novel design in structural wrought iron. (See Figure 10)

Pasley's role in all this may seem to have been somewhat retrograde, but on balance he can be given some credit for having contributed through his suggestions to the thought process that led to the final solution. Clearly Stephenson valued his criticism since he had no legal obligation to consult with Pasley and did adopt Pasley's idea concerning the method of erection of the tubes until a better one was found. Pasley's concern for keeping the chains was to add an extra measure of safety and to facilitate maintenance. He also had some confidence in the notion that the suspension principle could be made to work for railway bridges. These were not the mark of an engineer afraid to explore new ideas while maintaining a primary concern for public safety.

On 15 March 1850, Simmons inspected the first completed tube of the Britannia Bridge and referred to it as "this magnificent structure, which surpasses in magnitude any engineering work of the sort constructed up to the present time."[95] He approved the bridge with confidence, judging as he said "from prior experience of works constructed of the material and having full reliance in the care and skill displayed in constructing the immense tube."[96] Perhaps most significantly, he referred to the principle of continuity in the design which would add considerable strength, although he confessed:

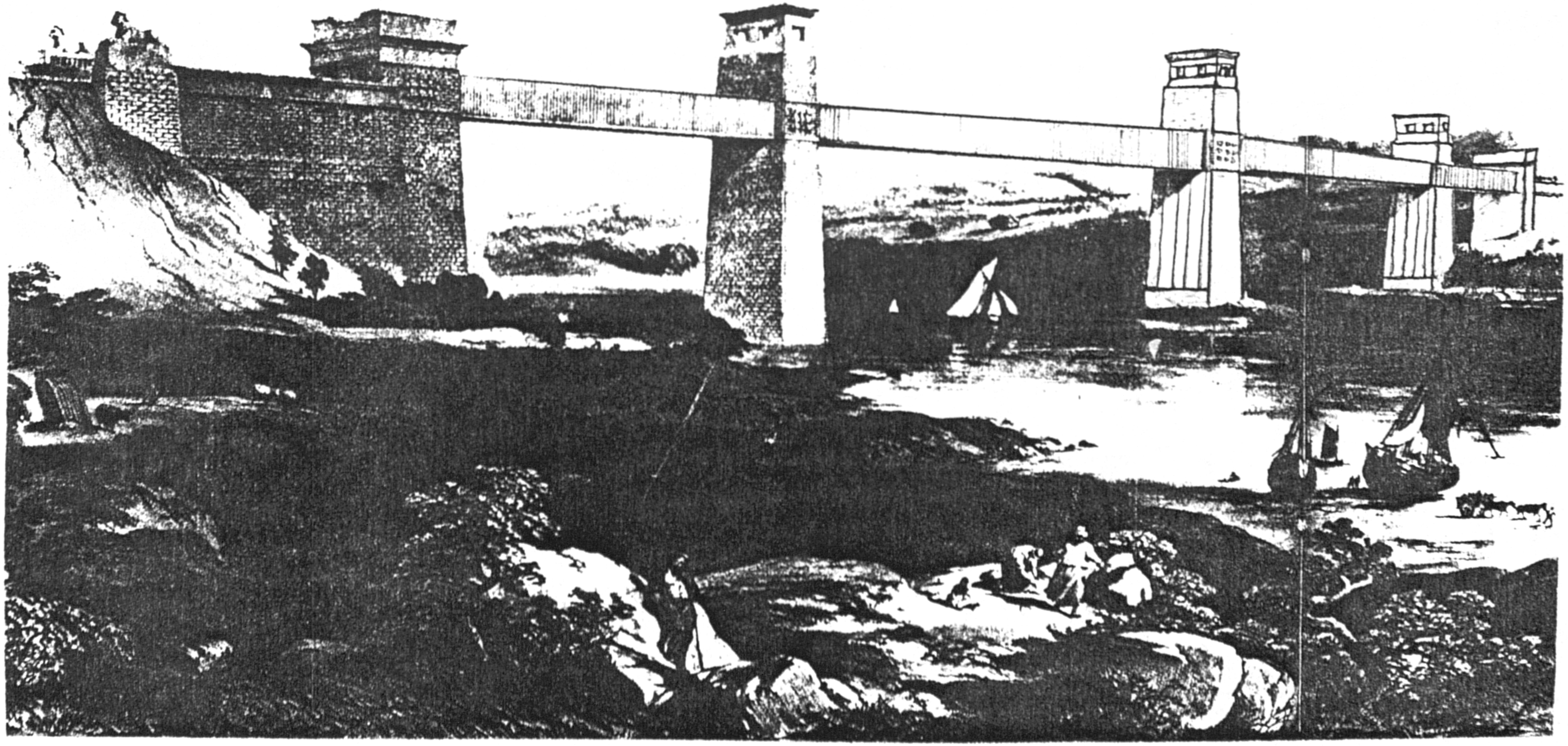


Figure 10 Britannia Bridge

"... it is difficult to define the exact amount of the benefit."[97] The issue of continuity was the basis of the celebrated controversy concerning Simmons and the Torksey Bridge which was at the height of its fury at the very time he inspected the great novel span at Menai.

Torksey Bridge over the River Trent was an open structure on a pair of parallel rivetted wrought iron box girders resting on masonry piers and comprising two clear spans of 130 feet each. (See Figure 11) It was designed by Sir John Fowler (1817-1898) and constructed by William Fairbairn.[98] Simmons inspected the bridge on 24 December 1849. He applied the then conventional load tests of bringing engines and tenders on the bridge at the openings and measuring deflections. The results of the tests added to his doubts about the design generally and he found he could not recommend opening unless some method of stiffening the bridge were devised. Simmons explained:

> "In wrought iron tubular girders, great care appears to be necessary in the arrangement of details of construction, and a departure from proportions fixed carefully by experiment should require a fresh series of experiments to arrive accurately at a knowledge of the strength of construction. ... I cannot do otherwise than report that, according to the knowledge as yet obtained on this subject, I do not consider that this bridge can be submitted to the continuous passage of trains for an unlimited number of times with safety..."[99]

The opening of the bridge was duly postponed for a month by the Railway Commission. Further inspections and postponements ensued over the next four months as a result of a difference of opinion between the bridge engineer and the railway inspectors on the critical issue of continuity and strength of the tubular girder design. Simmons was the major focus of the controversy in the railway inspectorate although Captain Robert Laffan inspected the structure too and provided an opinion which concurred with Simmons' view.

The report of the Royal Commission on the Application of Iron to Railway Structures was an early

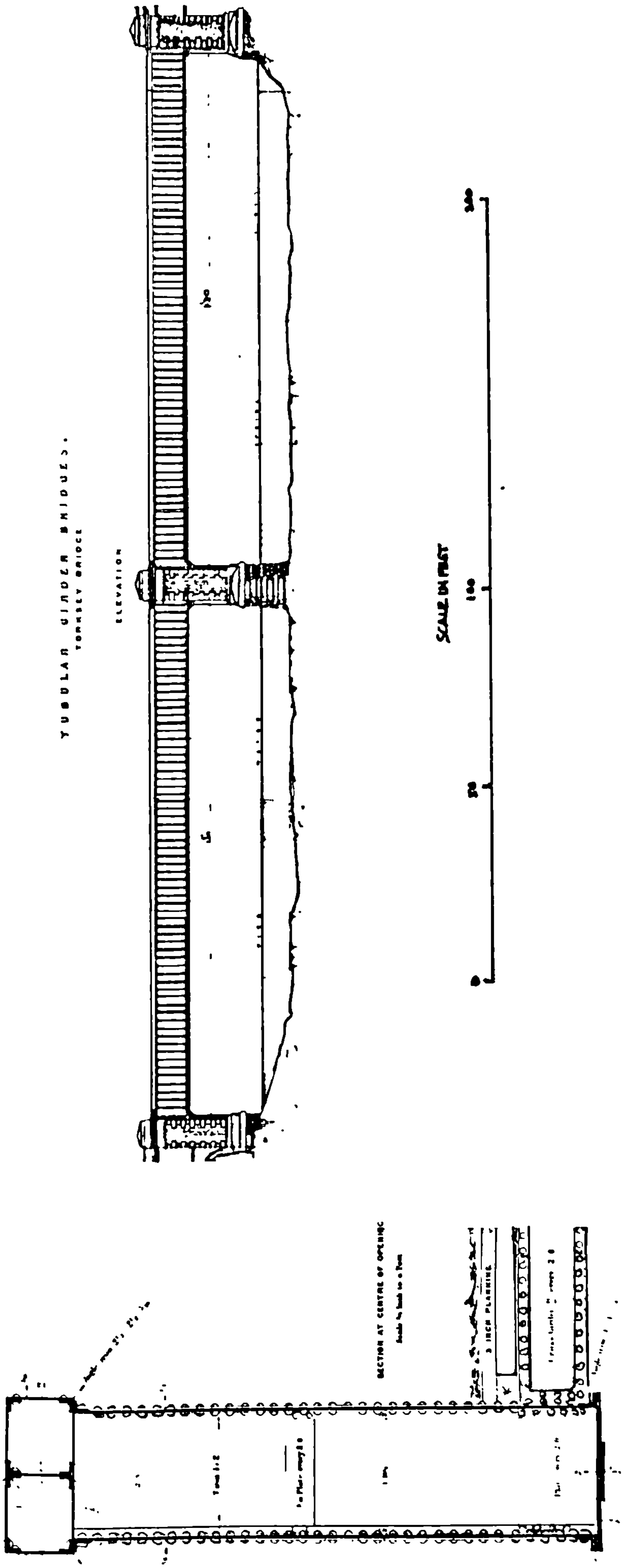


Figure 11 Torksey Bridge

point of contention in the Torksey affair. Fowler charged on 25 January 1850 that Simmons had used the report's recommendation that the load should not exceed 1/6 of the breaking weight of the girder, a standard which had been intended for cast iron only, not wrought iron.[100] Simmons and other railway inspectors had been sent a copy of the Royal Commission's report by Harness, the Secretary of the Railway Commission, on 24 December 1849, only four days before Simmons inspected the Torksey Bridge. With the copy had gone an instruction to report to the Railway Commission any bridges that did not appear upon inspection to be as strong as the Royal Commission report's recommendations suggested.[101] Confusion ensued on Fowler's allegation about the use of the 1/6 rule. In an effort to clarify the matter, Harness wrote to Lord Wrottesly, former chairman of the Royal Commission, for a ruling. Wrottesly replied that the 1/6 standard did indeed apply only to cast iron but that the Royal Commissioners' suggestion for a small compensation for velocity in strength calculation applied to "all elastic horizontal structures."[102] Simmons denied the charge that he had used the 1/6 rule in formulating his opinion of the Torksey Bridge and his inspection reports support this.[103] Fowler's allegation concerning a non-applicable standard was repeated later by John Scott Russell and others, illustrating some confusion in the engineering community about the interpretation of the Royal Commission report immediately following its release.[104]

The Torksey matter was discussed at length by the Institution of Civil Engineers beginning in January 1850. At one session Pasley participated and his remarks are interesting. He claimed he would have approved the bridge given the results of Simmons' load tests, saying the deflections were "utterly insignificant."[105] He also said he doubted the Royal Commission's conclusions on moving loads and felt a fair test for Torksey would be an actual test of heavy trains at speeds 5-60 mph. In his view, too much reliance should not be put on mathematical formulae such as Hodgkinson's. On continuity, Pasley thought it was a vital factor since the Dee Bridge had failed because of the lack of it and he had not paid sufficient attention to this when he inspected the ill-fated span.[106] This illustrates Pasley's continued interest in major issues surrounding the development of building technology even after retirement. His comment about the greater reliability of full scale tests is significant given Simmons' concern for this in proving the strength of Torksey Bridge.

On 20 February Simmons, pressed by the Railway Commission to resolve the issue, protested that he could not judge the safety of Torksey, as the Commissioners suggested, by comparison to others of its kind. He said the tubular girder type was too new, the first having been sanctioned by the Commission in 1847 (Fairbairn's at Blackburn of 60 foot span). In place of the rule-of-thumb approach of comparison he came up with a test of safety based on a stress factor - 5 tons per square inch. Simmons appears to have initiated the Railway Commission's use of a concept of safety based on a limit on working stress which developed with the introduction of wrought iron. This was an advance on the earlier concept of a margin of safety based on a single factor related to breaking loads. The Board of Trade standard of 5 tons per square inch for wrought iron was incorporated in the Railway Department's Requirements (1859) used by inspectors in their duties. These printed guidelines were based on experience and had dubious status in law. This new approach to safety standards was to have important consequences for the introduction of mild steel to railway bridges thirty years later.[107]

Fowler responded by enlisting the help of C.H. Wild who carried out wooden model experiments to find points of contra flexure in the analysis of continuous beams. These experiments proved that the Torksey Bridge met Simmons' 5 ton per square inch requirement but Simmons was still not satisfied that the issue was resolved.[108] On 28 March 1850 full scale tests were undertaken on the bridge by Fowler, Wild and William Pole with Simmons and Laffan present. As a result, Simmons accepted that the bridge was safe but required a condition on the weight of ballast. This was accepted by the company and the bridge was declared open to traffic on 25 April 1850 after a further inspection by Laffan.[109] In his report following the tests on the actual bridge, dated 6 April 1850, Simmons revealed he would have been willing to accept the argument of continuity on his initial inspection had Fowler made it clear from the outset that this principle had been used in the design and was an important element in the calculation of strength. Apparently Fowler had made only casual reference to the principle in a single conversation with Simmons.[110] It would be unfair to blame Simmons for not taking Fowler up on this - even Fairbairn had wrongly considered the bridge as two simply supported spans which Fowler freely admitted.[111] Simmons was familiar with the principle of continuity. The theory of a continuous beam had been used in the Britannia Bridge and he was well aware of that as he said in his inspection report on the Menai span. It appears that much of this controversy can be attributed to poor communication between the railway engineer and the inspector, a relationship whose importance was ever increasing as the inspectorate's knowledge grew. The bridge was the first notable span of an engineer who was to become, with Hawkshaw, the ablest railway engineer of the second Victorian generation. It is a testimony to the professionalism of both Fowler and Simmons that they kept their private feelings separate from business and became and remained friends following the Torksey controversy.[112]

Simmons and other railway inspectors could be very positive in their attitudes toward novelties in wrought iron once their experience proved the safety of the innovation. They were also quite knowledgeable about which civil engineers were responsible for pioneering new technology. In 1849 Jee used what he called a novel construction in wrought iron for a 65 foot span railway viaduct at Manchester. It was a girder with a cylindrical, 2 foot diameter tube on the top flange, with a middle web of three thicknesses of plate and a flat, 20 inch wide bottom flange. Simmons remarked in a discussion about the project at a meeting of the Institution of Civil Engineers in 1851 that he had inspected many of these wrought iron girder types and thought them generally excellent. He further commented that he believed I.K. Brunel was amongst the first to employ the type. Brunel confirmed Simmons' statement saying he had used this form of wrought iron girder on a large scale.[113]

Nevertheless, it was when the railway inspectors had a difference of opinion with bridge designers that a clear incentive was created for civil engineers and manufacturers to strive for excellence in the design and fabrication of wrought iron structures. An important case was in 1859 when inspector Sir Henry Tyler (1827-1908) had a disagreement with Fairbairn over the application of the Board of Trade's standard of 5 tons per square inch in calculating the strength of a wrought iron tubular girder bridge being erected by Fairbairn's firm. The issue was "the effects of continued changes of load upon iron structures, and to what extent they could be loaded without danger to their ultimate security."[114] Fairbairn agreed to strengthen the bridge but pointed out the need for further research on the matter of contention which he was willing to do if the government contributed £150 to the costs.[115] The Railway Department supported this proposal and Fairbairn proceeded with experiments (1860-1862) on wrought iron girders, the results of which were published by the government in 1864. Fairbairn demonstrated that for on and off loading conditions the Board of Trade rule of 5 tons per square inch provided an ample standard of strength for the bottom of a cellular wrought iron girder but that at 7 tons per square inch the girder was not safe, therefore showing that more material was needed in the top of the girder to resist compression.[116] Fairbairn's report was an important contribution to the understanding of fatigue in wrought iron girders.[117] Tyler deserves some credit as does the Railway Department for provoking and sponsoring private sector research which in turn led to the improvement of the railway inspectors' standards for judging the safety of wrought iron bridges.

The Steel Question

Bessemer's converter (1856) and Alleyne's rolling process (1861) brought expectations of an age of structural steel and gave rise to the need for strength and safety information for the new material comparable to the data on hand for cast and wrought iron.[118] Reliable information upon which to base engineering specifications for 'mild steel' was long in coming. This in turn affected the adoption by the Board of Trade of a standard working stress rule for steel and consequently the use of the material for railway bridges. The railway inspectors played an interesting part in these matters.

In 1865 Hawkshaw had wanted to use steel for his Charing Cross railway bridge and applied to the Board of Trade for permission to make his structure lighter in recognition of the superior strength of the new material over wrought iron. His proposal was rejected, however, on the grounds that the Board, not being sufficiently acquainted with steel, would not allow a greater stress coefficient for the material than for wrought iron - 5 tons per square inch.[119] In February 1866 John Scott Russell in a letter to Engineering suggested testing steel at Kirkaldy's laboratories. This was probably a response to Fowler's remarks to the Institution of Civil Engineers in January that he hoped the Board of Trade would modify its rules with respect to the structural use of steel and stop inhibiting progress.[120] A meeting of engineers was duly convened on 4 May 1866 to discuss the nature of Russell's proposed tests and a five member committee was formed comprising J.S. Russell, William Henry Barlow, George Berkley, Fowler and Douglas Galton.[121] Although Galton had resigned from the Royal Engineers four years earlier, it is important that he was selected as a committee member. Undoubtedly it was a recognition of his experimental skills with structural iron gained in collaboration with fellow officer James in tests for the Royal Commission on the Application of Iron to Railway Structures and also of his knowledge of the politics and prejudices of the Board of Trade for whom he had worked.

The so called 'Steel Committee', mainly through neglect and poor communication, got into a row with Kirkaldy after initial experiments were published in 1868 and the next year moved operations to the cable testing machine at Woolwich naval dockyard . The Woolwich apparatus was much inferior to Kirkaldy's and was the oldest large materials testing machine in England, having been first built in 1813 by Bramah and modified in 1832.[122] Final results were published in 1871 and severely criticised in the technical press, especially in Engineering.[123] Galton apparently had taken little if any part in the tests. Fowler and J.S. Russell were not active participants either. Barlow was the most responsible. Smith claims that the 'Steel Committee' fiasco set back the widespread acceptance of steel as a structural material in Britain by at least the years taken in publishing its nearly worthless results.[124] Indeed, the 1874 edition of the Railway Department's Requirements for the use of inspectors declined to offer rules on steel until investigations had been undertaken for the new material comparable to those of the Royal Commission on the Application of Iron to Railway Structures.[125]

In spite of this the late 1870's were to witness some progress in the development of standards for the use of mild steel and the Royal Engineer railway inspectors had a role in it. W.H. Barlow, leader of the hapless 'Steel Committee', addressed a meeting of the British Association at Bradford in 1873 on the 'steel question'. The Association then appointed a committee which conferred with the Board of Trade on the matter. Following upon this, the Board established a committee to consider the practicability of assigning a safe stress coefficient for the use of steel in railway structures. This committee consisted of William Yolland (1810-1885), inspector of railways, John Hawkshaw and W.H. Barlow.[126] In its report of 18 March 1877, the Committee explained that it had examined the 1871 report of the 'Steel Committee', experiments by the War Department at the Gun Factory of the Royal Arsenal, Woolwich, regulations for the use of steel then in use by the Admiralty and some information which Hawkshaw had obtained on the use of steel in Holland for the construction of railway bridges and other structures.[127] After due consideration of this evidence, the Committee recommended the Admiralty's standard - 6½ tons per square inch - but added that a higher stress coefficient could be allowed by negotation with the Board of Trade on a case by case basis, subject to test results.[128] The Board of Trade admitted steel as a structural material in 1878, adopting the Committee's recommendation.[129] It is not surprising that the Board of Trade would approve a standard based on the Admiralty rule since the Board was responsible for the regulation of shipping as well as railways. Steel girders were first used for a railway bridge in Britain in 1883 on the Chester and Holyhead line, and W.H. Barlow used steel decks for rebuilding Sir Thomas Bouch's ill-fated Tay Bridge (1882-1887).[130]

Not surprisingly, the Board of Trade's new standard for steel proved unworkable because it did not allow the economic specification of the new material and civil engineers soon called for raising the stress limit. Sir Benjamin Baker led the way. He pointed out that the existing rule based on Admiralty standards was conservative since shipbuilders needed a tougher steel than bridge builders.[131] For the Forth Bridge (1882-1990) Baker and Fowler approached the Board of Trade for a higher stress factor. The Board appointed a committee in 1881, consisting entirely of railway inspectors and headed by Yolland, to review the proposal. These Royal Engineers recommended that the standard rule not be insisted upon and that the use of steel in the Forth Bridge be guided by Baker's and Fowler's experiments and their common sense principles.[132] Baker credited the wisdom of the Royal Engineers in this recommendation: "... the Board of Trade officers knew too much about steel to follow the course which some people had supposed."[133] These engineer officers were no ordinary bureaucrats.

The Wind Question

The catastrophic failure of Thomas Bouch's Tay Bridge created the circumstance for an important advance in bridge building technology, albeit late in coming. This was a calculation factor for wind pressure. William Yolland, chief inspector in the Railway Department, made a contribution to its development. A brief review of this story reveals something of the character of the railway inspectorate and the British engineering profession in the closing decades of the nineteenth century.

The Tay Bridge was not an innovation other than in its great length. It was constructed of cast and wrought iron. Major-General Hutchinson inspected the bridge on 25 to 27 February 1878. In the penultimate paragraph of his report he said that he would like to observe on a future visit the effects of high winds when a train was passing over the bridge. Because of illness he never made that visit. The Tay Bridge fell in a gale on 28 December 1879.[134]

A commission of enquiry into the accident included Yolland, W.H. Barlow and Henry Cadogan Rothery, Her Majesty's Wreck Commissioner. The official report attributed bridge failure to wind pressure and insufficient strength of iron cross bracings. In his testimony before the Commission, Hutchinson revealed that at the time of inspection he had no data whatsoever to which he could refer on wind pressure nor did he have a Board of Trade rule to apply to the matter. He added that it was not customary in his experience for wind pressure to be taken into account for bridges of the Tay type.[135] Hutchinson was right. Stoney in 1873 identified 25 pounds per square foot as a calculation factor but apparently he was largely ignored.[136] Bouch said after the accident that he had used a factor of 20 pounds per square foot. French practice was 55 pounds per square foot and in America 50 pounds per square foot was generally adopted.[137] The commissioners of the Tay disaster enquiry recommended that the Board of Trade take steps to establish a standard for the calculation of wind pressure in railway structures since there did not appear to be any understood rule in the British engineering profession.[138]

In 1880 the Board of Trade appointed a committee to act upon this recommendation. It comprised Yolland, Sir William Armstrong, W.H. Barlow, J. Hawkshaw, and G. Stokes. The committee collected data from various meterological observatories around the country, made enquiries with railway companies about the force of wind which had proven sufficient to overturn railway carriages and studied French standards on wind pressure. Its recommendation was: "... for railway bridges and viaducts a maximum pressure of 56 pounds per square foot should be assumed for the purpose of calculation."[139] Baker used this factor for his Forth Bridge, the climax of British bridge building achievement in the nineteenth century.[140] The Tay tragedy, however, had reflected a complacency in the search for engineering excellence and improvement in late Victorian Britain.[141] To a certain extent, the Royal Engineers in the Railway Department were part of this. It should not have taken a tragedy to establish a design standard for wind pressure.

Even so, recognizing its notable contributions to progress in the construction of safe bridges during the heroic age of railway development, the inspectorate's complacency on the wind question was a minor blemish on an otherwise distinguished record of public service. The Royal Engineers' achievements in the inspectorate were all the more remarkable because they had no personal and very little legal control over design decisions. Persuasion was virtually their only power. It is not surprising that, when given the opportunity to work in a civil office with considerable personal and corporate responsibility for design matters, engineer officers could make even more significant contributions to advances in the technology of building. Such was the case with the Admiralty Works Department, a discussion of which follows.

4. PIONEERING WORKS IN THE NAVAL DOCKYARDS

Engineer officers in the service of the Admiralty made a significant contribution to pioneering works in the Victorian naval dockyards. Achievements in structural iron dominated but there were also some noteworthy advances in the use of concrete. Progress in building technology was a triumph of collaboration amongst the engineer officers, their civilian colleagues in the Admiralty Works Department and private sector engineers, contractors and manufacturers. Together they introduced novel materials and structural forms in buildings to meet the ever expanding accommodation and servicing requirements of the navy. Indeed, the naval dockyards, the nation's greatest capital investment in defence, were major locations of substantial industrial buildings and civil engineering works - storehouses, boat stores, covered shipbuilding slips, smitheries, factories, docks, basins and breakwaters. The critical requirements in protecting and maximizing this investment were security, especially against fire, and economy and efficiency in the workplace. Buildings, to satisfy these needs, required innovative and adaptive skill and more than an ordinary measure of design virtuosity.

The Royal Engineers and the Admiralty Works Department

Before the last decade of the eighteenth century very few naval dockyard buildings and installations were designed by architects. Master shipwrights drew up designs which were submitted for approval to the Navy Board surveyor in London. The first and only Inspector-General of Naval Works, Sir Samuel Bentham (1757-1831), was appointed in 1795. His title changed to Commissioner of the Navy, Civil Architect and Engineer in 1807 but this position was abolished five years later. Samuel Bunce (- 1802) was appointed to the post of Architect in Bentham's department 1796-1802, and was succeeded in turn by Edward Holl (- 1824) and George Leadwell Taylor

(1788-1873) who served 1804-1824 and 1824-1837 respectively. Under civilian control, the architectural and engineering office of the Admiralty made some important contributions to building technology - in 'fireproof' iron construction (Bentham and Holl), in prefabricated cast iron building frameworks for Bermuda and Jamaica dockyards (Holl and Taylor) and in concrete foundations (Taylor). The Civil architects left the office in a condition favourable to continued creative genius in building when the Royal Engineers took over.[1]

At the end of 1837 Taylor resigned or lost his position as a result of an Admiralty reorganization, and Captain Henry Brandreth was appointed Director of a newly constituted Department of Architecture and Civil Engineering, an office which was later called simply the Works Department.[2] During the next two years several Royal Engineer officers were appointed under Brandreth as superintendents in various dockyards - Woolwich, Deptford, Chatham, Sheerness, Portsmouth, Devonport, Pembroke and Bermuda.[3] Brandreth's office was in Somerset House, London. He and his engineer officer colleagues were responsible for "all engineering and architectural works not connected with the construction of ships of war, manufacture of stores or conversion of materials for shipbuilding" in the naval dockyards and victualling establishments in Britain as well as Bermuda, the West Indies, Malta and other naval stations abroad.[4]

According to one Royal Engineer, the appointment of the engineer officers to the Admiralty Works Department was "to place this branch of that service upon a better footing... "[5]. Another pointed out that the Corps had been called upon to direct and superintend the preparation of designs and estimates for an extensive expansion of the naval dockyards.[6] Indeed, by the early 1840's the Admiralty was committed to a new steam power navy. Because steam vessels were longer than entirely sail powered ships, new dry docks and shipbuilding slips were required as well as basins unaffected by tides. Also needed were new factories for the repair of the machinery of steamers.[7]

The size of the expansion programme in the dockyards is reflected in construction costs. In the second year after the Royal Engineers took over the Admiralty Works Department expenditures on repair and new works in the dockyards increased by 76.4%, and during the decade 1839-1849 it grew by 164.3% from £214,380 to £566,506.[8] The government was entrusting the Royal Engineers with a considerable responsibility. Notwithstanding this expression of confidence in the competence of the Corps, the authorities no doubt also appointed engineer officers over civil engineers and architects because their services could be obtained at less cost, as has been pointed out earlier in Chapter 1.

Engineer officers, serving or retired, continued to act as Directors of the Admiralty Works Department throughout the nineteenth century.[9] Nevertheless, the critical period for contributions to advances in building technology was 1838 to 1873 during which time the following held office: Henry Brandreth (1838-1846); Archibald Irvine, a retired Bengal Engineer (1846-1849); Godfrey Thomas Greene, another retired Bengal Engineer (1850-1864); and Sir Arthur Clarke (1864-1873). All except Irvine made important personal contributions. Nevertheless, during this critical period the Royal Engineers' positions as superintendents of works in the various dockyards were gradually abolished from 1848 to 1853 only to be reinstated at Chatham and Portsmouth in 1865 and 1879 respectively in response to a second wave of dockyard extension works.[10] Amongst these engineer officer superintendents in the Admiralty Works Department, important personal contributions to pioneering works in the naval dockyards were made by William Thomas Denison (Woolwich/Deptford 1837-1845 and Portsmouth 1845-1846), Roger Stewart Beatson (Portsmouth 1839-1845 and Woolwich 1845-1848) and Henry James (Portsmouth 1846-1850).

Civilians worked alongside engineer officers in the Admiralty Works Department. In the Director's office, civilian positions included draughtsmen and a Chief Assistant (from 1840), later called Deputy Director (1852).

As well, there were clerks of the works in the various dockyards and, from the late 1850's, civil engineers and assistant civil engineers. Amongst the civilians, the most distinguished was William Scamp (1801-1872). He served as clerk of the works at Woolwich (1838-1841) and in Malta (1841-1845), and later as Chief Assistant to the Director (1845-1852) and Deputy Director (1852-1867). Also of importance was Edwin Arthur Bernays (1822-1887) who was first appointed as a clerk of the works at Woolwich in 1841 but later reclassified as Assistant Civil Engineer in 1859. Bernays was next posted to Pembroke (1860-1862) and Chatham (1862-1886). His most important work was done at Chatham as part of a major dockyard extension project. Another civilian worth mentioning was Henry Wood (1805-1886). He had been apprenticed as a draughtsman at Portsmouth and after qualifying served in that capacity at the dockyard until 1864 when he was appointed Superintending Civil Engineer. Wood served a total of forty-five years at Portsmouth. Scamp, Bernays and Wood all became members of the Institution of Civil Engineers. After 1853, when the Royal Engineers ceased to act as superintendents in the dockyards for over a decade, the role of the civilians was especially critical.[11]

The Director of the Works Department reported directly to the Civil Lord of the Admiralty. In communications with the various dockyards, the Director's office followed the established chain of command through the dockyard Captain Superintendent, an officer of the Royal Navy, to the superintending Royal Engineer and Works Department civilians. While building matters passed through the Captain Superintendents, they do not appear to have had a significant influence on design though they did make suggestions on occasion. There were also mechanical engineers (Chief and Assistant Engineers) in the dockyards who reported to the Captain Superintendent and they were consulted on building layout and other design features affecting the function of structures as workplaces.[12]

In testimony before a Parliamentary commission appointed to inquire into the control and management of the naval dockyards in 1860, Greene outlined in some detail the design process and contracting procedures of the Works Department. The Director was virtually in total control. He reported directly through the Civil Lord of the Admiralty and did not need to seek approval by the Board of the Admiralty either for design details and contracting or for the supervision and management of construction. Requests for works originated in the individual yards in preliminary design form though Greene said he would look over initial plans and make remarks on them before the local officers sent their requests to the Board of the Admiralty for approval in principle. After that, the Director entered fully into the design process, and every matter of plans and details of all sorts was revised in his office, from those sent from the yards. Sometimes the original plans were entirely remodelled, but at other times the submissions of local officers were adopted with modifications. All estimates to accompany the printed estimates were prepared in the Director's office; and after works were approved by Parliament, the Director prepared preliminary instructions for the calling of tenders in all important works. Contracts were prepared in his office and then the subsequent details in carrying out the works were his responsibility. Works usually began in late autumn following approval of the estimates by Parliament in the spring. Works were supervised by local officers. Greene used the example of Bernays at Pembroke.[13] Greene's description of the tendering process is especially revealing:

> "As a general rule we select a certain number of well known and recognized contractors of station and presumed means; the plans and specifications are prepared in full detail, and those selected contractors are called upon to tender for works, either at lump sum or at a schedule of prices, and in every case, the lowest tender is accepted, where selected parties are called upon to tender. Where the tender is thrown open to public competition, which is

> sometimes the case, but very rarely, I consider myself at liberty to select any tender I like, without going to the lowest."[14]

In his testimony Greene was clearly referring to the time since he became Director (1850). The evidence suggests that previously major innovative works in iron were not designed in the Director's office with plans and specifications prepared in full detail before going to tender. Generally, engineering contractors did most of the important designs, although some were done by engineer officers in the dockyards. Design was very much decentralized. The usual practice of selecting contractors to tender was also true in the 1840's. This was important since it allowed the Royal Engineers to develop a close working relationship with a few highly skilled engineering contractor firms in the design and execution of pioneering works.

Greene told the Parliamentary Committee on Dockyard Economy in August 1859 that his office had been the source of necessary innovation and improvement in naval dockyard works:

> "... this office is constantly engaged in designing and constructing such buildings at one or other of the establishments, and consequently an amount of experience and practical knowledge of details of all naval buildings is contained in this office, such as no local officer of any length of service could possibly acquire. It is only through this office that improvements which have been adopted by any one yard can be introduced into another. Such innovations or improvements are very frequently opposed to local practices or prejudices; ... Almost everything in the way of improvement connected with this department has either emenated from, been matured in, or disseminated by this office."[15]

The Mechanic's Magazine in its response to the Committee's report paid tribute to Greene and his deputy Scamp saying: "... the introduction of many great and real improvements have originated with them..."[16] It seems clear that Greene had centralized design within his office very effectively during the 1850's since it was an annoyance for the local dockyard officials, some of whom complained to the Committee that they had been poorly consulted on the development of plans for new buildings with the result that these structures did not meet the needs of those who had to use them or were otherwise inconvenient. The Committee recommended that local officials should have the right to approve final plans before construction began. It should be remembered that there were no Royal Engineers in the yards at this time. Greene objected vehemently and won the argument. The Committee's recommendations were not approved and were much criticised in the technical press.[17] The major protest against Greene's control had come from the civilian mechanical engineers in the dockyards, especially Andrew Murray (1813-1872), Chief Engineer at Portsmouth (1846-1869),who was a member of the Committee and the principal author of its report. Murray had participated in the design of naval dockyard buildings. In the period 1843-1846, as Assistant Chief Engineer at Woolwich, Murray had made a report on all the smitheries in the dockyards. Also, in collaboration with engineer officers Denison and James, he had produced plans for the steam factories at Portsmouth.[18]

Iron and Fireproof Construction

Fireproof construction was one of the principal design imperatives in the naval dockyards. The massive capital investment in ships, which were all wooden before 1860, as well as in buildings and flamable naval stores, needed special protection against accidental fire and arson. From the 1760's timber for dockyard buildings had been consciously replaced with brick and stone, and in the 1780's thin iron plates were nailed to floor joists as a primitive fireproofing technique.[19] As early as 1795 Bentham may have been using iron for fireproof construction in the dockyards. He claimed in his memoirs that in 1794 he had: "... designed and caused the iron work to be cast for a very extensive building for the public service, the first as far as I have learnt, that was designed and made entirely of incombustible materials."[20] It is not known whether this building was actually constructed. The early date, however, places it within the same period as Charles Bage's cast iron frame Flax Mill at Shrewsbury of 1796.[21] In any event, by 1812 Holl used a form of fireproof floor construction in the Plymouth ropery whereby close spaced cast iron joists were slotted in cast iron beams and the whole covered with flags as a substitute for the brick jack arches customarily used in 'fireproof' mills. Holl also used this technique in a lead and paint mill at Chatham (1817) and in the Quadrangular Storehouse at Sheerness (1824-1829).[22] Fireproofing with structural iron, therefore, had preceded the Royal Engineers in the naval dockyards but they were to carry this technique to new lengths. Moreover, from the early 1840's the engineer officers were quick to utilize for fireproof construction the newly introduced product of corrugated galvanized iron, a material which they also used for other reasons as will be discussed in another section of this chapter.

Brandreth appears to have been a major force in expediting fireproofing improvements in the naval dockyards, especially through all iron buildings - cast and wrought iron for structure and corrugated galvanized iron sheathing. His obituary which appeared in the Royal Engineer Professional Papers explained:

> "One of the most important considerations which engaged the attention of Captain Brandreth, as Director of Works, was the gradual substitution of incombustible for combustible materials, having found in the dockyards many temporary wooden and canvas buildings for which he was desirous of gradually substituting those constructed of iron, zinc, slates and tiles; and that sheets of corrugated iron should be supplied to the yards for temporary buildings when required."[23]

Brandreth's foremost contribution was in specifying that iron should be used instead of wood for covered shipbuilding slips, an important innovation which is discussed in detail in a later section of this chapter. Indeed, it can be argued that the major novelty with the slip roofs was not the use of iron to achieve greater spans, since the iron roofs were actually shorter than their wooden predecessors, but to provide a more durable construction and a fireproof envelope for shipbuilding and repair.[24] Brandreth issued directives to the engineer officers in the dockyards on fireproofing techniques. For example, in May 1846 he drew their attention to the desirability of iron roofs and floors in storehouses rather than conventional timber.[25]

Also exceptionally active in investigating and applying fireproofing techniques were Denison and Green. In 1845 Denison travelled to Liverpool to inspect some fireproof storehouses with the view of using this experience in the construction of buildings at Woolwich and Deptford.[26] Two years earlier Denison had undertaken some experiments on a type of brick jack arch on iron beam fireproof floor system which had been sent to him by a Mr. Fox who had proposed to use the method in projects at Liverpool. This system differed from the commonly adopted practice of turning an arch from girder to girder in the arrangement of the bricks which were turned on end with the joints all vertical. Denison built a scale model of a brick arch to Fox's specifications and tested it with good results.[27] Denison used brick jack arches on iron girders for fireproof floors in the Royal Marine Barracks at Woolwich which he designed 1844-45 (constructed 1845-1847).[28] Denison was especially quick to adopt for fireproofing, wrought iron roofs and corrugated galvanized iron, which will be discussed further below. Greene continued Brandreth's earlier campaign in promoting fireproof construction. In 1855 he issued a directive that new saw mills being planned by local officers for Devonport and Pembroke should have floors and roofs constructed of fireproof materials instead of wood.[29] However, Greene did not always practise what he preached. His celebrated Boat Store (1858-1860) at Sheerness, built of structural iron clad in corrugated galvanized iron, had timber joists and planks in the upper three floors.[30]

Cast Iron in Dockyard Buildings

The heyday of cast iron in building was the period 1830-1850.[31] From the beginning of the nineteenth century, cast iron had been used as the modern structural material in the dockyards for interior fireproof construction with masonry load bearing walls, and as prefabricated building frameworks in Bermuda and Jamaica. In the 1840's and 1850's the Royal Engineers used cast iron on an even larger scale in designs for interior fireproof frameworks of masonry buildings. The spans obtained by using simple girders on columns were short. Nevertheless, in one important case the engineer officers designed a cast iron beam trussed with wrought iron rods to achieve a much greater clear span. They also produced three early examples of a freestanding cast iron building. The use of cast iron as a structural material, especially in composite construction with wrought iron, was to be an important part of the modernization programme of the 1840's to accommodate steam assisted warships. Factories and other workplaces were made more productive by the elimination of many interior columns allowing for maximum flexibility in use, and cast iron framed windows permitted larger openings and greater natural light in work spaces.[32]

There is little written evidence of the theoretical basis for the Royal Engineers' cast iron designs. It appears that they relied on the work of Thomas Tredgold for calculations, at least until the mid-1840's. They also recognized the advantage of a beam section with a wider bottom flange, an idea proven by the experiments of Eaton Hodgkinson in 1830.[33] (See Figure 12) Engineer officers are known to have required proof tests on cast iron girders. For example, in February 1847 Captain Mould attended Mr. Swift's foundry to witness the testing of cast iron girders intended for use in the floor of the Hemp House at Chatham.[34]

While the evidence suggests that in the 1840's the Royal Engineers in the dockyards were responsible for

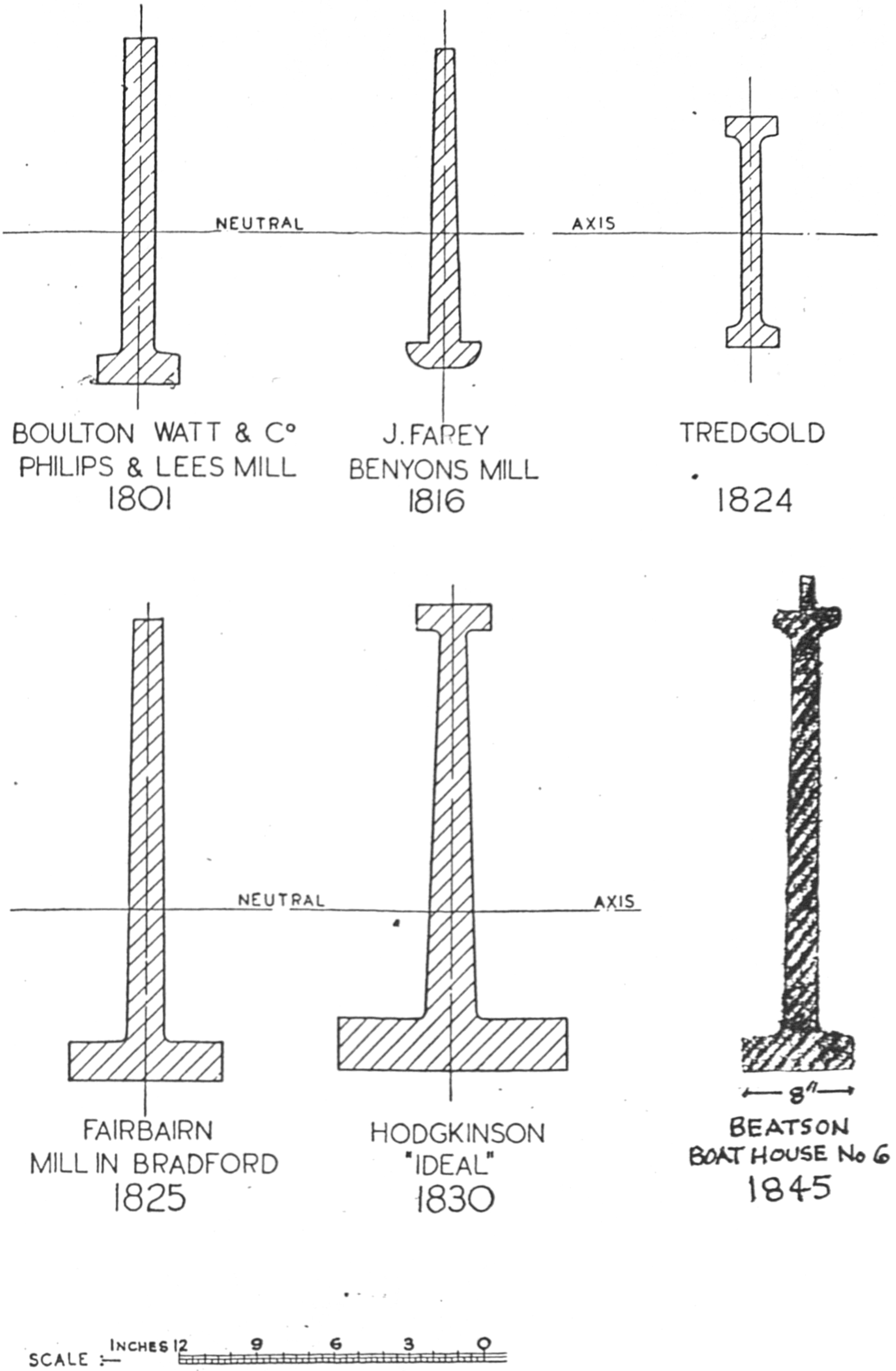


Figure 12 Cast Iron Beam Sections 1801-1830 and Lieutenant Beatson's of 1845

cast iron designs, they worked closely with contractors on details in many instances. Portsmouth provides some examples. For the Mast Store House (1843), Beatson prepared drawings before the cast iron work was sent for tender. Beatson's drawings, which show details of columns and girders, are also signed by Benjamin Bramble who was one of the iron founders asked to tender. It is presumed from the context of surviving evidence that Bramble was awarded the contract. Both the call for tenders and the surviving drawings are dated 31 May 1843 suggesting either that Bramble worked on the design before tendering or more likely that his signature was placed on the drawing after he had been awarded the contract as an indication that he had modified Beatson's original plans.[35] In the case of the Steam or West Factory (1847-49), a 600 foot long, two storey brick and stone building with the first floor carried on brick vaulting supported on cast iron girders, Denison prepared a report with concept drawings in November 1845, *followed* by a plan and description in February 1846. Both were sent to Brandreth for approval. James revised the design and selected a new site in 1847 and in the same year Peter Rolt's tender was accepted.[36] Rolt was originally a timber merchant of Deptford but later was connected with the Thames Iron Works.[37] He was contractor for most of the works on the new steam basin, docks and factory at Portsmouth 1846-1850.[38] Circumstantial evidence suggests he collaborated closely with the Royal Engineers for the ironwork in the West Factory as well as the other buildings for which he was contractor. This does not mean that the Royal Engineers always collaborated with the private sector in cast iron designs. In 1844 Beatson prepared detailed drawings of cast iron columns and girders and decorative cast iron spandrel brackets for some new timber sheds at Portsmouth, and there is no evidence that he was assisted in this endeavour by a contractor or ironfounder.[39]

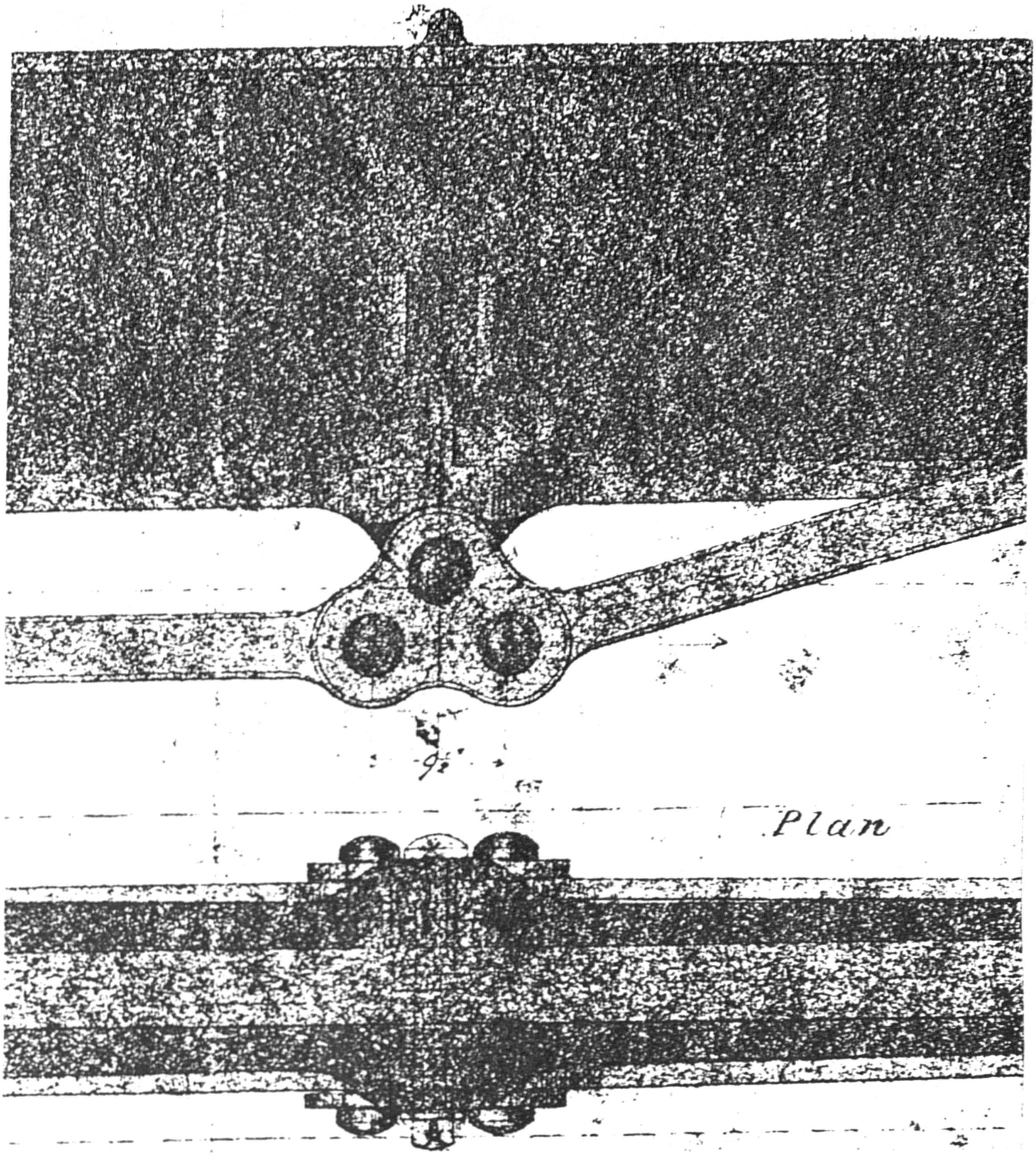
By the 1850's, cast iron work had become quite sophisticated with H section columns and other cast iron elements being used in composite construction with wrought iron. At that time design was centralized in Greene's office but collaboration with contractors continued. An example was the Saw Mills and Testing House (1856) at Sheerness. On 23 June 1856 Greene signed detailed drawings of a 26 foot span composite iron truss roof and of the supporting cast iron columns and girders. Originals were sent by Scamp to the clerk of the works at Sheerness the next day. Only four days later, Messrs. Fox, Henderson's tender was accepted. The timing of this contracting process suggests collaboration on the design, especially considering that Fox, Henderson was one of the major engineering contractors for structural ironwork in the dockyards in the 1840's and 1850's.[40]

The Royal Engineers' single pioneering work with a trussed cast iron beam was in Boat House No. 6 (1845-48) at Portsmouth. It is a three storey building, 120 feet wide, with brick outer walls and two rows of interior cast iron columns supporting the 40 foot trussed beams each of which bears in the casting the inscription: "The load on this girder should not exceed 40 tons equally distributed over its length."[41] Subsidiary girders were slotted in position and lettered to assist in erection, indicating that components were not interchangeable.[42] The beams were cast in one piece and strengthened with wrought iron trussing bars in a manner which Sutherland has described as "logically placed and faultlessly detailed."[43] This technique allowed the Royal Engineers to achieve safe loading conditions for the floors of a storage building with clear spans where simple cast iron beams would have been at their practical limits.[44]

Available evidence suggests fairly conclusively that responsibility for the design of the trussed beam may be attributed to Roger Stewart Beatson (1812-1896), superintendent of Admiralty works at Portsmouth, 1839-1845. Born in Campbeltown, Scotland, Beatson was commissioned in 1832. Unfortunately, nothing is known of his career prior to his appointment at the Admiralty. He would later serve at Woolwich naval dockyard (1845-1848) and after leaving the Admiralty he served as Commanding Royal Engineer in Canada (1849-1854), Gibraltar (1856-1859) and New Zealand (1865-1869) as well as a number of home stations. He retired from the Corps in 1869.[45]

As early as 1842, the "Officers of Portsmouth Yard" submitted a plan for a new boat house to be provided for in the Navy Estimates for 1843.[46] In May 1843, Beatson sent to Brandreth a report and estimate with an explanatory drawing for the Boat House.[47] The following year, in November, Beatson proposed increasing the height of the building to allow for more space which he argued would be very advantageous.[48] In January 1845 Beatson prepared detailed drawings of the trussed beam (See Figure 13).[49] Also, a drawing showing a plan of the Boat House and dated 1845 was signed by Denison who had recently taken over from Beatson.[50] The contract for constructing the Boat House was awarded to a Mr. Rigby sometime in 1845 since he is named as contractor in a letter dated 4 February 1846 in which it is stated that the ground floor was scheduled for completion by 1 July of that year.[51] Despite this, in April 1848, it was reported that Rigby had not carried out the ironwork as stipulated and James, who had succeeded Denison, was to prepare a detailed criticism of the unsatisfactory work.[52] Unfortunately, James' report seems not to have survived. It was also reported that Messrs. Grissell had been awarded the contract for the roof of the Boat House and claimed compensation for delays for which the firm was duly awarded £50.[53] Boat House No. 6 was ready for opening in November 1848.[54]

The trussed beam in Boat House No. 6 is a superb surviving example of the successful design of this distinctive early nineteenth century girder type. Whereas in this case the casting is in one piece, in other examples, some of which were not so successful, the trussing had been used not only to increase the bending strength of the cast iron beam but also to provide effective joints for multiple castings where long beams could not readily be cast in one piece. Such was the



Designed & drawn by
R. W. Beatson
Lieut. Engrs
7th Jany 1845

Figure 13 Detail of Beatson's Trussed Cast Iron Beam, 1845 situation in the trussed beams in Stephenson's ill-fated Dee Bridge which collapsed in 1847.[55] The failure of a trussed beam had also been the cause of the fall of Messrs. Grays' cotton mill at Manchester two years earlier.[56] It is tempting to speculate that Beatson may have discussed trussed beams with his brother officer Pasley in the railway inspectorate, who was reasonably familiar with this type of girder design. Engineer officers were in close contact on major technical issues. Pasley had explained in his testimony before the Dee Bridge disaster coroner's jury that he had inspected a number of trussed beams in railway bridges, some it would seem at about the same time that Beatson designed his girder for Boat House No. 6.[57] Beatson deserves credit for his achievement in designing at an early date a safe and efficient trussed beam which has performed well for nearly 140 years. This is especially so considering that during the 1840's the collapse of industrial buildings due to faulty cast iron beams, trussed or simple, was not an uncommon experience.[58]

Portsmouth naval dockyard was also the scene of the Royal Engineers' early experience in the construction of freestanding cast iron buildings. The first was a two tier cast iron watertower erected in 1843 which still survives (see Figure 14). Originally it supported a 770 ton capacity metal reservoir used for firefighting and as a supply of cooling water for steam engine condensers. The tank was later removed, although the building continued as the dockyard fire station.[59] This structure is 165 feet long and 35 feet wide internally, with columns on a 12 foot square grid.[60] Beatson was in charge of the project and wrote to Brandreth in May 1842 recommending that the iron tower for supporting the metal tank be executed by contract.[61] It is not known for certain who was awarded the contract but it is most likely Messrs. Fox, Henderson since this firm won a contract in April 1843 "to furnish wrought iron stays or braces" for the "Cast Iron Reservoir".[62] Apparently, the cast iron frame was designed to depend for stability on the stiffness of its joists but this had proved

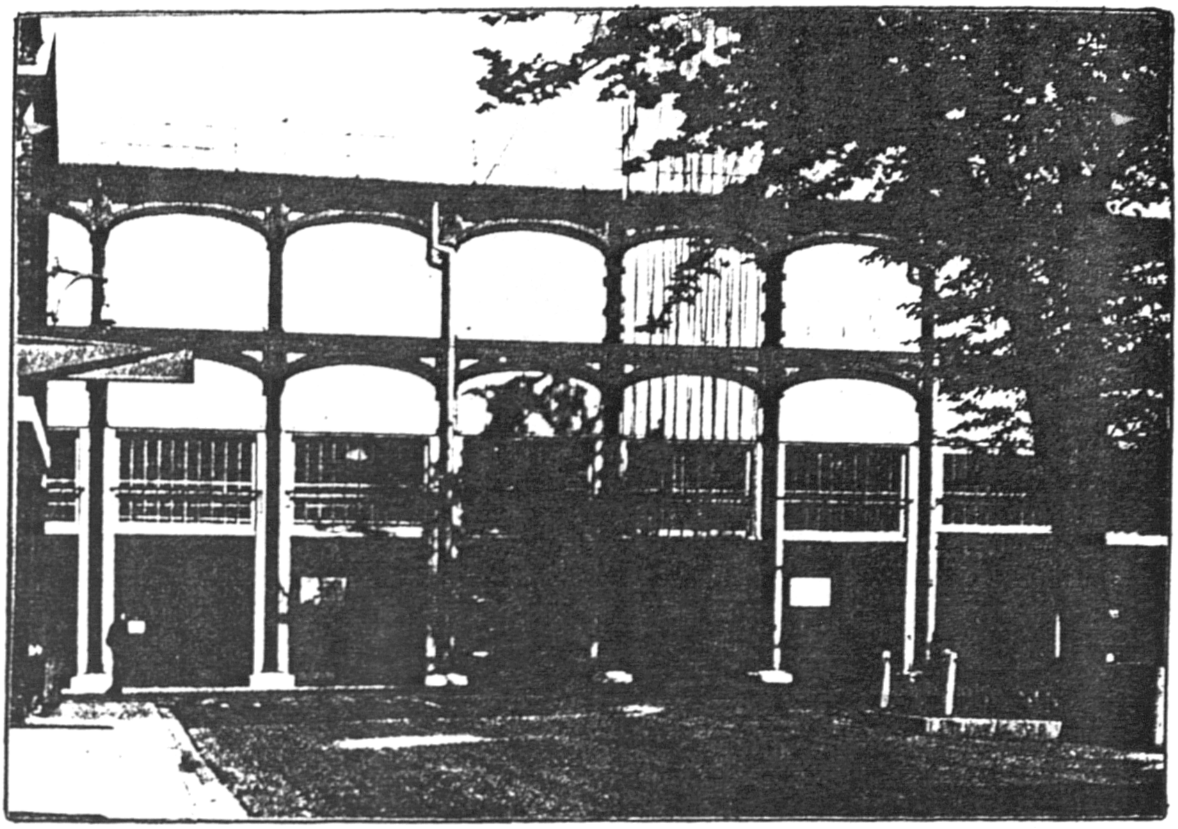


Figure 14 Cast Iron Watertower, Portsmouth, 1843

unsatisfactory. Diagonal tie rods were installed between some of the columns in the direction of the shorter side with fixings cut into the mouldings of the cast iron columns.[63] While the design of the watertower cannot be attributed with certainty, Beatson was probably responsible for it and perhaps in collaboration with Fox, Henderson on the details, especially the wrought iron diagonal bracing. This building, if it can be called a building at all, was by no means the earliest freestanding iron structure. Charles Fowler's cover building at Hungerford Market of 1835, a double butterfly form section cast iron roof supported on cast iron girders and columns, was clearly an earlier and more notable achievement.[64]

The next freestanding iron structure at Portsmouth was a temporary smithery erected by James sometime between June 1846 and 1850, the term of his office at the dockyard, and likely closer to the earlier date, judging from his description of the project. James devised this temporary accommodation until the new steam factory smitheries then at the planning stage could be built. As he explained, in view of the short term purpose of his project, "it was therefore desirable that as little expense as possible should be incurred, and that all the materials employed should again be available."[65] Accordingly, James used some cast iron columns and semicircular girders which had been used previously in a shed for the victualling yard, along with some available cast iron window frames similar to the ones intended for the permanent smitheries, to design a makeshift structure that could later serve as a timber shed.[66] It was 110 feet by 50 feet and 20 feet 6 inches in height to the roof tie rods with no internal columns. The ends and spaces between the columns were of corrugated galvanized iron as was the roof. Cast iron window frames were supported on dwarf walls, half a brick thick. More than half the space along the walls was occupied with windows. (See Figure 15) The principal achievement of this temporary building was its effectiveness as a workplace. James explained: "...

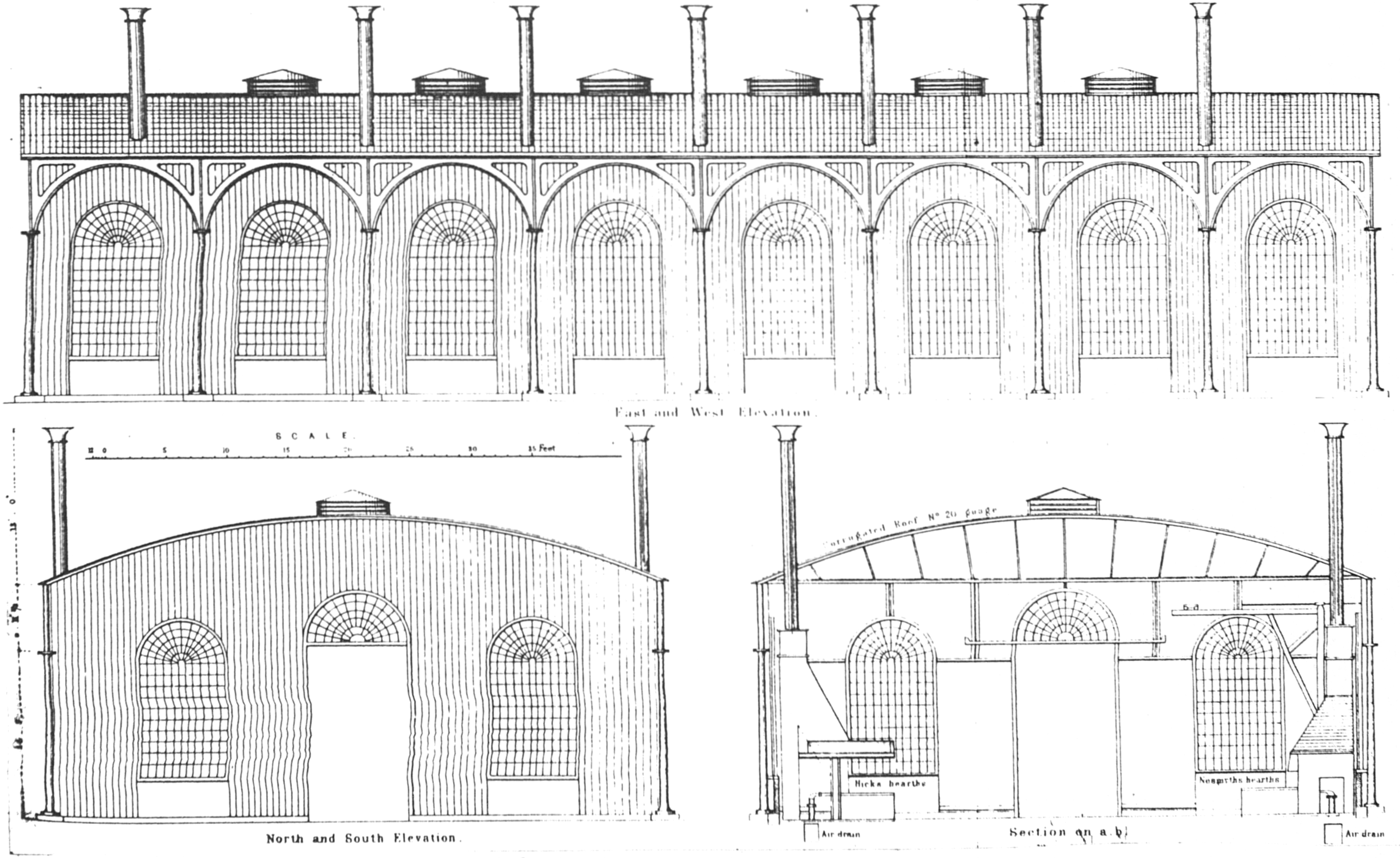


Figure 15 Temporary Smithery, Portsmouth

in consequence of the great quantity of light thus obtained, the great height and perfect ventilation, and the ample space between the forges and through the centre of the building, it has been pronounced to be one of the best workshops that was ever erected."[67]

James' temporary building was replaced in 1851-1852 by the permanent new smithery. It was an iron frame clad with corrugated iron sheeting, larger than its makeshift predecessor and with rows of internal cast iron columns.[68] The structure was planned at the preliminary stage by Greene and his dockyard works superintendent, Captain Thomas Mould, in June 1851.[69] The next month, Fox, Henderson offered to construct the project and the firm was asked to send in drawings.[70] A contract was awarded to Fox, Henderson in October following their submission of the necessary drawings and a tender, but work did not begin on the project until late December 1851 or early January 1852.[71] Fox, Henderson were also awarded a contract in June 1852 for "strengthening the middle row of columns."[72] Mould and Scamp were closely involved with project management. In October 1851 Mould had suggested that the materials from the temporary smithery be sold as part of his plan for the clearing away of James' makeshift structure.[73] One source claims that the new smithery was partly constructed of materials from the Great Exhibition building of 1851 as an economy measure.[74] This last work in a freestanding iron structure still survives.[75] It is an interesting case study because the evidence clearly suggests that the design details were by Fox, Henderson, therefore linking it to the cast iron watertower of 1843 and indicating a well established collaborative relationship between this distinguished engineering contractor and the Royal Engineers in the construction of freestanding iron buildings at Portsmouth.

Wrought Iron, Composites and Wide Span Roofs

The 1840's witnessed the maturation of wrought iron as the modern structural material offering expanded opportunities for wide spans. It was superior to cast iron in bending strength and was light and durable.[76] By the 1840's composites of cast and wrought iron frameworks were highly developed where the two materials worked in complete partnership. A composite iron roof truss of 27 feet 6 inch span was developed as early as 1810 by William Murdock for his Soho foundry in Birmingham. Charles Fox designed the first all wrought iron truss, made up of angles and tees, for Robert Stephenson's Euston Station train shed in 1837.[77] These were triangular trusses. Richard Turner later developed an early form of the rolled wrought iron I beam for his ribbed arch roof in the Palm House at Kew Gardens 1844-1848, achieving a span of about 50 feet.[78] The Royal Engineers' works in wrought iron developed within the context of these advances by the private sector.

Engineer officers in the dockyards designed and constructed moderate span triangular truss roofs of wrought iron angles and tees from the early 1840's. No written evidence has been found on the design theory which they used but it is known that they regularly employed proof tests as part of the design process. Their designs were based on those of the private sector for contemporary wrought iron and composite iron roofs in train sheds and workshops which achieved clear spans up to about 65 feet.[79] William Denison, who was responsible for Woolwich and Deptford in the early 1840's, appears to have been the leader for the Royal Engineers in introducing wrought iron roofs to the dockyards. He put the case for wrought iron succinctly in 1843:

> "The reduction in the price of iron within the last few years has led in many ways to an extension in its application to the purposes of construction: most especially is this to be remarked in roofs which are so frequently erected over workshops, railway stations, and other similar buildings; where we find light wrought iron taking the place of either wood or cast iron, and considered as superior to both as regards lightness, and to the former, in addition, as regards durability... "[80]

As early as June 1842, Sir John Hill, Royal Navy, Captain Superintendent at Deptford, forwarded a report to Brandreth on a proposal for establishing iron roofs in the dockyard. The report was from a Mr. Rivers whose identity is unknown.[81] By the following year Denison had adopted wrought iron roofs for a number of workshops at Woolwich. Perhaps the most notable example was one for a new boiler shop, the contract for which was awarded to Peter Rolt in July 1843.[82] It had triangular trusses of 62 feet 4 inches span with T section wrought iron principal rafters and struts assisted by tie rods (See Figure 16).[83] The roof had skylights with cast iron frames and was slate covered.[84] It is likely that E.A. Bernays, clerk of the works under Denison, had a hand in the design and possibly Rolt, the contractor, as well.[85] As part of the design process, Denison undertook proof load tests on two trusses fixed on granite blocks and arranged to simulate their condition of use in the proposed roof. This experiment satisfied Denison that this form of wrought iron truss could be used to advantage and with safety. His insistence on proof testing new wrought iron building technology was to have a significant impact on his later collaboration with the private sector in the most important pioneering works undertaken in the naval dockyards during the Victorian age - the wide span roofs for shipbuilding slips.

The first of these innovative wrought and composite iron slip roofs constructed in the mid-1840's pre-date the well known wide spans achieved in railway train sheds, beginning with Turner's Lime Street Station at Liverpool, designed and built 1846-1849.[86] Notwithstanding that the span for Lime Street Station was nearly twice that of the largest slip roof, this pioneering work in the naval dockyards was an important contribution and has received insufficient recognition from scholars to date.[87] Iron slip roofs were built at Pembroke, Portsmouth, Woolwich, Deptford and Chatham. During the period 1844-1857, a total of sixteen were erected at the five dockyards. Construction of the type came to an end shortly before the introduction of iron clad ships in the

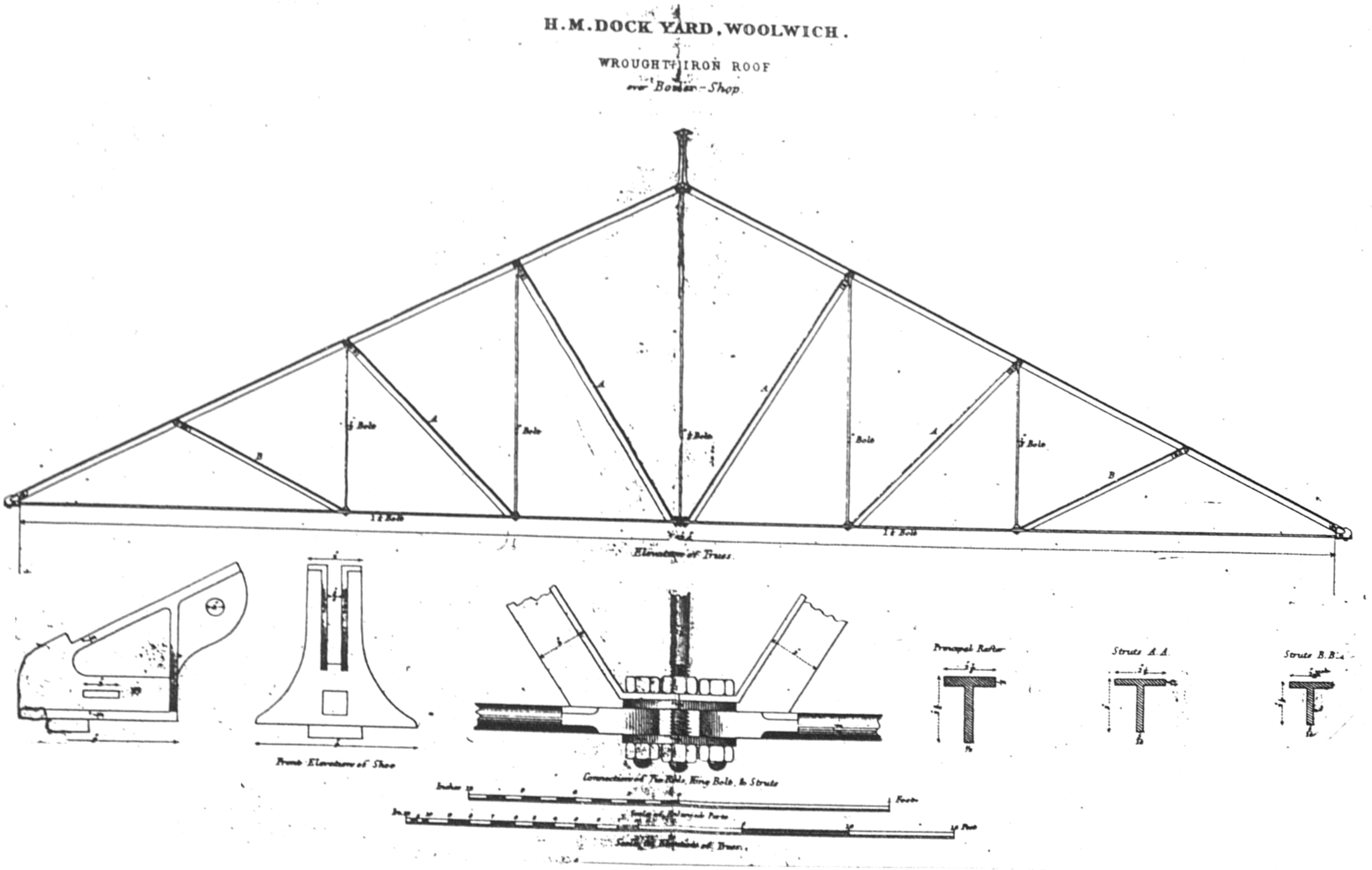


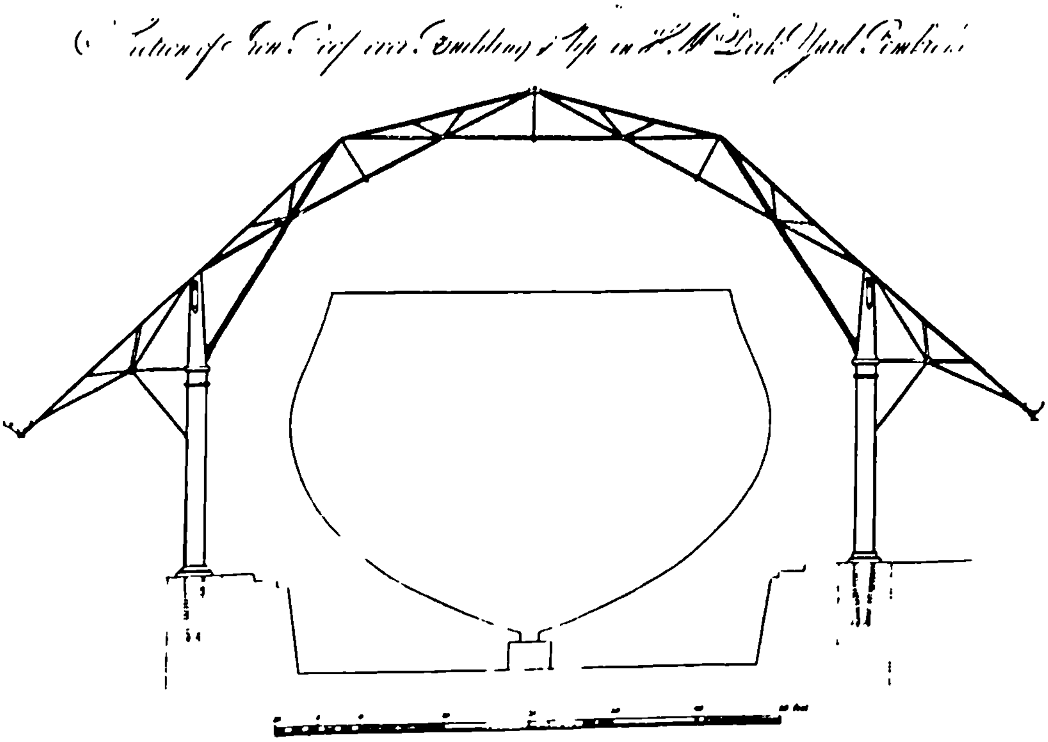
Figure 16   Denison's Boiler Shop Roof, Woolwich, 1843

1860's which did not require cover buildings. Naval dockyard slip roofs of the 1840's were almost entirely the work of two engineering contractors - Messrs. Fox, Henderson and Messrs. George Baker and Sons. The former was responsible for five and the latter nine.[88] This was an indication of the growing practice of engineering contractors supplying all the project skills, a phenomenon perhaps best exemplified in the Great Exhibition building of 1851.[89] Royal Engineers who made some contribution during the formative years of slip roof construction were Brandreth and Denison. It was not until the 1850's that an engineer officer took prime responsibility for design - Greene in Slip No. 7 (1852-1854) at Chatham. Greene incorporated the legacy of experience from the previous decade and made some important improvements. It is instructive to review the Royal Engineers' participation in the construction of the innovative iron slip roofs, especially to reveal the nature of their relationships with the private sector in developing pioneering works in iron.

The idea of covering shipbuilding slips was not itself new. Bentham had visited the Swedish naval base, Karlskrona, in 1807 where he inspected slip cover buildings constructed of timber. In 1812 Bentham proposed to the Navy Board that covered slips be adopted for the British naval dockyards. His plan was for a brick building with internal cast iron standards for the support of the roof but it was not accepted.[90] The first permanent slip roofs in the naval dockyards were wooden ones at Portsmouth (1812-1814) and Plymouth (1814) followed by Chatham (1817). By the 1840's, timber slip roofs had long been universal in the naval dockyards but were unknown in private shipbuilding establishments. Initially they were ordinary shed-like structures but later models were much enlarged and improved to the design of Sir Robert Seppings, naval architect and Surveyor of the Navy (1813-1832).[91]

The first iron slip roofs, constructed 1844-1845 at Pembroke naval dockyard for Slip Nos. 8 and 9, were designed and erected by Fox, Henderson and Company with works under the supervision of their resident engineer, Mr. J. Hughes.[92] Each roof was a lightly constructed composite wrought and cast iron trussed structure of 80 feet 7 5/8 inches clear span. It was approximately 312 feet long by 120 feet wide overall and was supported on cast iron columns and girders. The roof was covered in corrugated galvanized iron with openings cut out for skylights (See Figure 17). The principal structural element of the roof framework was the main strut or gib - two bars of double angle iron placed back to back, formed into a bowed figure and rivetted together with cast iron distance pieces fixed by rivets and with cast iron shoe and head bolted to opposite ends of the assemblage (See Figure 18).[92]

Brandreth had recommended that the decayed wooden roofs over Slip Nos. 8 and 9 in the Pembroke dockyard be replaced by iron ones.[93] Admiralty correspondence records indicate that Brandreth forwarded tracings, plans and sections for iron slip roofs to Pembroke as early as September 1842 but there is no evidence that these drawings were used either for Slip No. 7 then under construction at the dockyard or for Slip Nos. 8 and 9.[94] Brandreth deserves credit for promoting iron, especially for its fireproof qualities as mentioned earlier. He was noted for being progressive in his engineering views and for recognizing the benefits of employing top designers. As his obituary in in the <u>Minutes of the Proceedings of the Institution of Civil Engineers</u> declared: "... he demonstrated zeal and talent in rendering available every improvement in science, and in obtaining the best advice and assistance of eminent men in every profession... "[95] Brandreth's superintendent at Pembroke, Captain Montgomery Williams, seems to have had little or nothing to do with the construction of the iron slip roofs. Nevertheless, his description of the project in the Royal Engineer <u>Professional Papers</u> provided full technical details. He also wrote to Brandreth in June 1846 "supporting the masterly manner in which they have been executed by



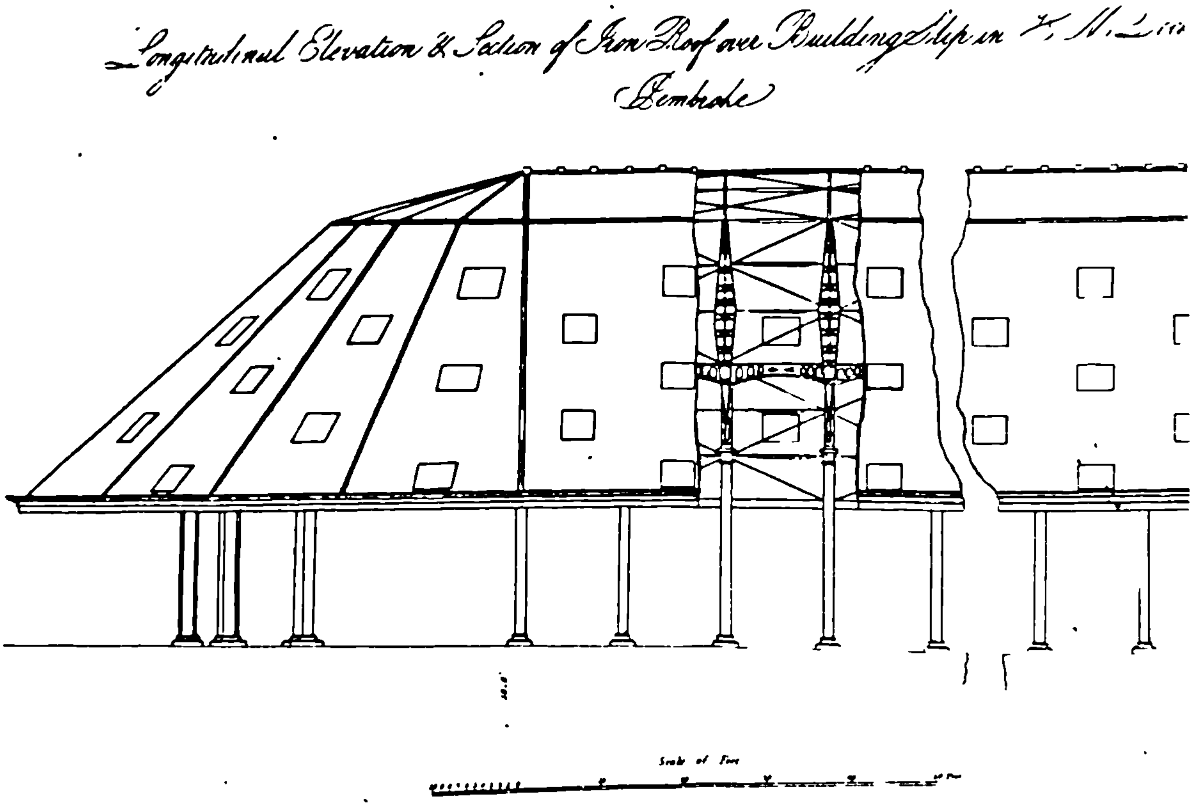


Figure 17 Slip Roof Nos. 8 & 9, Pembroke, 1844-45 : Elevation and Sections

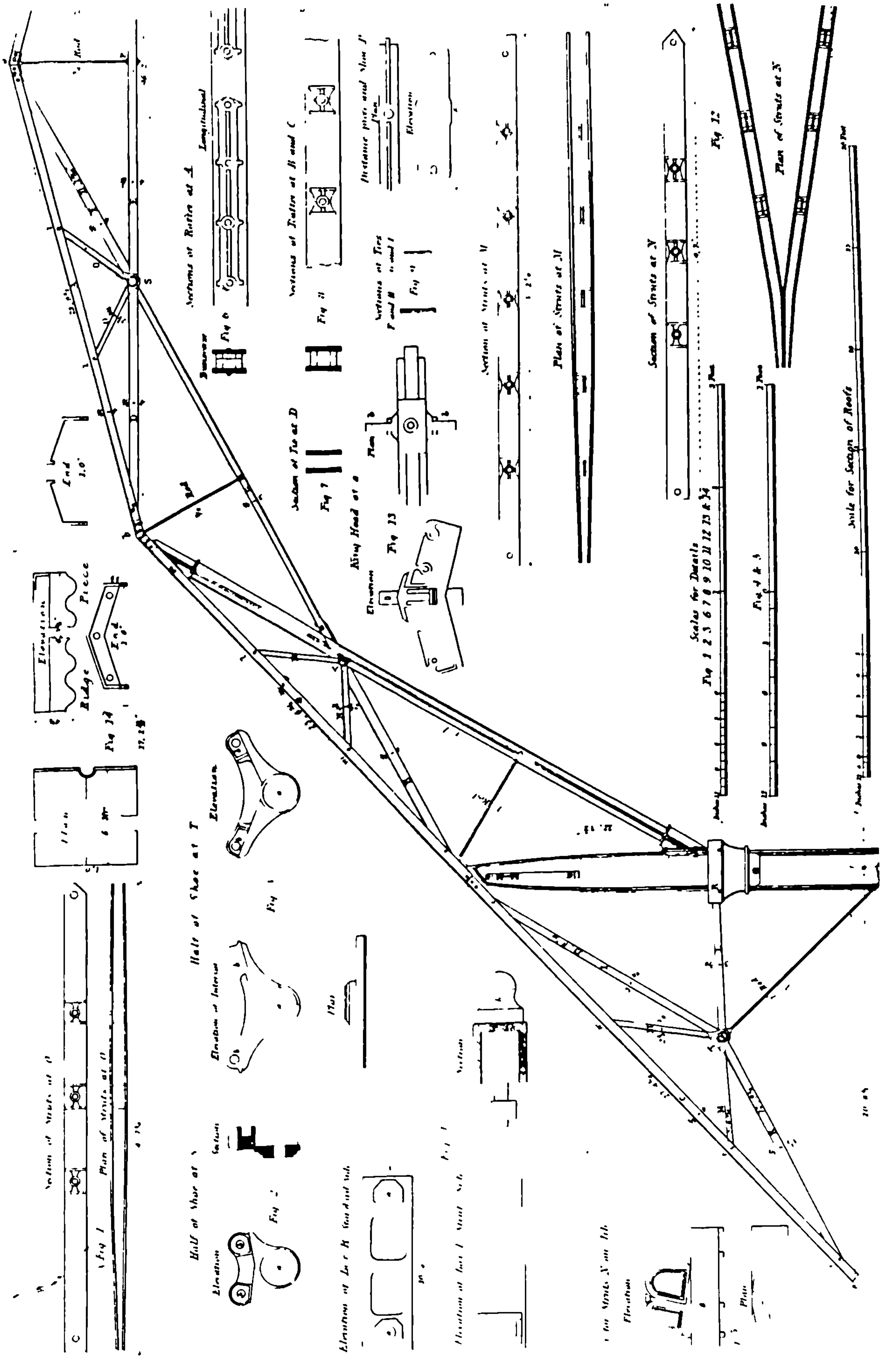


Figure 18 Slip Roof Nos. 8 & 9, Pembroke, 1844-45 : Details

Fox, Henderson and Co."[97] Williams provided clear evidence that the Royal Engineers had little responsibility for the design of the slip roof and that it was the result of an extensive competition in which Fox, Henderson's proposal proved the best: "Several designs were proposed; but that of Messrs. Fox, Henderson and Co., of the London Iron Works, Birmingham, having met with approval, they entered into a contract to put up the two roofs for the sum of £15,480, taking the responsibility of stability upon themselves."[98] As Director of the Admiralty Works Department, Brandreth would have made the decision on the contract award and it would appear that it was not simply on the basis of price. Williams assessed succinctly the nature of the achievement made by Fox, Henderson:

> "A considerable degree of enterprise and mechanical skill was required to carry out with reasonable economy this sound measure; for no iron roof hitherto constructed equalled what was now called for, either in magnitude or difficulty of combination, to meet the conditions peculiar to slip roofs."[99]

Almost certainly, responsibility for Fox, Henderson's design may be attributed to Sir Charles Fox (1810-1874), one of the most distinguished of mid-Victorian engineers, who developed a special expertise in iron construction, amongst other things.[100] Fox was to be involved in other dockyard slip roofs and later in important train shed roofs, especially New Street, Birmingham (1854, 212 foot span) which employed a principal strut design first used in his firm's roof for Slip No. 4, Woolwich (1846-1847).[101] To some degree it may be argued that Brandreth had recognized this civil engineer's developing talent and helped it to mature, and that Williams promoted Fox's professional skills by informing the engineering community, especially the Royal Engineers, of Fox, Henderson's achievement at Pembroke.

Following quickly upon the novel contributions at Pembroke were the iron roofs for Slip Nos. 3 and 4 (1845-1846) at Portsmouth. As in the earlier case, tenders were called for designs in iron. An unsuccessful proposal was submitted in December 1844 by John Rigby of the Hawarden Ironworks, Flintshire, the drawings for which indicate a light trussed roof system somewhat similar in form if not in details to Fox, Henderson's roofs at Pembroke.[102] A contract was awarded to George Baker and Sons of Lambeth in September 1845 for a very different design and work commenced on the roofs in the succeeding December.[103] Each roof consisted of composite wrought and cast iron curved ribs with wrought iron trussed purlins running longitudinally supported by cast iron girders and columns. The roof was covered with corrugated galvanized iron with openings cut out for skylights.[104] Roof clear span was 84 feet 6 inches with overall dimensions of 90 feet length and 140 feet width.[105] (See Figure 19)

What is most interesting about this project, with respect to the participation of the Royal Engineers, is that Denison ordered and directed experiments on the strength of the wrought iron trussed purlins (See Figure 20). Two of the purlins were bolted to logs in a manner precisely the same as they would be fixed to the principals of the roof and covered with corrugated iron as in actual practice. The test roof was then loaded with gradually increasing weights to destruction and deflections measured at each stage. Also observed was the behaviour of different components of the trussed purlin under load. It was discovered that the truss finally failed when the cast iron traps broke. Moreover, judging by the extent of elongation in the various wrought iron components, it was determined that the whole of the strain under load was on the centre bar which was the same section as the others in the assemblage. Also, when wind pressure was considered along with the customary calculations for loading, it was found that the weight which could be brought to bear on each purlin exceeded the breaking weight as determined by the experiments. Accordingly, Denison directed that the trussed purlins be strengthened by increasing the section of their centre tie bars and by adding to the thickness of the metal in the cast iron traps.[106]

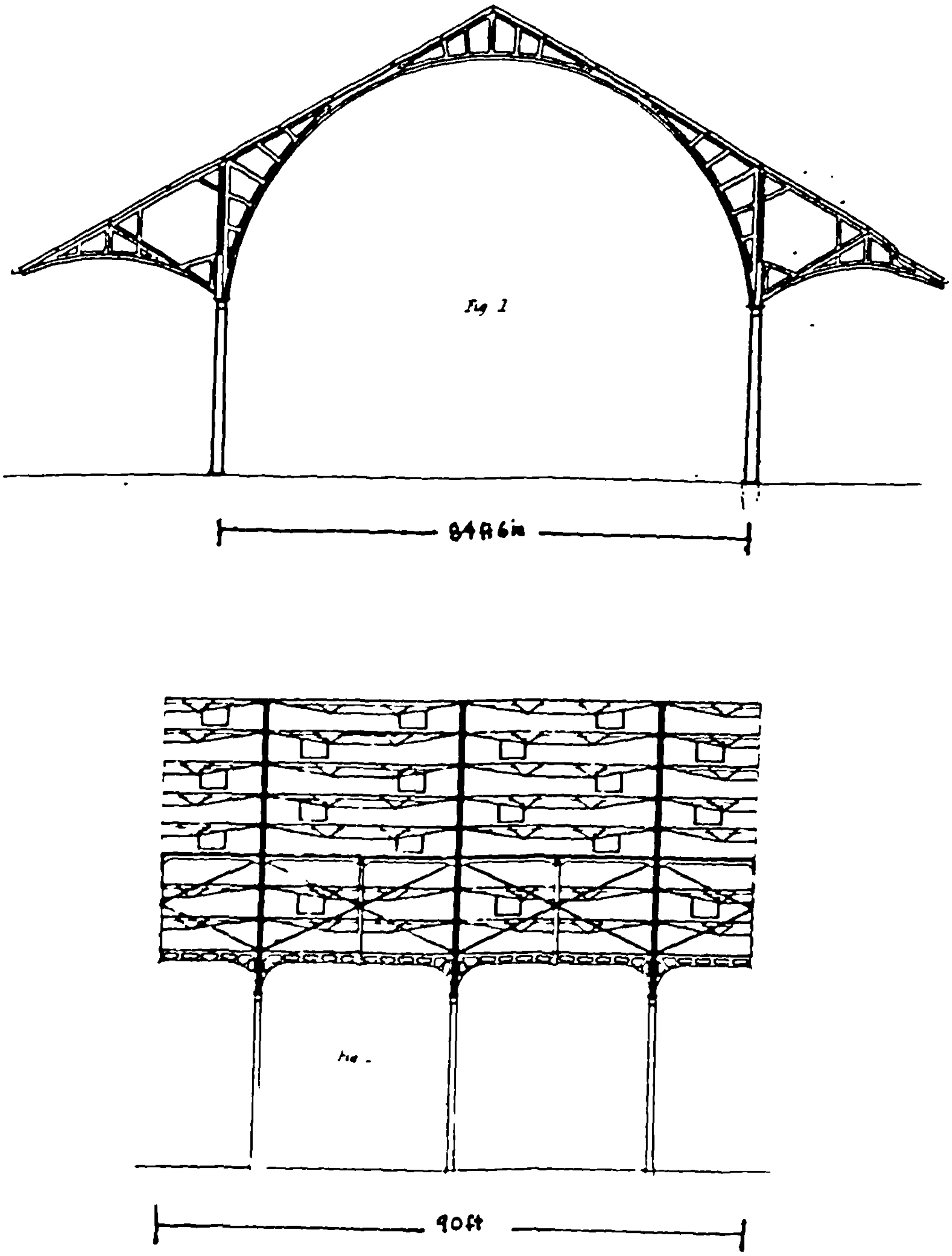


Figure 19 Slip Roof Nos. 3 & 4, Portsmouth, 1845-46 : Sections

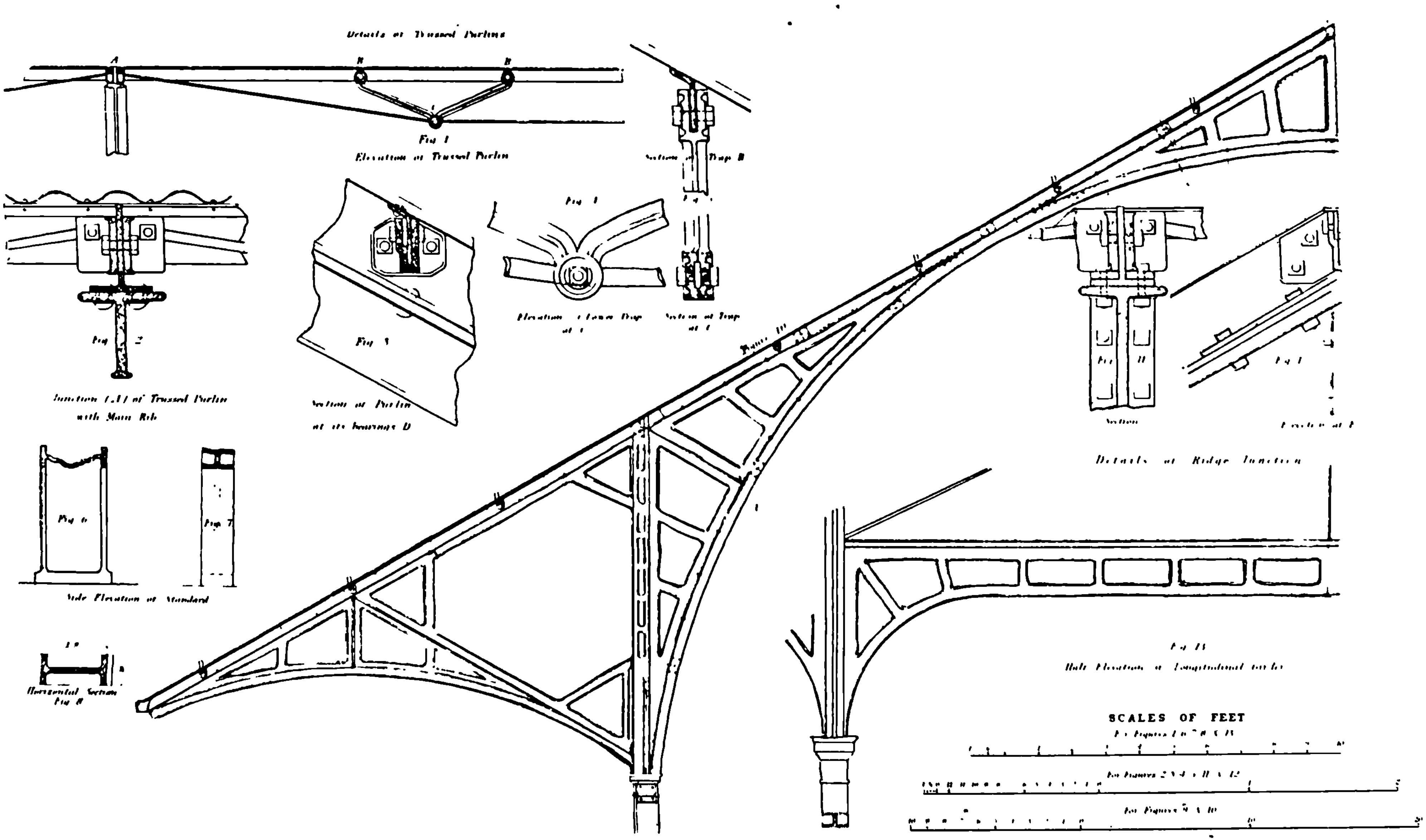


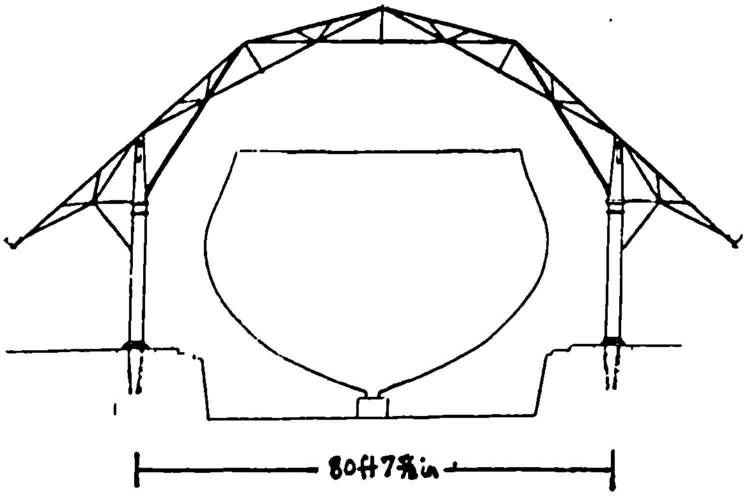
Figure 20 Slip Roof Nos. 3 & 4, Portsmouth, 1845-46: Details

William Denison therefore can be credited with contributing to the safe design of Baker and Sons' pioneering structures. He was one of the foremost exponents of experimental science in design amongst the Royal Engineers and this is a key example of his collaboration with the private sector in this regard. There is some evidence that the Royal Engineers', especially Denison's, insistence on proof testing may have influenced civil engineers' design practice. Richard Turner in his account of the building of Lime Street Station, Liverpool, indicated that the railway company engineer, Joseph Locke, insisted on rigorous tests of actual portions of the wrought iron curved roof to prove the merits of the construction. Trials were carried out at Turner's Dublin works. Turner stated specifically that Locke had required these experiments "... as the roofs erected for the Admiralty were subject to similar tests..."[107] Turner himself was well aware of the wide span roofs in the naval dockyards and attempted, without success, to win commissions for these novel structures. In September 1847 Turner exhibited to the Admiralty Works Department his patent roofing system which utilized, as arched principal, the deck beam, an early form of rolled wrought iron I beam, hoping to be awarded a contract for slip roofs at Pembroke. He was later told by the department's Director that he would be called upon to tender when any large roofs were required.[108]

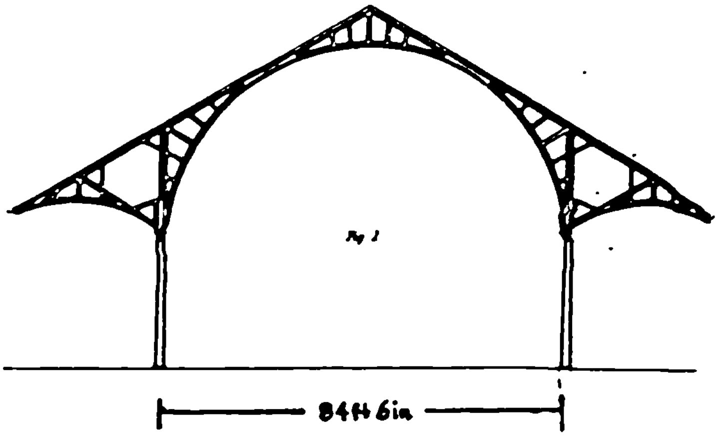
Indeed, additional iron slip roofs were being planned for Pembroke at that time and the story of the contracting process reveals another aspect of the Royal Engineers' contribution to the development of advanced building technology in the naval dockyards - good management. It does not appear that Turner tendered for the job but both Fox, Henderson and Messrs. Baker did. Baker was awarded the contract for iron roofs over Slip Nos. 1 and 2 (1847-1849) in October 1847.[109] Unfortunately no details of the design have been found. Even so, this is an interesting case because the Admiralty Works

Department did not accept Fox, Henderson's tender even though the firm had enjoyed a monopoly of slip roof work to date at Pembroke.[110] The reason was price. Fox, Henderson tried offering to match Baker's bid to get the job after the latter's tender had been accepted, but following an investigation by the Director of the Works Department, Colonel Archibald Irvine, they were turned down. This indicates that the awarding of slip roof contracts was relatively free from patronage and was done on a fair, competitive basis amongst qualified engineering contractors. To that date Messrs. George Baker and Sons had constructed four iron slip roofs - two at Portsmouth and two at Deptford - and had finished a large portion of the work on a contract for roofs for Slip Nos. 4, 5 and 6 (1847-1848) at Chatham.[111] The firm was certainly well qualified and its structures had proved satisfactory in addition to being competitive on price.[112] It was a credit to the Royal Engineers as Directors of the Admiralty Works Department that market forces were allowed to work freely in stimulating efficiency and economy in the design of the wide span iron slip roofs in the formative stages of their development.

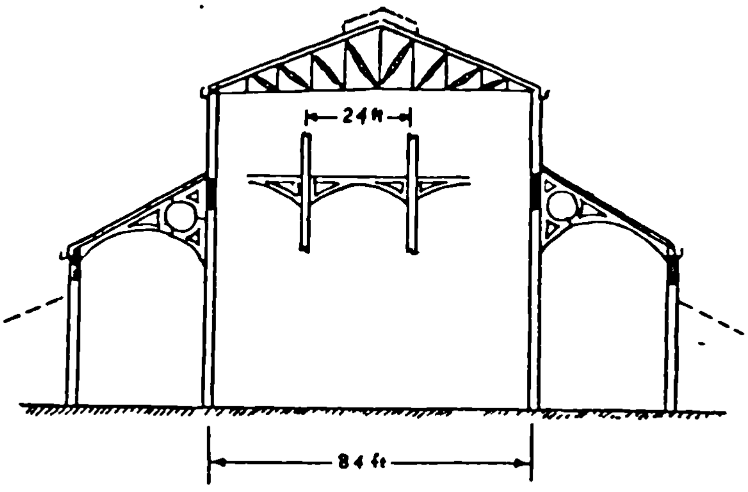
By the time Godfrey Greene designed an iron roof for Slip No. 7 (1852-1854) at Chatham, he had available for reference in the naval dockyards, a legacy of no less than fourteen examples of this distinctive building type, representing at least three basic designs which are known to have been used by Fox, Henderson and George Baker and Sons (See Figure 21 and Appendix F). Drawings with specifications for the roof of Slip No. 7 were signed by Greene 16 July 1852.[113] Two months later Greene called for tenders and Messrs. Grissells' proposal was accepted. George Baker wrote to Greene complaining that his tender was not successful but Greene replied explaining why Baker's bid was turned aside and stood firm in his decision on the contract award.[114] Henry Grissell likely worked out the details for the ironwork from Greene's design. Messrs. Grissell completed the project



SLIP Nos 8 & 9, PEMBROKE, 1844-45



SLIP Nos 3 & 4, PORTSMOUTH, 1845-46



SLIP No 4, WOOLWICH, 1846-47

Figure 21 Slip Roof Designs, 1844-1846

in 1854.[115] Greene's iron slip roof measured 300 feet long and 90 feet high to the ridge and was a rigid frame structure which employed cast iron bracing girders of the open trellis type, bolted to H section cast iron columns. The centre section of this aisled building was spanned by an 82 feet wrought iron triangular truss roof. Its two side aisles of 34 feet each had shed roofs continuous with the roof line of the central span and consisted of composite wrought iron and cast iron trussing supported by the transverse cast iron trellis girders. Trussed purlins carried the roof longitudinally supported by diagonal bracing of wrought iron rods. The roof was covered in corrugated galvanized iron 2 3/4 pounds to a foot and had skylights and a lantern. It was entirely of iron except for wooden perpendicular sashes and skylight bars.[116] (See Figures 22 and 23)

Greene's design was markedly different from the light curved rib designs of Messrs. Baker and Sons for the adjacent Slip Nos. 4, 5 and 6 (1847-1848) and was decidedly an improvement on all of the earlier slip roofs although not as great in clear span as some. The cast iron H section column, however, had been used in Fox, Henderson's Slip No. 4 (1846-1847), Woolwich, as had a triangular truss roof, though to different design. Also, the open trellis type cast iron girder was perhaps adopted from the experience of the Crystal Palace (1851) for which Fox, Henderson had been contractors; but the earlier building used octagonal, not H section columns and the girder connections differed. Neither building had true portal bracing using solely a rigid joint between columns and a solid web beam of normal proportions. As suggested already, the roof for Slip No. 7 was not remarkable as a wide span for the times. It was dwarfed by the then record span for train sheds of 212 feet achieved by the New Street Station, Birmingham, which was completed in the same year.[117]

What is perhaps most important about Greene's slip roof is that it represented the first of his many collaborations with ironfounder Henry Grissell (1817-1883).

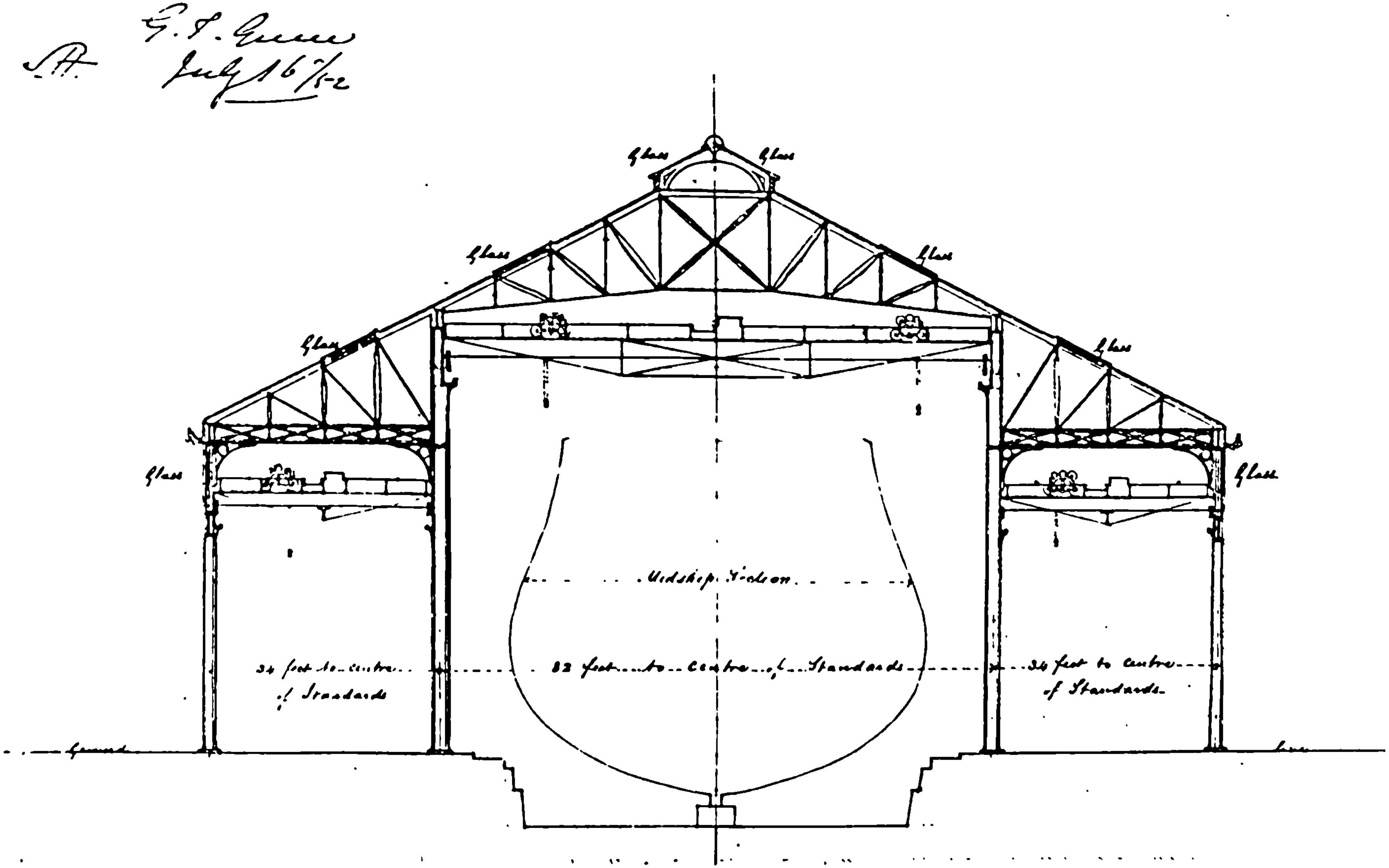
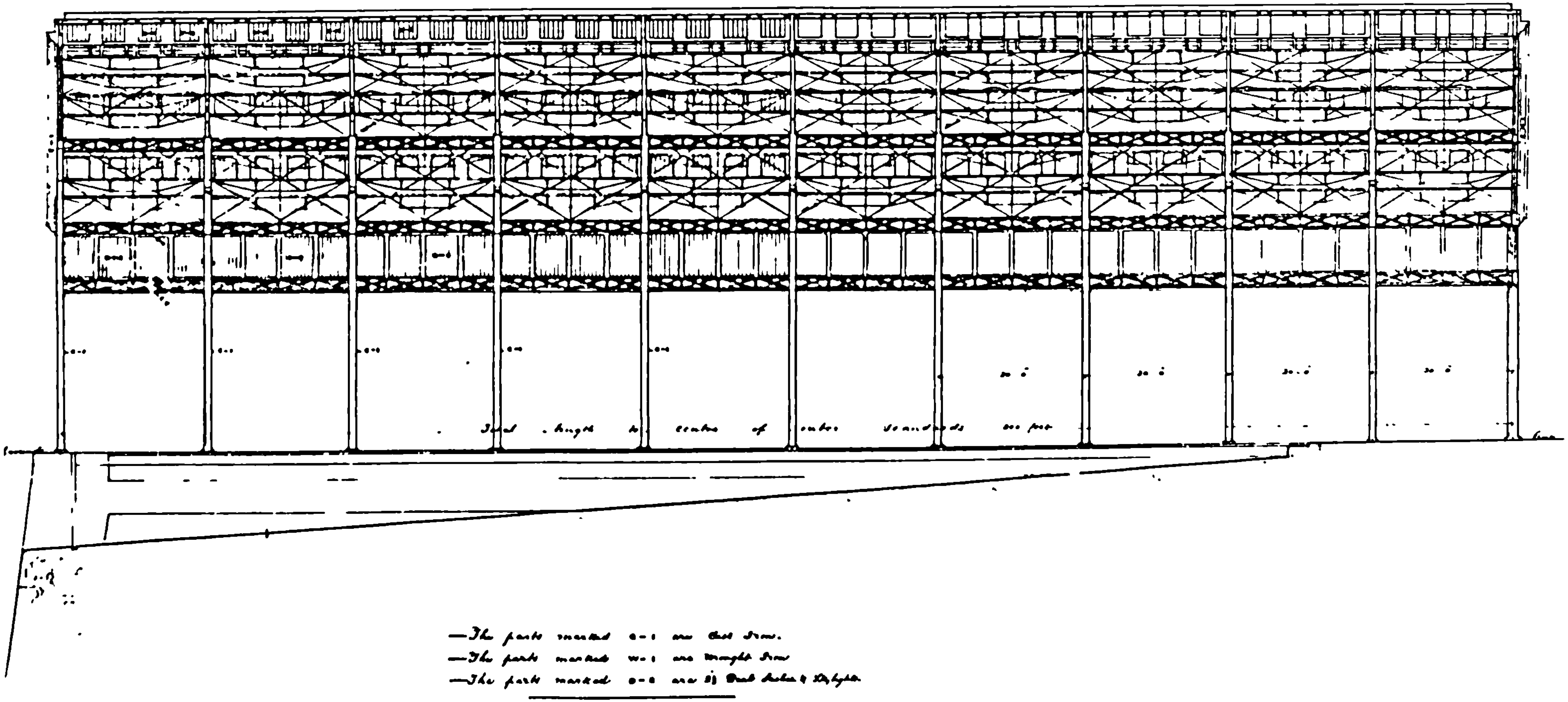


Figure 22 Slip Roof No. 7, Chatham, 1852-54 : Transverse Section



—The parts marked c-i are Cast Iron.
—The parts marked w-i are Wrought Iron
—The parts marked c-e are of Deal Sashes & Skylights

Figure 23 Slip Roof No. 7, Chatham, 1852-54 : Longitudinal Section

Grissell had been a pupil of John Joseph Bramah and started in business in partnership with brother Martin at the Regent's Canal Ironworks, Eagle Wharf, Hoxton, in 1841. In the 1840's he produced ironwork for many important roofs and bridges including roofs for the new Houses of Parliament. His ironworks also gained a reputation as a materials testing laboratory.[118] It appears that Grissell's first contract in the naval dockyards may have been the one for ironwork for the North Smithery, Devonport, in 1846.[119] Perhaps more important was Grissell's contract in 1848 for the roof of Boat House No. 6 at Portsmouth.[120] Collaborations between Greene and Grissell were to include, for example: the Iron Foundry roof, Chatham, 1855; the Chain Cable store roof, Woolwich, 1856; the Testing House iron shed, Chatham, 1856; corrugated galvanized iron roof coverings for Slip Nos. 1 and 2, Woolwich, 1858; and most importantly the Boat Store, Sheerness, 1858-1859.[121] Greene's iron slip roof represented both the culmination of years of development in a building type, largely by the private sector, and the beginning of a new era of co-operation between engineer officers and talented civilians.

Corrugated Galvanized Iron in the Naval Dockyards

Corrugated iron was a quick, inexpensive means of roofing and enclosure. It gave promise of a sheathing material far superior to wood because of its impermeability to water, invulnerability to insects and resistance to fire.[122] The material was first produced on a commercial basis in the 1820's. Henry R. Palmer was granted the initial patent in 1829 for a manufacturing process but Richard Walker of Rotherhithe, who purchased Palmer's patent, was most noted for the early fabrication of corrugated iron and its application. By 1833 Walker had used the new material for several roofs in the London docks.[123] Corrugated iron for enclosure was used initially in dockyard and railway sheds and warehouses. Examples from the period 1840-1844 included elliptical sheds varying from 30 to 40 foot span located at the London terminus of the Eastern Counties Railway, at the London Docks, the St. Katherine's Docks, and at various places on the Birmingham, Great Western and Blackwall railways.[124] Not until the development of the hot-dip zinc galvanizing process for sheet iron, first patented in 1837 by Sorel in France and Crawford in England, was the durability of corrugated iron made satisfactory by the addition of a protective surface.[125] The first use of corrugated galvanized iron for roofing in Britain was claimed to have been made by John Porter at Southwark in 1843.[126] The Royal Engineers in the naval dockyards were not far behind.

William Denison appears to have been the first of the engineer officers in the naval dockyards to employ corrugated galvanized iron. He used it at Woolwich to cover the roof of a machinery shed in July 1844 and again in the following October for repairs to the roof of Slip No. 4 which was a wooden structure at that time.[127] Prior to that, Denison had used zinc for roofing as a substitute for slate,although on one occasion in 1843 he proposed to use asphalt but abandoned the idea after inspecting its performance on a structure at Deptford.[128]

Nevertheless, it was in the iron slip roofs that corrugated galvanized iron made a major appearance in the naval dockyards, beginning with Fox, Henderson's design for Slip Nos. 8 and 9 (1844-1845) at Pembroke. In addition to its previously mentioned benefits, it was also convenient for cutting out openings for skylights. According to Charles Fox, the engineering contractors responsible for designing and erecting the iron slip roofs were guided in the specification of corrugated iron roof coverings by the Admiralty Works Department's stipulation that only zinc galvanized iron be used. The Works Department had carried out experiments and found this process produced the most durable corrugated iron. It insisted on the zinc being put on the iron directly and not over iron which had gone through a tinning process first.[129]

The use of corrugated galvanized iron was the subject of a lively debate in the early 1850's. Critics pointed to a number of failures of the material since its introduction in the previous decade. Fox defended it by pointing to the success of corrugated galvanized iron to Admiralty Works Department specifications used in the Pembroke slip roofs. Hawkshaw revealed that he had been encouraged to use the material after seeing its successful application at Pembroke but that his roofs had failed four years after installation. The corrugated galvanized iron roof on Turner's Lime Street Station, Liverpool had also failed.[130] It appears that the new material was vulnerable to chemical decay from the smokey atmosphere of Victorian towns as well as from the fumes of manufacturing processes in cases where roofs covered foundries and similar industries. Hawkshaw argued that the roofs at Pembroke had stood up well for nine years because they were in pure air away from smoke and fumes but Fox earlier stated that he had "... expected to have found some difficulty with roofs constructed by him for the Admiralty at Pembroke Dockyard, on account of their being exposed to the action not only of sea air, but the spray in heavy weather, but there had been no failure in those roofs."[131] On balance, it would appear that the Royal Engineers in the Admiralty Works Department, working with the private sector, had met with more than ordinary success in the early application of a new material.

Engineer officers in the dockyards continued to use corrugated galvanized iron with confidence for roofing and siding. Fireproofing was perhaps their chief motive, as discussed earlier. For example, in 1851 after a wooden roof in a Coke Store at Chatham was destroyed by fire, the dockyard clerk of the works sent tracings to Brandreth recommending a corrugated iron roof be built as a replacement. The suggestion was approved and Richard Walker was awarded the contract for the job.[132] In the same year, pioneer manufacturer of corrugated galvanized iron, Tupper and Carr, asked to inspect the state of the different corrugated iron roofs at the naval dockyards and to make a report. This was permitted and the report was reviewed by both the Director of the Works Department and the Admiralty Board.[133] The firm won contracts for iron roofs at Portsmouth and Chatham.[134] Evidence suggests, however, that virtually all of the well known pioneer manufacturers and suppliers of corrugated galvanized iron were awarded contracts for work in the naval dockyards with no one in particular predominating.[135]

Portal Bracing and Mature Works in Iron

The freestanding iron frame brought the need for wind bracing to the attention of nineteenth century builders. Fowler's Hungerford Market building (1835) had an iron roof frame supported by cylindrical cast iron columns and bracing provided by spandrel brackets curving outward from collars fixed to the columns. Arched girders were later developed to provide rigidity. These were first used in Fox's Euston Station roof (1837). Both types were employed in the naval dockyards together with diagonal bracing in the arrangement of X's connecting main bearing members. The use of corrugated iron for siding and roofing also added a measure of stiffness to dockyard structures. Sir Joseph Paxton's and Charles Fox's Crystal Palace was the first structure to use a form of proto-portal bracing. Fox designed rectangular open trellis type cast iron trusses fixed to octagonal columns by flanged collars. The Great Exhibition building, though, depended on diagonal bracing bars for stability and therefore was not true portal bracing in the modern sense.[136] The breakthrough came in the naval dockyards.

Godfrey Greene's Boat Store (1858-1860) at Sheerness is recognized as a monument in structural history for being perhaps the world's first multistorey iron framed building stabilized by portal action. Greene used H section columns and I beams bolted together throughout the depth of their connection forming a rigid joint.[137] The Boat Store is a four storey aisled building 210 feet long by 135 feet wide with a total height to the ridge of 53 feet. There are four rows of columns in each of the 45 foot wide aisles spaced at 14 feet 6 inch centres transversally and at 30 foot centres longitudinally except in the walls where they are 15 feet apart. The central section, also 45 feet wide, is open to the roof. Columns are cast iron as are transverse beams. The longitudinal beams are rivetted wrought iron plate girders. Intermediate floor joists are timber and the upper floors are oak planks. The roof is three triangulated composite wrought and cast iron roof trusses of 45 foot span each. These trusses are pin-jointed at their supports on the longitudinal girders and external capping beams. The Boat Store was enclosed by corrugated galvanized iron wall panels and roofed with slates. It is lighted by windows resting on angle iron and skylights in the centre section. Now the ground floor is a concrete slab but originally it was pig iron ballast. The columns are founded on piles.[138] (See Figures 24 and 25)

Godfrey Thomas Greene (1807-1886) was the son of an East India Company army officer. He was trained at Addiscombe (1821-1823) and at the Royal Engineer Establishment (1823-1824). Commissioned in the Bengal Engineers in 1823, he arrived in India two years later. Initially he served in the North West Provinces in canal work and in various executive positions but his later career was spent in Calcutta in offices of the presidency's central government. While in India service he was a barrack master, executive officer, civil engineer, garrison engineer, secretary to the military board, superintendent of embankments and mint master. Greene retired from the Bengal Engineers in 1849.[139] While he was not unfamiliar with structural iron on taking up his position as Director of the Admiralty Works Department, his twenty-five years experience in India did not equip him with any extraordinary expertise in advanced techniques of building with the material.[140] However, after joining the Works Department, Greene developed increasing skill in the design of structural iron working in collaboration with private sector engineers and contractors who had considerable experience in naval dockyard projects, especially Fox, Henderson and Henry Grissell. Highlights included: the Smithery (1851-1852) at Portsmouth with

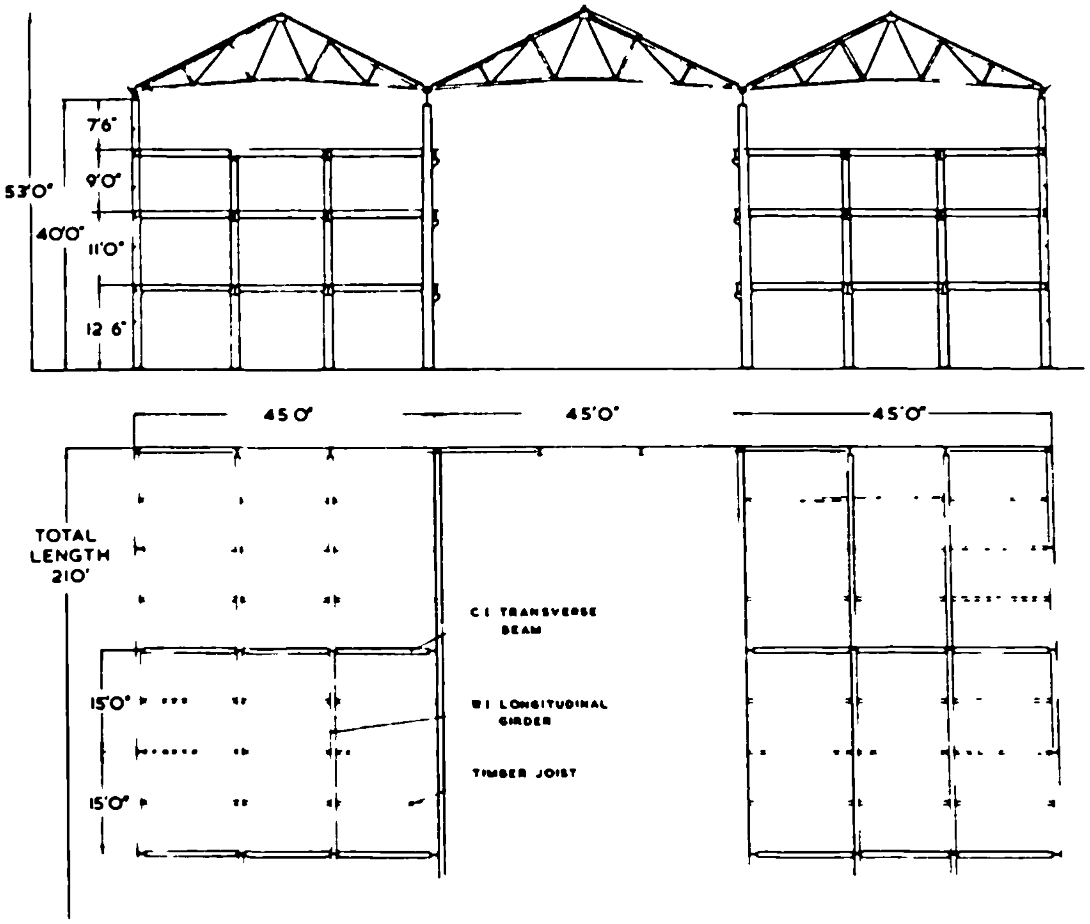


Figure 24 Boat Store, Sheerness, 1858-60 : Plan and Section of Iron Framing

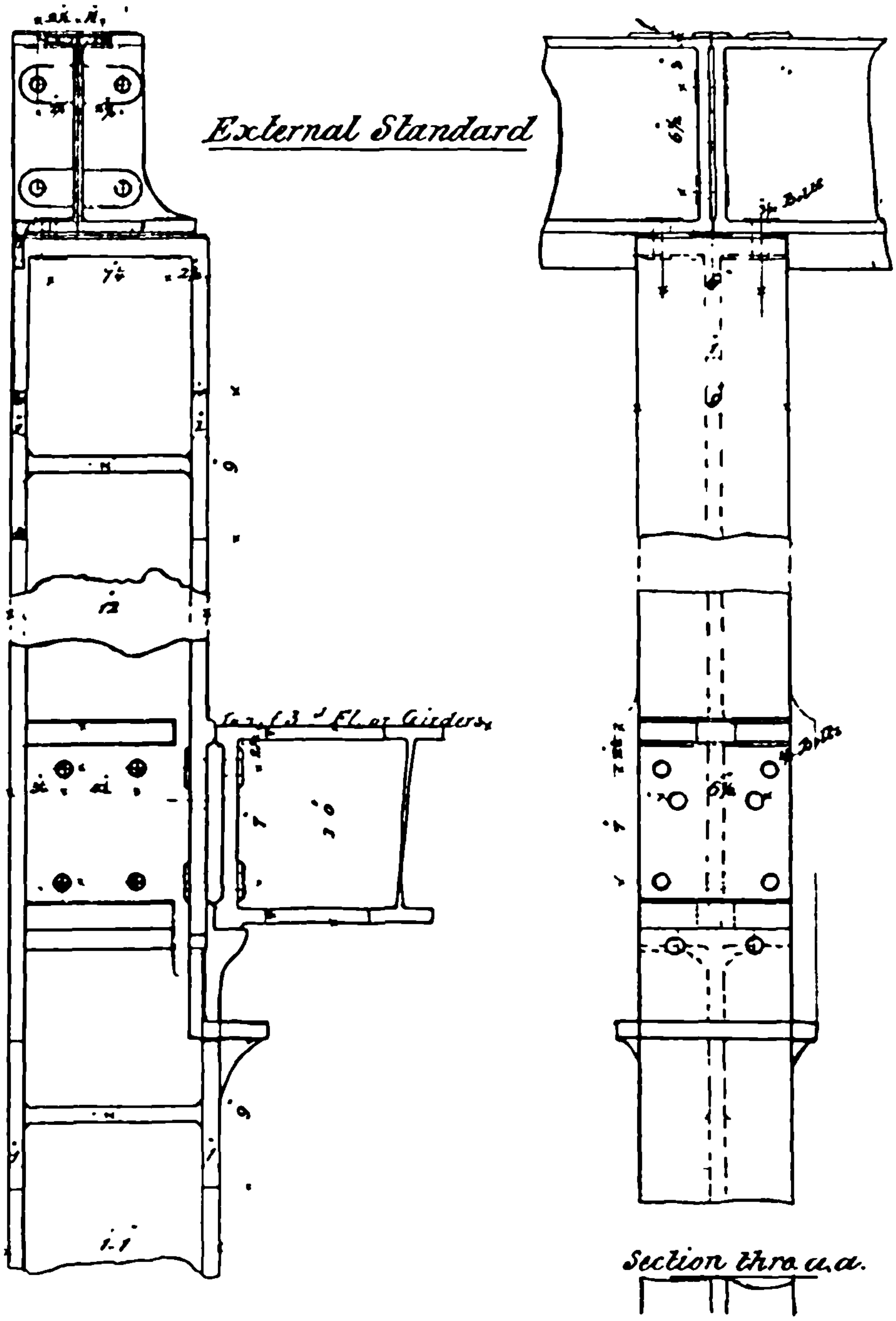


Figure 25 Boat Store, Sheerness, 1858-60 : External Columns

Fox, Henderson; Slip No. 7 (1852-1854) at Chatham, with Henry Grissell; the Smithery (1855-1856) at Sheerness with Henry Grissell; and the Saw Mill and Testing House (1856) at Sheerness with Fox, Henderson.[141]

Skempton has argued, largely on the basis of a substantial collection of drawings for the Sheerness Boat Store signed by Greene, that this retired engineer officer indeed was the genius responsible for the novel design. Moreover, although evidence has not survived of the specific date of the contract, Henry Grissell was the contractor for this remarkable structure as clearly established by records of the project. Skempton has maintained that Greene had become the master of iron construction by this time and that the detailed design was essentially complete by the time Grissell took up the contract.[142] While Skempton has acknowledged that William Scamp, Deputy Director of the Works Department, worked closely with Greene on day to day matters, he gives him little direct credit for the Boat Store on the basis that Scamp did not sign any of the surviving drawings and the assertion that it was the general practice for each to sign his own designs in the office. Furthermore, he has suggested that Scamp's work was mainly in planning and heavy engineering and Greene's in buildings.[147] All the same, evidence suggests that Greene probably owed much to Scamp in the development of the knowledge and skills which he required to design the Boat Store and it is not unreasonable to argue that Scamp may have contributed to both the concept and details by way of discussion at the Works Department's office in Somerset House, London.

It is true that Scamp had a special talent for the planning of buildings and docks. For example, he reported in 1858 on a new system of siting and layout for the mast house and mast stores for Sheerness and Devonport.[144] Nevertheless, Scamp had some twenty years experience in the Works Department at the time the Boat Store was constructed. He had designed several structures in Malta under Brandreth (1841-1845), served as Chief Assistant or Deputy Director for the Department since 1845, experienced the formative period of the wide span iron slip roof, and had often taken part in project management working with private sector engineering contractors and Royal Engineers in the various dockyards.[145] Scamp frequently deputized for Greene during the latter's leaves of absence and other times away from London. On these occasions he exercised full powers of the Director's office.[146] In 1860 Greene himself said of Scamp: "Deptford, Woolwich, Sheerness, Portsmouth, Devonport and Pembroke, owe many of their best buildings to his professional talent."[147] Perhaps a better balanced interpretation of the Boat Store at Sheerness is to view the structure as the mature work of a public office design team which had been collaborating for nearly a decade with private sector engineering contractors. It is to Greene's credit that he was responsible for the Works Department taking leadership in the design process and in the relationship with the private sector, a situation which had not prevailed before he became Director.

The Boat Store at Sheerness was an isolated phenomenon in structural history with no discernable influence. It would appear that this was the case partly because of its location in the naval dockyards where it was hardly in the public eye but perhaps more fundamentally because prevailing architectural taste did not favour such utilitarian construction. As long as people preferred masonry walls there was no need for complete iron framing.[148] Indeed, it is interesting to observe that the Boat Store precedent did not revolutionize building practice even in the naval dockyards themselves. Large factories and warehouses to serve the steam powered, iron clad fleet of the 1860's and later, continued to be built in brick, albeit with iron interiors.

Unfortunately, no evidence survives to indicate what Greene thought of the Boat Store as an achievement in structural engineering or otherwise but William Scamp expressed a revealing opinion in testimony before the Commission on the Control and Management of Her Majesty's Naval Yards which reported in 1861. Some of the Commissioners had questioned why the cost of the Boat Store had exceeded the estimates and focussed their attention particularly on seeking explanations for the use of valuable pig iron ballast for the ground floor and the necessity of roofing the centre section. Scamp provided the answers and in so doing stressed the efficiency and labour saving merits of the new building. Scamp allowed that he would not have used the pig iron ballast for flooring but explained that this had been done at the request of the yard Captain Superintendent simply to get the material which was lying about out of the way with the intention of using it at the foundry at some future date. He attributed most of the overspending to this decision.[149] Nevertheless, he went on to defend the economy of the construction on functional grounds, including the roofing of the central section. Scamp explained that he had found some 300 boats lying around in the yard and that it was impossible to know what state they were in, thus making it extremely difficult to equip a warship with the usual complement of six boats when required with dispatch. Moreover, he argued that the old boat house was overcrowded and inefficient.[150] Still, the critical feature of Scamp's defence of the expense incurred in the construction of the Boat Store was that it was a sound investment in working efficiency which would save labour and permit optimum use of other dockyard buildings.

> "Everything in a dockyard should be done with a view to save labour. When you find an establishment of 400 or 500 men employed, whose labour is valuable, everything should be done to save labour, but especially everything should be provided to do the work with dispatch. That was the object of the boat-house. By taking the centre part of that working space, you will have released the upper storey at least of the old boat-house for other purposes for which it is very much required at that very valuable site."[151]

Scamp had explained at the outset of his testimony that the original estimate for the Boat Store was £25,000 but that the initial design was modified to diminish the building by two bays which reduced the estimate to £20,000. The entire cost of the completed Boat Store was £21,040, out of which £13,908 was paid to Henry Grissell, major contractor and ironwork fabricator.[152] Given the relatively minor overspending on the estimate it would appear that the Commissioners thought that the expense of producing such an advanced building was excessive in itself. Scamp acknowledged this when questioned on whether or not he considered the Boat Store an economical work. He replied: "Looking at the circumstances I do; taking it as an isolated case, it may not appear so."[153] It is tempting to speculate that herein may lie another reason why the Boat Store had no successor.

Early Concrete and the Royal Engineers in the Naval Dockyards

The Royal Engineers became superintendents of the Admiralty Works Department in the naval dockyards at the very time that interest was developing in the use of Ranger's concrete and artificial stone. In 1834 George Leadwell Taylor, Civil Architect to the Admiralty, had worked with Ranger in employing the latter's patent concrete for underpinning a storehouse at Chatham.[154] As discussed in Chapter 2, Denison, on assuming his duties at Woolwich in 1837, had witnessed the performance of Ranger's artificial stone blocks and mass concrete in river walls at the dockyard as well as at Chatham. These too had been constructed under Taylor.[155] Denison undertook experiments on concrete blocks made from hydraulic lime in conjunction with Pasley's extensive experiments at the Royal Engineer Establishment. His experience led him to condemn the use of Ranger's concrete in wharf walls because of its lack of resistance to frost and mechanical action, and in this Pasley concurred.

By 1845, however, Denison had modified his view of concrete in marine works in making an important proposal, while in the employ of the Admiralty, for the construction of a major breakwater at Dover Harbour of Refuge. It was presented to a government Commission which had been formed a year earlier to examine alternative methods and materials for breakwater construction with the object of recommending the best approach for the Dover project.[156] Questioned by the Commissioners about his views on Ranger's concrete at Woolwich which had been published in 1838 both in the Royal Engineer Professional Papers and in The Civil Engineer and Architect's Journal, Denison replied that over the last seven years he had used concrete in the dockyards to a great extent in foundation walls and in other situations where it was "protected from violence".[157] He further explained that though in 1838 he had proposed refacing the Woolwich wharf wall with brick or iron, he no longer saw this as necessary and testified to the soundness of the interior of the concrete blocks in the wall, saying he had done core tests three months earlier.[158] Denison's view in 1845 was that frost would have very little adverse effect on concrete once set and that it was "mechanical action alone which concrete is unable to stand."[159]

In his proposal for the Dover breakwater, Denison specified an upright wall constructed of large hexagonal concrete blocks (made of hydraulic lime and puzzolana) up to within 3 feet of low water and granite for the superstructure. He explained that he preferred concrete to the more conventional mass brick laid in cement mortar because the former was cheaper. Denison claimed that under water concrete would be safe from mechanical action, and that even though he considered that frost was not a concern, the concrete would be protected from that too because seawater did not freeze on the Dover coast.[160]

Denison's proposal for the use of concrete blocks in marine works was not a novel idea but it was not common practice in Britain to employ this type of construction in the mid-1840's. The French engineers had used the method successfully, although blocks in exposed situations had experienced failure.[161] Most of the civil engineers and architects who testified before the government Commission concurred on the matter of the upright wall design but many preferred mass brickwork in cement mortar over concrete blocks.[162] George Godwin, who in 1836 had won the first gold medal ever awarded by the Institute of British Architects for his paper on the nature and properties of concrete, told the Commission that he preferred concrete in mass rather than blocks, and for substructures only. He also said that, on the basis of his examination of river walls at Woolwich in 1838, he did not recommend concrete for such situations. It would, he said, put the material under too severe a test. He greatly preferred brickwork in cement to concrete blocks for the proposed Dover breakwater.[163] Robert Smirke, pioneer of concrete construction for foundations, said bluntly in a letter to the Commission's chairman that he thought concrete blocks made of lime and gravel would fail in a sea wall and that mass brickwork would be more durable but probably more expensive than stone.[164] Charles Vignoles dissented from the prevailing view and supported the use of concrete blocks under water. So too did Charles W. Pasley, then Inspector-General of Railways, and another prominent Royal Engineer, Lieutenant-Colonel H. Jones, an expert on breakwater design and advocate of the upright wall. The Rennie brothers were virtually alone in preferring very decidedly a sloping stone wall - the traditional design. In the end, the Commission recommended an upright wall in mass brickwork and cement.[165] The project was undertaken in 1850 by Messrs. Walker and Burges. They used the upright wall but constructed it with a stone foundation and facing, and with blocks of Portland cement concrete for hearting.[166] This story illustrates that the Royal Engineers, especially Denison with his experience in the naval dockyards, could be amongst the more progressive minded British engineers in their views on concrete for marine works in the mid-1840's.

Portland Cement Concrete and Dockyard Extensions 1867-1879

Dockyard extensions at Portsmouth and Chatham were necessitated by the coming of an ironclad fleet, beginning with the 'Warrior' in 1860. The rapid increase in size of the new warships made new dock accommodation with special features, a pressing need. Works were much larger than any previous extensions and involved major government expenditure - £2 1/4 million at Portsmouth and £2 million at Chatham. These were very high profile projects much followed by civil engineers and therefore influential on private sector practice. The extension works were authorized by Parliament in 1864 but work began three years later.[167]

Overall responsibility for the design of the extensions at Portsmouth and Chatham rested with Sir Andrew Clarke (1824-1902), Director of the Admiralty Works Department (1864-1873). He piloted the necessary legislation through Parliament by making extensive explanations of plans and estimates. Commissioned in 1842, Clarke had served in civil administration positions in Australia, first under Governor Denison in Van Dieman's Land and later as Surveyor-General of Victoria (1853-1859). In the period 1859-1864 he served in the Gold Coast and briefly in England before being appointed to the Admiralty. His civil engineering experience was limited but he was very knowledgeable with respect to the administration of major engineering projects, a great ability to control cost being his foremost skill.

The first major use of Portland cement was in Cherbourg harbour works (1846-1853), 6,000 tons of the material being shipped to France by English manufacturer J.B. White and Sons. It was used in massive concrete blocks in exposed situations, not simply as backing for stone or brickwork. The blocks were reported to be in good condition nine years after installation.[169] While French engineers were prepared to use Portland cement in this way for extensive marine works, the British were clearly timid on the matter. Some English manufacturers advocated following French practice but even by the late 1850's civil engineers in Britain were not prepared to use exposed concrete either in mass or in blocks for docks, harbours, breakwaters and other works in seawater. They had restricted Portland cement to mortar for brickwork and for concrete blocks used as backing for stone or brick construction.[170] This was the prevailing situation when Clarke took responsibility for the dockyard extensions at Portsmouth and Chatham.

The Portsmouth extension works were designed by Clarke and his deputy William Scamp and were executed under the supervision of Henry Wood, Superintending Engineer at Portsmouth, as well as civil engineers Charles Colson and J. Macdonnell. The contractors were Messrs. John Towlerton Leather and George Smith, with their general manager Edward Pease Smith being in immediate charge of works.[171] The works involved extensive use of Portland cement in mortar and in mass concrete (350,000 cubic feet).[172] Retaining walls, docks and locks were built primarily in coursed brickwork bonded in Portland cement mortar and with some use of hoop iron reinforced brickwork. Portland cement concrete was used as backing and in foundations. Granite was used as facing in areas subject to severe mechanical action. No exposed concrete was used.[173] (See Figure 26) Portland cement was not specified originally but was selected over Roman cement and blue lias lime (hydraulic) after these products presented problems in use.[174] One source credited E.P. Smith with the substitution saying it was done because of his great experience of Portland cement's good qualities and high value and his ability to show how it could be used without extra cost.[175] It was Clarke, however, who claimed credit for what he called the pioneering use of Portland cement concrete on an extensive scale in Britain. He said that at the time he took the decision to adopt mass concrete, its use was a "novel experiment" and many experienced engineers warned him that he was employing a material about which little or nothing was known, and that great caution was needed.[176] He thought "that he might claim the credit of having been one of the earlier pioneers in the use of this material by selecting it for a large public work of this character."[177] At least two civil engineers who discussed this project during the late nineteenth century described Clarke's work as "advanced" or "pioneering."[178]

At Chatham, the extension project, also designed in Clarke's office, was under the supervision of engineer

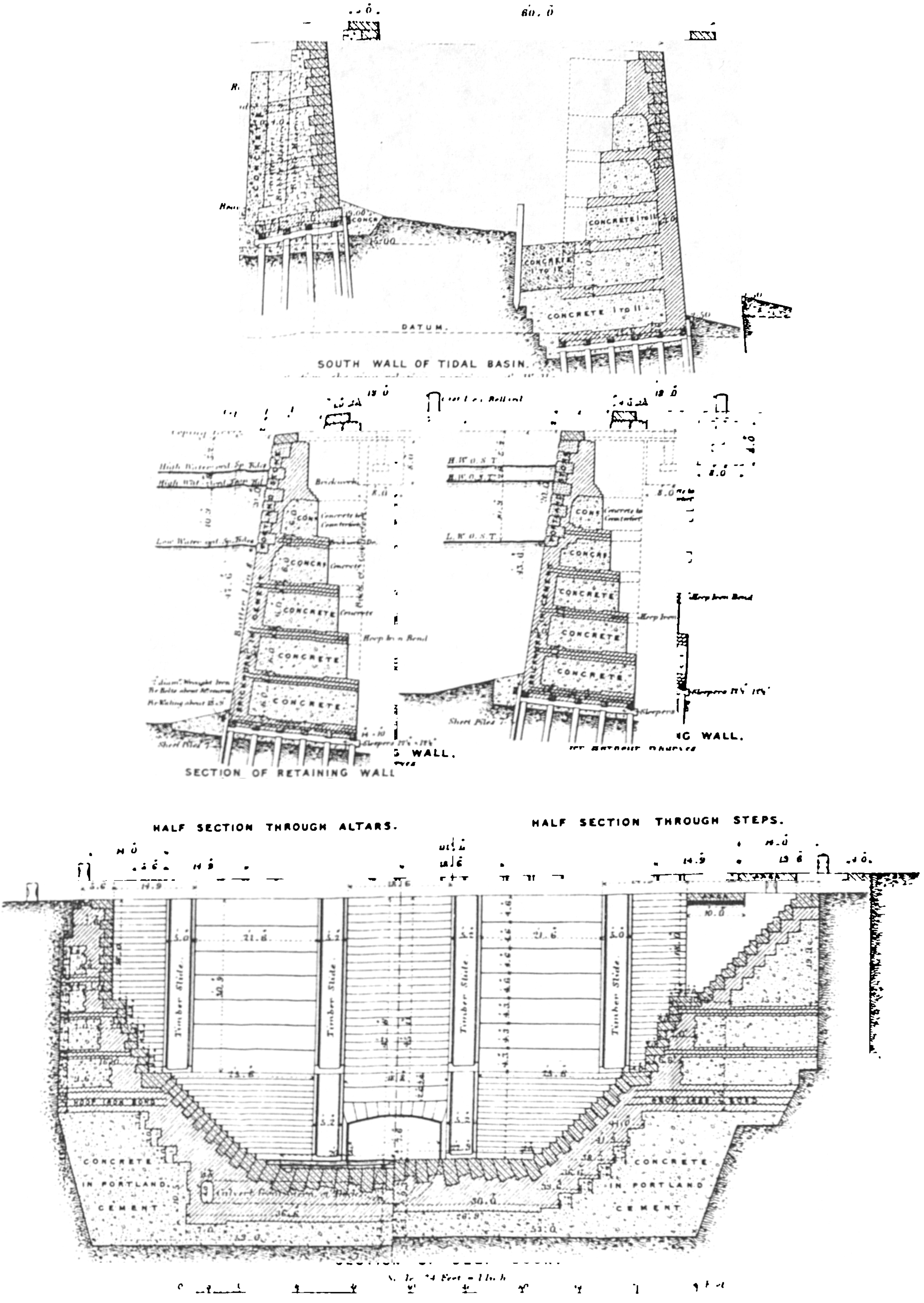


Figure 26 Portsmouth Dockyard Extension Works

officer Charles Pasley but was carried out by E.A. Bernays, Assistant Civil Engineer for the Admiralty Works Department in the dockyard.[179] Pasley, son of C.W. Pasley, was a former classmate of Clarke at the Royal Military Academy and a close personal friend. Like Clarke, he too had served in Australia where he was Commissioner of Public Works for Victoria (1855-1859). Pasley succeeded Clarke as Director of the Works Department (1873-1882).[180] Bernays was responsible for recommending the use of Portland cement at Chatham before 1870 and he was more daring in its use than Clarke. As well as using Portland cement in mortar,and in concrete as backing to masonry and in foundations, Bernays used it in about a quarter of the works as exposed mass concrete. His motive was economy. In an initial experiment in 1874, he developed a system of using a very low proportion of Portland cement to aggregate (1 to 12) for common mass concrete laid in a specially designed formwork to allow facing with a superior Portland cement concrete made with ironworks slag and sand so as to achieve a perfect bond between the two grades of concrete. Success led him to use his system of mass concrete construction in all manner of walls, steps, paving and in blocks for house building. About 50,000 tons of Portland cement were used in the works to 1879.[181]

In a discussion at the Institution of Civil Engineers on Portland cement in 1880, C.H. Meyer, a civil engineer who had been in charge of the extensive steam machinery for the Portsmouth extension works, criticised Bernays' principle of making the mass of walls of a comparatively weak concrete faced with a better quality, saying that it was a false economy and would not prove durable. However, at the same time he praised Clarke's sound use of Portland cement at Portsmouth.[182] In the same discussion,Thomas Dyke, engineer to the Portland Harbour Commissioners of Hartlepool, said he had used concrete blocks made of Portland cement faced with a superior quality of the material in a breakwater at Hartlepool shortly after 1869.[183] Nevertheless, Bernays' obituary described his works as "without precedent" and claimed his efforts proved "entirely satisfactory" and a "great saving".[184] Bernays had been in the Admiralty Works Department twenty-six years at the beginning of the Chatham extension programme.

It is not surprising that Bernays' greater experience led him to be more innovative than his superiors, Pasley and Clarke, who had been in the department only two and three years respectively. Yet the engineer officers deserve some credit for sanctioning his recommendations. The Royal Engineers and their civilian colleagues in the Admiralty Works Department, working in co-operation with engineering contractors, can be credited with advancing the technology of concrete for marine works construction in late nineteenth century Britain. This probably also helped in some measure to increase the confidence of civil engineers in the use of Portland cement concrete generally.[185] Interestingly, some of the engineering contractors who worked with the engineer officers in the dockyard extensions also collaborated with the Royal Engineers in the construction of fortifications.[186] The following chapter takes up the question of new building technology and national defences.

5. NEW TECHNOLOGY AND FORTIFICATIONS

Military building technology was a specialized concern of the Corps and the construction practices developed for fortifications had limited application to civil architecture and engineering. There were, however, some important connections to non-military building in the adoption and use of new materials and techniques. Moreover, the study of military building technology reveals some interesting aspects of the Royal Engineers' relationship with civil engineers, contractors and manufacturers as well as with other branches of the British armed services and foreign military engineers. The development of building materials and techniques in fortifications took place within the context of changing military technology and government defence policy and more generally as part of the ongoing search for economy and effectiveness in military construction. The focus of this chapter is on the engineer officers' attempts to build durable, bombproof, fireproof and waterproof structures using concrete, asphalt and iron, three 'new materials' of the nineteenth century.

Changing Military Technology and Defence Policy 1815-1880's

Following the Napoleonic Wars, the prevailing attitude in Britain was that the nation was invulnerable and the defence of the realm assured by naval power alone. As well, between 1792 and 1815 the direct cost of the British military establishment had soared from £4.5 million to £58 million and the war with France was barely over when drastic cuts in expenditure began.[1] Financial reformers in the government kept a tight purse on military appropriations. Consequently, plans developed in the 1780's to fortify the naval dockyards and other strategic locations remained dormant throughout the long peace of Victoria's early reign.[2] Nevertheless, changes in the technology of warships and artillery, along with the course of events in European international relations, were to effect a transformation in the government's attitude towards land defences and consequently to the construction of fortifications. Although the Royal Engineers had experimented with new materials and techniques for defence works from the late 1820's, it was markedly increased government capitalization of fort construction beginning in the 1860's that provided the Corps with the necessary means and opportunity to introduce advanced building technology to fortifications on a substantial scale. Sometimes they did this with the benefit of the lessons learned from their earlier experimentations. However, novel materials and methods were generally adopted with caution, and few, if any, of the Royal Engineers' works of fortification were to be bold and daring ventures with new building technology.

The critical decade for formative advances in military technology was the 1840's. In 1842 groove rifling and studded shot for muzzle loaded guns were developed in France and in the same year the British navy got its first steam assisted frigate. The Americans launched in 1843 the first screw propelled warship, the 'Princeton', designed by Swede, John Ericsson, and the Royal Navy followed suit the next year with 'H.M.S. Dauntless'. Cavalli invented a rifled breach loaded gun in 1845 and the following year Britain launched its first steam assisted warship of the line, 'H.M.S. Ajax'. By 1850 the Admiralty was experimenting with armour plating for warships at Portsmouth, especially with the 'H.M.S. Simoon'.[3]

Change in the technology of war accelerated in the 1850's and 60's with the Crimean War (1854-1856) and the American Civil War (1861-1865), both of which provided an incentive and proving ground for the armaments makers. By 1854, the 'Armstrong' breach loaded gun had been introduced. In the same year the French navy built five armour plated floating batteries, three of which were used successfully in 1855 for the bombardment of Kinburn during the Crimean conflict. It was the first trial of ironclads against forts. In 1857 the French began to build an ironclad fleet and two years later launched four

'La Gloire' class warships. The Royal Navy's first armour plated warship, 'H.M.S. Warrior', was launched in 1860. Two years later the first clash of ironclad warships took place in the battle of the 'Monitor' and the 'Merrimac' during the early stages of the American Civil War.[4]

Essentially, the challenge facing Britain at mid-century was an arms race in fast moving, increasingly manoeuverable, ironclad warships equipped with ever more accurate and powerful guns which could not only threaten the nation's sea supremacy but also make her vulnerable to invasion. The weak link in Britain's defence was inadequate coastal fortifications and obsolete methods of constructing batteries. Major General P. Yule addressed the later issue succinctly in 1857:

> "As long as sailing vessels alone existed, the present form of embrasures was not inadequate for its object, as a sure close and concentrated fire could not always be brought against a battery; but it is not sufficient to resist attacks of fleets of large ships when placed in position by means of screw power, under the supposition, at least, that there are fewer guns in the battery than in the ships brought against it."[5]

Three years later Captain Henry Whatley Tyler correctly identified the future of fortifications design in response to rifled weapons when he emphasized in an article in the Royal Engineer <u>Professional Papers</u> that "<u>systems of fortifications</u>" must give way to "<u>principles of construction</u> and ...systems of defence."[6]

As early as 1846, Inspector General of Fortifications, Sir John Fox Burgoyne, began a movement to improve the land defences of Britain with the publication of his <u>Observations on the Probable Results of a War with France Under Our Present System of Military Preparation</u>. Burgoyne served in the post 1845-1868 and was to be a central figure in the modernization of Britain's land defences. He had been commissioned in 1798 and saw extensive action in both the Napoleonic and Crimean Wars.

Before becoming Inspector General of Fortifications, he had been Chairman of the Board of Public Works in Ireland for nearly fifteen years (1831-1845) during which time he gained much experience in a wide range of construction projects and was a founder of the Institution of Civil Engineers of Ireland in 1835. He was consulted by many leading engineers both at home and abroad.[7]

In 1859 the Palmerston government appointed a Royal Commission to Consider the Defences of the United Kingdom in response to the French programme of building ironclad warships and the improvement of the defences of Cherbourg. In its report of 1860, the Commission recommended fortification of the Royal Navy dockyards and Woolwich Arsenal and the harbours of Portland, Dover and Cork. Coastal batteries were to be built to resist sea attack and a ring-fortress system to defend against land assault. The estimate for works was £10,350,000.[8] However, the government reviewed the Commission report and eliminated certain works, cutting the estimate to £6,180,000. The first appropriations for the fort building programme were under the Defence Act of 1860. Estimates in 1865 stood at £6,995,000.[9]

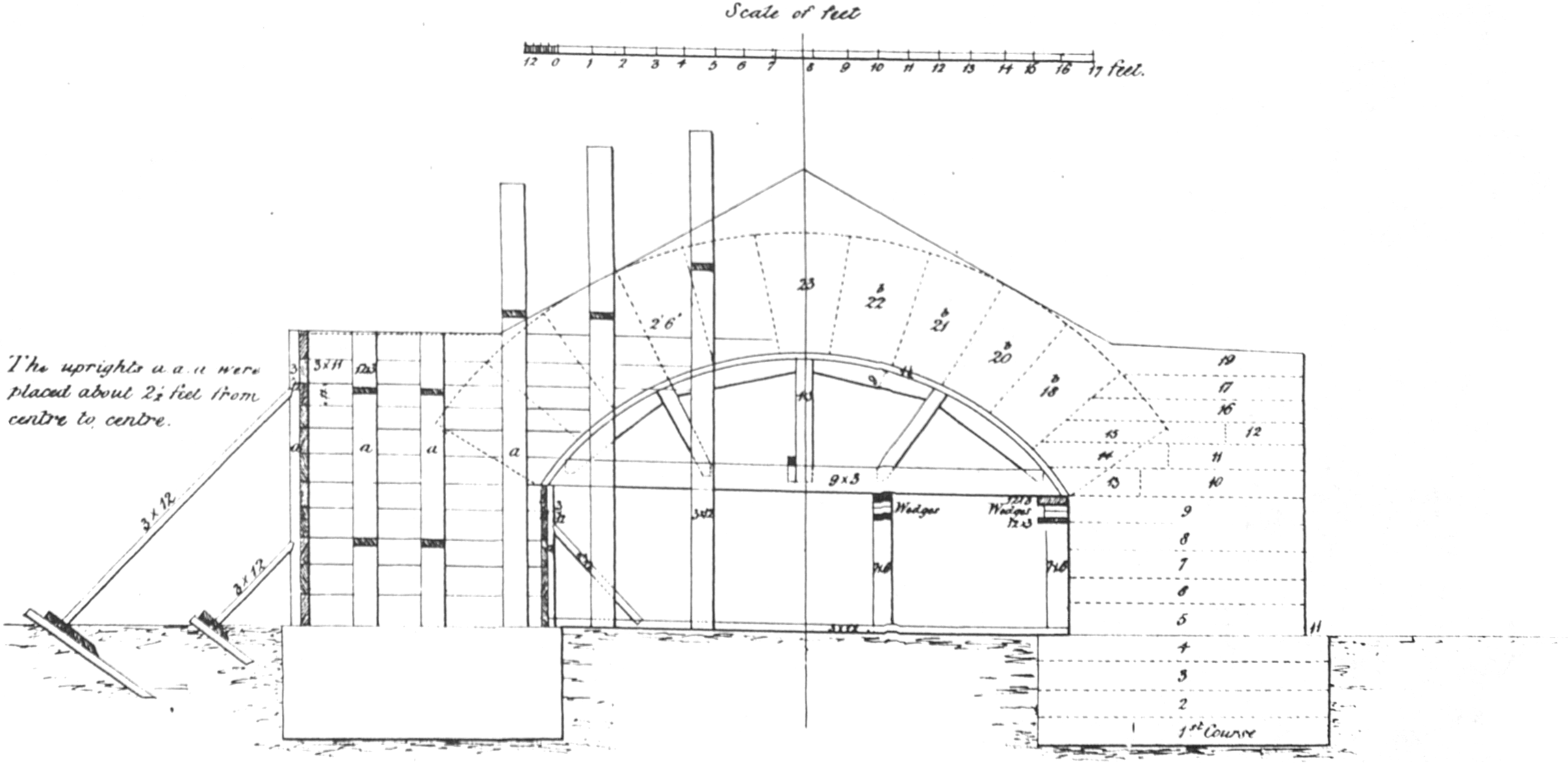
The Commission Forts were designed by the Royal Engineers in the Fortifications Department of the War Office working in collaboration with Corps officers at the local stations.[10] In charge of the design and construction programme was Sir William Drummond Jervois (1821-1897). The principal officers assisting him were Sir William Crossman and Sir Edmund Frederick Du Cane. Captain Thomas Inglis was the engineer officer under Jervois responsible for iron in fortifications. Lieutenant Colonel Jervois had been commissioned in 1839 and first built fortifications in Cape Colony, South Africa (1841-1848). While in command of a company of Royal Sappers and Miners at Woolwich and Chatham (1849-1852), he constructed defences for the new harbour at Alderney (1852). In 1856 Jervois was appointed Assistant Inspector General of Fortifications. Three years later he was made secretary of the Royal Commission on the Defences of the United Kingdom and its report of 1860 was largely written by him. In 1862 Jervois was appointed Director of Works of Fortification, nominally under the Inspector General of Fortifications, but in practice confidential adviser of successive Secretaries of State for War on all questions of defence. Jervois investigated and reported on the defences of British North America (1864-1865) and later undertook similar enquiries in Bermuda, Gibraltar, Malta, India and Canada (Halifax). He left the Fortifications Department in 1877.[11]

The building of the Commission Forts began in the early 1860's and proceeded into the next decade. Works at Chatham were not completed until 1899 and were considerably different in construction from the initial projects. For the design of the Commission Forts Jervois abandoned the classic fortress design because of cost, time and efficiency and adopted a simple polygonal trace. The coastal forts were generally built of granite or Portland stone, casemated with roofs of masonry, brick and concrete. Nevertheless, some of the original designs were modified for fortification in iron and these proved to be a major controversy. Land forts were mainly of brick, brick with flint, earth and to a small extent stone, iron and timber. In these a thick layer of earth was used to protect compartments below from shot. Asphalt was used for roofing, flooring, paving and in some cases as a mortar. Concrete was used increasingly in fortifications from 1875 in preference to brick and stone, especially in the Chatham ring of land forts.[12] It is interesting to trace the roots of the Corps' use of new materials in the Commission Forts since it reveals much about the Royal Engineers' attitude towards advanced building technology as well as about the climate of support that prevailed for innovation in fortifications.

Concrete in Fortifications

As discussed in Chapter 2, Pasley and other Royal Engineers had been early advocates of concrete for substructures. It would appear that the material was adopted for this purpose in fortifications without controversy. Such was not the case, however, with the application of concrete for fort superstructures. The Corps first experimented with the material for walls and arches in a model vault constructed to simulate part of a casemate or magazine. It was built at Woolwich Marshes in February and March 1835 and tested for its resistance to artillery fire the following May. This trial had been undertaken on the order of Sir Frederick W. Mulcaster, Inspector General of Fortifications, pursuant to a directive from the Board of Ordnance to ascertain the fitness of Ranger's patent concrete for casemate arches. The model vault was constructed by Ranger under the superintendence of Lieutenant Colonel Sir George Judd Harding (1788-1860) assisted by Captain Charles C. Alexander. It had a span of 17 feet and a rise of 9 feet, and the total amount of concrete in its foundations, abutments and arch was 5,947 cubic feet. The materials used by Ranger were seven parts gravel and sand mixed together with one part Dorking lime and one part and a half of boiling water. Wooden formwork and centering were used to construct the vault.[13] (See Figure 27).

The test model stood up well under bombardment notwithstanding the fact that the arch had already cracked because of inadequate foundations on the marshy soil and even though the core of the structure was still soft (lime concrete used in Ranger's process was quick setting but very slow in hardening). Harding reported on the expense of the project that "concrete in foundations may generally be formed at one-third, and in arches and walls at less than half the cost of brickwork."[14] He therefore was prepared to recommend that Ranger's concrete be adopted in arches by virtue of its strength and economy although he was doubtful about using it for the core of brick piers because of the difference of compression and expansion in the two materials. He also concluded that a 4 foot thick arch of concrete would be bombproof and that the material could be used with safety in small magazines and casemates. For large magazines it would have to



The uprights a a a were placed about 2½ feet from centre to centre.

NB The joints of the arch at bb &c were successively secured for the reception of the Concrete of each Voussoir. The Voussoirs (excepting the 1st) were filled in one thickness from top to bottom, but in 3 parts of the length of each, the parts being separated during the building, like the joints, by rough frame work secured to the centre and side boarding. The Nos shew the order in which the courses succeded each other, the 2 courses 22 & 23 formed the key of the arch.

Figure 27 Method of Constructing Harding's Concrete Model Casemate, 1835 await further experiments to see how far dampness would affect it and whether a large mass would harden more and with greater consistency over time. Harding pointed to the advantages of concrete as a quick way to repair damage to fortifications under an enemy's fire as well as a cheap method of building parapets, counterscarps and other works. In short, Ranger's concrete was for Harding an economical, durable and tactically advantageous way to build fortification superstructures.[15]

No evidence has been found that Harding's recommendations were accepted and implemented. It is most likely that Pasley, as Director of the Royal Engineer Establishment and acknowledged expert in the Corps on limes, cements and concrete, advised the Board of Ordnance against the adoption of concrete for above ground works, if not directly, certainly by his well known publication of 1838. Pasley strongly preferred brick laid in cement mortar and coated with cement because he believed by experiment that this construction was superior in both strength and anti-dampness.[16] Harding had been commissioned in 1802 and had served in the Napoleonic Wars and later as Commanding Royal Engineer at Woolwich where, except for his 1835 experiment, he appears not to have had much to do with testing and employment of advanced building technology.[17] The Royal Engineers' interest in concrete for fortification superstructures was to remain dormant for two decades following Harding's experiment in collaboration with Ranger.

The leading advocates in the Corps for a reassessment of concrete were Francis Fowke and Henry Scott. Fowke's interest in concrete appears to have been stimulated while he was serving as secretary of the British delegation at the Paris International Exhibition of 1855. As part of his responsibilities, Fowke prepared a report entitled <u>On Civil Construction</u> and in it described an exhibit of Francois Coignet's concrete (beton pisé). As mentioned previously, Coignet had pioneered mass concrete construction for building superstructures, beginning in 1852 with his celebrated factory at St. Denis in France.[18] Fowke explained that the new material had been used in a house near St. Denis and that it had "excited considerable interest in Paris."[19] He went on to describe Coignet's formula and process for making concrete and the manufacturer's claims for the durability, strength and economy of his product. Fowke was decidely impressed and commented:

> "If all these statements as to cost, &c, are correct, the material of M. Coignet would appear worthy of being further inquired into, as it would seem to afford a means of construction at a price hitherto unheard of."[20]

In the summer of 1856, Fowke was appointed an inspector for the Science and Art Department but continued to take an active part in the Royal Engineers' discussions concerning building technology and fortification. About 1860 Fowke wrote a paper advocating experimentation with concrete construction for revetments using the technique of pouring concrete in between a formwork of boards as in pisé work practice of Southern Europe. He argued for the advantage of concrete as a monolithic material where the destruction of part of a revetment wall by enemy artillery would not cause the collapse of the whole necessarily. Fowke also thought savings would be achieved in the use of concrete as a substitute for brick and stone masonry only at a large scale where the building process was systematized to the point where it was reduced to machine work. Fowke's paper was circulated in the Corps by the Inspector General of Fortifications.[21]

Fowke himself experimented with concrete for building superstructures, although in a few minor projects only. Scott indicated in 1862 that Fowke had built two or three hut-like structures of mass concrete using the pisé work technique, one of which was a dry powder magazine for the South Kensington Volunteers.[22] Also, in 1861 Fowke built a rustic entrance lodge-cum-guardhouse of concrete for the South Kensington Museum.[23] Concrete had been used for fireproof floor construction from the 1840's, and Fowke's attitude toward this practice is interesting. Evidently he was not generally confident that Messrs. Fox and Barrett's concrete encased I beam fireproof floor system could be used with safety in fortifications. In a proposed design for an arms storehouse in 1858 Fowke rejected the Fox and Barrett system and chose instead to develop a modified form of the conventional brick arch floor which he also recommended for use in roofing magazines, casemates and other defence works.[24] Fowke apparently counselled prominent citizens on building in concrete. The Builder reported that he advised the Marquis of Salisbury in the use of the material for the construction of a chapel and some labourers cottages on the latter's estate at Hatfield in 1862.[25]

Scott's advocacy of concrete during his career as an instructor at the Royal Engineer Establishment has been reviewed in Chapter 2. Essentially, Scott reinforced Fowke's earlier promotional efforts by offering 'scientific' evidence in support of the strength and durability of the material and examples of its successful use in building superstructures.[26] In a lecture at the Royal Engineer Establishment in March 1862, Scott offered a design for a cellular revetment in concrete (see Figure 28). Like Fowke as well as Harding almost thirty years earlier, Scott stressed not only the strength and economy of concrete but also its military advantages:

> "I believe that the weight of evidence is so much in favour of the strength and cheapness of concrete, when compared with brickwork or large stone masonry, as to justify extensive trials of it in fortification works and I think that the formation of a breach in a cellular revetment, such as I propose, would occupy sufficient time to confute the notion that a revetment should be regarded only as a method of retaining the pressure of earth behind it, and of keeping a work secure against surprise."[27]

No evidence has been found that Scott's particular cellular design was adopted by the War Office for revetments. All the same, it is not surprising that the first large scale fortification works in mass concrete above foundation level in Britain were undertaken only three years after Scott's lecture and that he should be involved. The project was

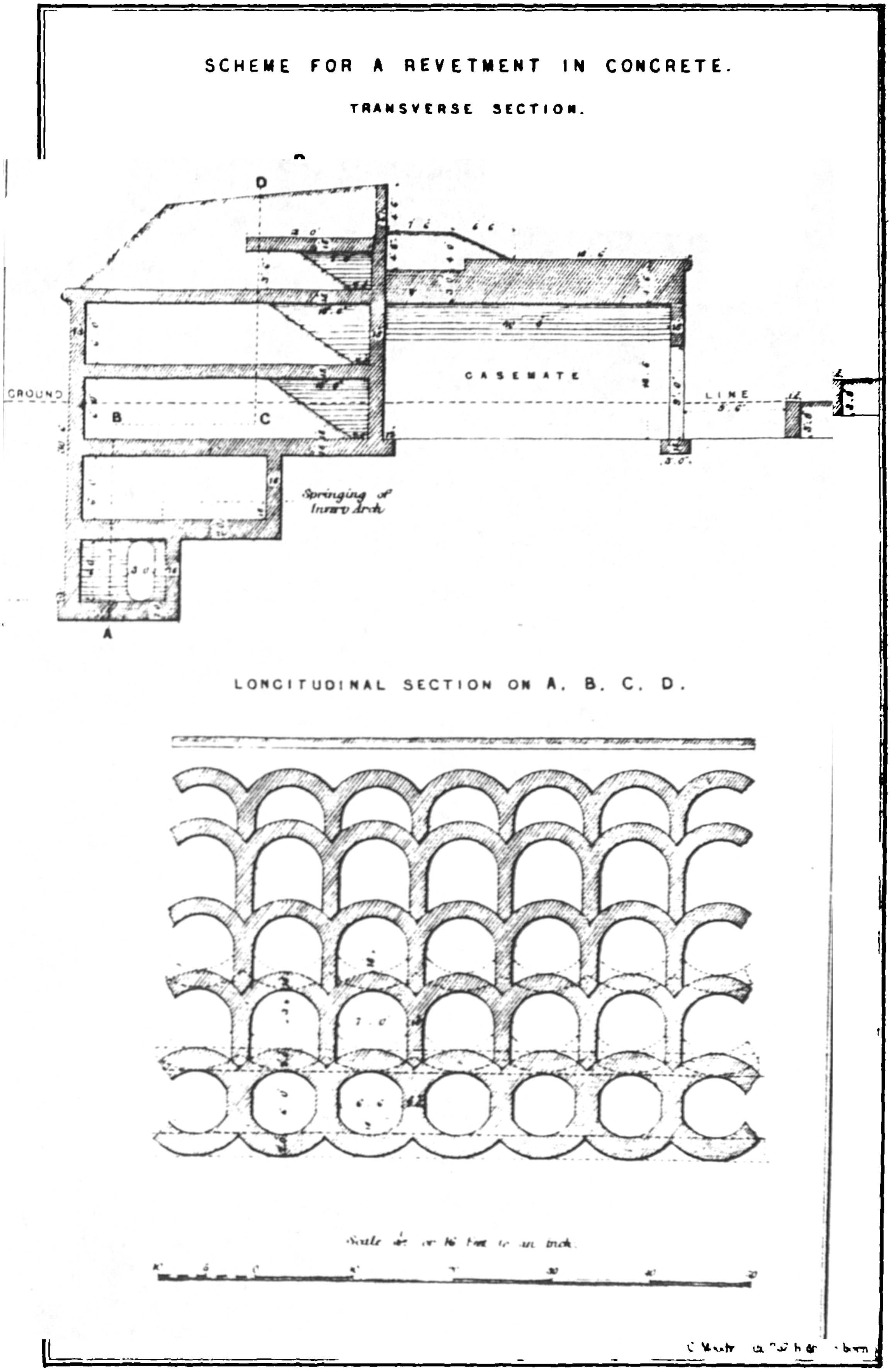


Figure 28 Scott's Proposal for a Revetment in Concrete

the revetments of the new coastal fortifications at Newhaven constructed as part of the Commission Forts programme.

While Newhaven Fort was the earliest major use of mass concrete for fortification superstructures in Britain, it was not the first time the Royal Engineers had used the material on a significant scale for above ground works. This distinction appears to have been won a year before by the engineer officers stationed in Nova Scotia. Portland cement concrete was used in the construction of an escarp wall at Fort Ogilvie, one of the outlying defences of Halifax harbour, in 1864.[28] It was an important early use of the material in North America and a full discussion of the project is presented in Chapter 8. The story of the revetments at Newhaven Fort, however, is perhaps the most revealing case study of the attitudes of the Corps and the War Office towards the use of mass concrete in the Commission Forts era.

Early in 1864, experiments were carried out under Lieutenant Colonel Sir Gerald Graham (1831-1899), Commanding Royal Engineer at Brighton, on a variety of limes and cements to determine which material was best for mass concrete revetments proposed for Newhaven Fort. Tests were performed to ascertain resistance to crushing and adhesive strength as well as the breaking weight of moulds and bricks of each material. Graham worked closely with Henry Scott who was present at many of the experiments. Scott's cement was one of the materials tested and it was to be selected for the concrete used at Newhaven Fort.[29] Graham had been commissioned in 1850 and had received the Victoria Cross for distinguished service in the Crimean War. Afterwards he had served in Scotland and as Commanding Royal Engineer at Lucknow in India (1858) and at Canton and Hong Kong (1859-1860). On returning to England in 1861 Graham was Commanding Royal Engineer at Shorncliffe and Brighton. In 1865 he was transferred to Aldershot. Nothing in Graham's experience prior to the building of Newhaven Fort indicates he had a particular expertise in permanent fortifications or in work with cements and concrete. His initiative in undertaking experiments with Scott is a mark of the versatility of engineer officers.[30]

Newhaven Fort was designed by Lieutenant Sir John Charles Ardagh (1840-1907) and constructed under his supervision in 1865. Ardagh was commissioned in 1859 and had initial duty in the construction of new forts at Pembroke naval dockyard as part of works under the Defence Act of 1860. In 1862 he was stationed in New Brunswick, Canada to construct a telegraph line. On his return to England he served at Chatham and then in the Southern District where he was employed in building forts at Spithead and the Isle of Wight. Ardagh was one of the Corps' most qualified young officers to engage in innovative fort construction in concrete. He had trained under Scott at the Royal Engineer Establishment and had nearly five years experience in new military works. By 1868 his skill in fortifications was well recognized and he was selected to serve as secretary to the Committee Appointed to Enquire into the Construction, Condition and Cost of Fortifications Erected or Under Construction. The next year he accompanied Jervois on a tour of inspection of forts at Halifax, Nova Scotia and Bermuda. In 1871 he was posted to Malta but three years later was appointed to the War Office Intelligence Department where he was to have a distinguished career for the next thirty years but was no longer involved in building.

Mass concrete was used at Newhaven Fort in almost all the revetment of the ditches, totalling some 20,000 cubic metres.[32] Accommodation and storage space in subterranean casemates was constructed in conventional brickwork.[33] Scott's cement was used for the concrete. The Royal Engineers' experience on Scott's cement in comparison to Portland cement had proved the latter to be considerably stronger but Scott's was probably selected because it was cheaper and had been tried already as mortar in various military works (see Chapter 2). Scott's cement was obtained from Messrs. Rickman at Glynde, near Lewes.[34] Part of the reason for selecting concrete for the revetments was the large accumulation of shingle at the base of the cliff upon which the fort was sited which provided a readily available source of aggregate and added therefore to the economy of the material over brick.[35] The specification called for one part coarse, sharp sand, six parts ballast, shingle or flint, to one part of Scott's cement. It was laid in courses 1 foot high and rammed, with care being taken to prevent large stones from coming to the surface which was a problem with the large particle size aggregate used in contemporary concrete. The revetment was drained by a 3 inch agricultural pipe jointed in the concrete. Twenty-nine batches of Scott's cement concrete were tested before use and "proved superior to brickwork as a material for construction of retaining walls, being 40 per cent heavier, and more than twice as strong."[36] Hamilton-Baillie has shown by laboratory analysis of core samples (1978) that the counterscarp was in a weaker material than the scarp.[37] The counterscarp was begun in March 1865 and the scarp the following June.

About the middle of November 1865, the counterscarp began to show vertical cracks. Ardagh undertook tests using tell tales to measure changes in crack width during the summer and winter months and the results led him to rule out the cause of cracking as poor construction or subsidence. He was inclined to attribute it to thermal expansion and contraction. In view of his analysis, he recommended that the revetment walls be cut through at some points of fracture and dry-tongued brickwork built in on each side to allow for movement. Ardagh was interested in further experiments to determine the precise amount of linear dilatation caused by temperature change and if different materials in concrete would have a marked influence.[38] The concrete cracking problem was also due no doubt to shrinkage as well as thermal movement - cracks were worst where exposed to the sun showing the aggravation of the failure by lack of curing.[39] Despite this, the work was sound and durable - 115 years later it was described by an expert as still serviceable.[40] (See Figure 29)

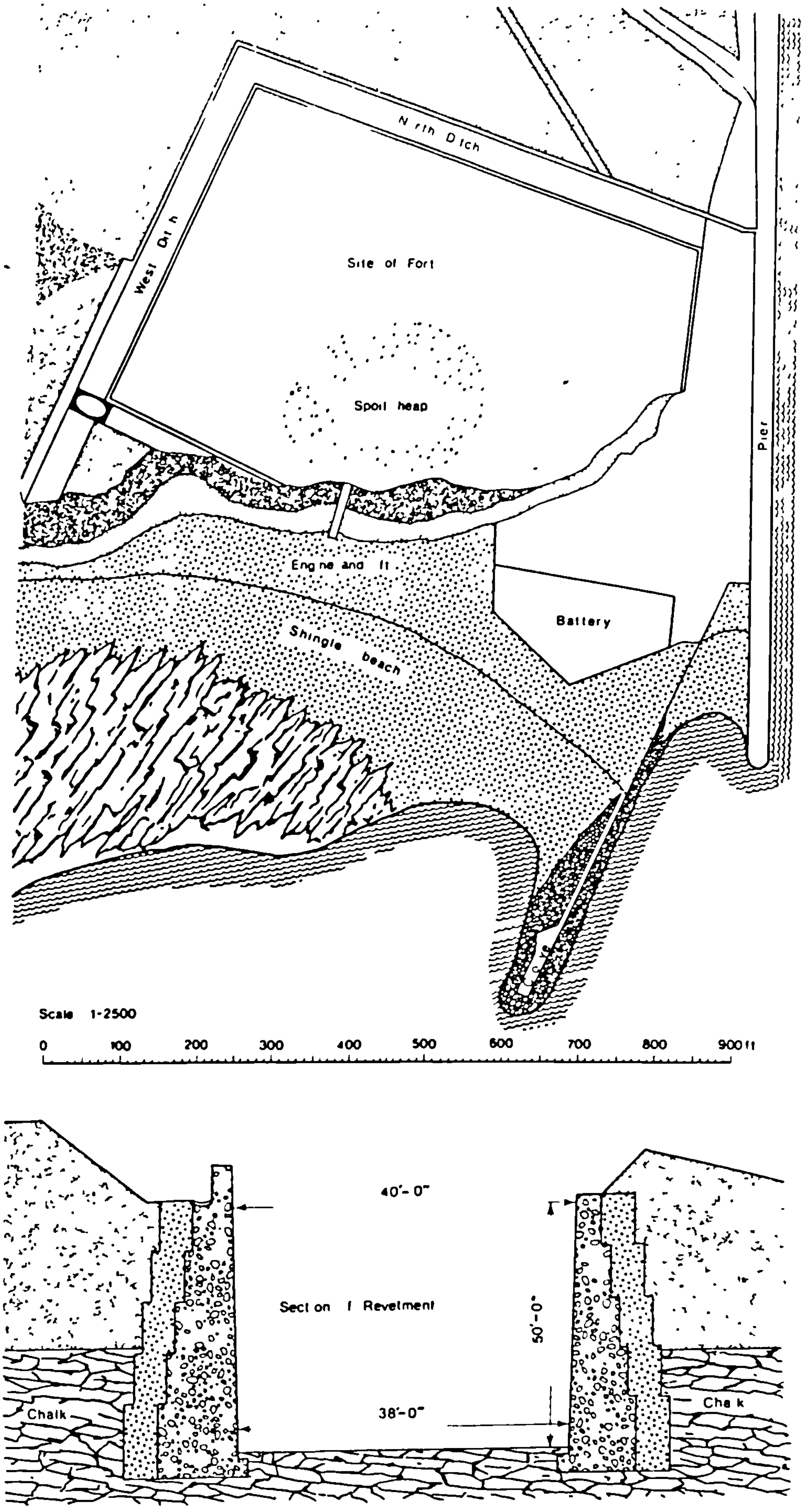


Figure 29 Plan and Section of Newhaven Fort, 1865

The Newhaven Fort experiment with mass concrete did not lead to widespread use of this method of construction in the Commission Forts. It is significant that the experiment was tried at Newhaven which was in a relatively safe location and had only a minor coastal battery and not at Portsmouth, Chatham or Dover which were large scale strategic works.[41] The probable motivation for the trial of concrete in fortification superstructures was the escalating costs of the Commission Forts programme. Jervois reported in February 1867: "... since 1862 labour costs have risen 15 per cent and ... some materials, more especially granite, have, owing to great demands for this stone for fortifications and other work, risen in price."[42] Ardagh's experiment proved in convincing fashion that mass concrete was a considerable economy. As he explained:

> "The economy of using concrete instead of brickwork is very great. In the case of Newhaven, the contract price of brickwork, per rod, is £8 5s. That of concrete, in Scott's cement, is per yard, 5s 10d, or £3 6s per rod. When additions for labour to faces, cuttings, splays, pointing, etc. are made to the brickwork, its cost is raised to nearly three times as much as concrete."[43]

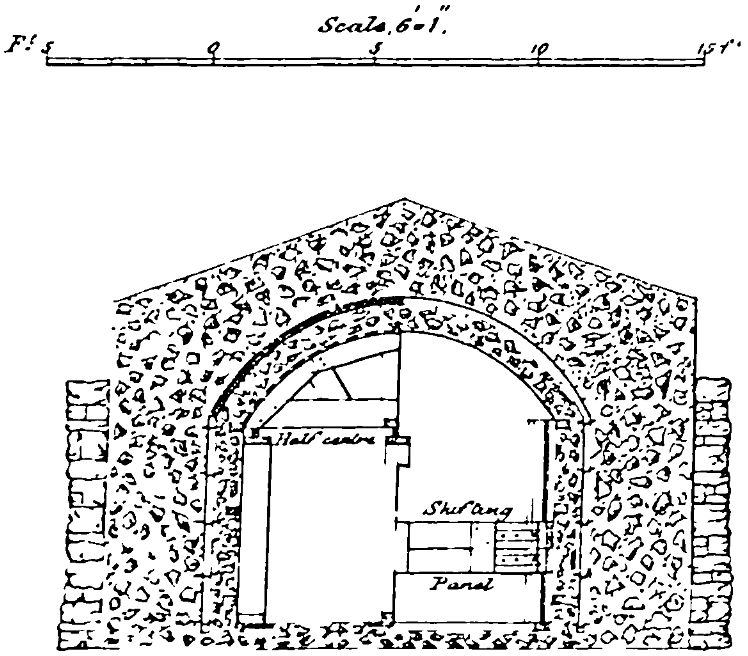
The fact that the War Office did not use the Newhaven experiment to introduce mass concrete on a wide scale is therefore somewhat puzzling. No hard evidence has been found to explain this conservatism but one possible reason may be the character of eighty-three year old Sir John Fox Burgoyne, Inspector General of Fortifications, the Royal Engineer in charge of the Fortifications Department of the War Office. Burgoyne had long been a friend and colleague of Pasley. Perhaps he was too accepting of Pasley's decided opinion against concrete in superstructures to change in favour of the views of the much younger Scott, forty years Burgoyne's junior. An example of Burgoyne's conservatism in old age was his reluctance in 1860 to let Harness reform Pasley's thirty-four year old architectural course at the Royal Engineer Establishment (see Chapter 1). Nevertheless, it seems reasonably clear that the Corps was divided in its opinion of exposed concrete above foundation level, from the 1830's well into the 1860's. Harding, Fowke, Scott, Graham and Ardagh were advocates and Denison a qualified one after initial scepticism. Pasley was the unwavering foe of concrete in building superstructures but even he softened his view by the mid-1840's to allow the material might be used in marine works underwater. The conservatism of the War Office on concrete therefore did not reflect the unanimous opinion of the Corps. Indeed, one might argue that it was contrary, although one rarely knows what the silent majority thought.

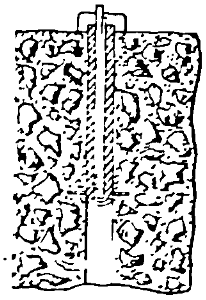
In the early Commission Forts of the 1860's concrete was used in conventional, well-tried ways - for a seal to brick casemate arches, for floors in magazines, in foundations, for bombproofing works from plunging fire and other minor applications. It was not expected at this stage to resist direct artillery fire.[44] The most extensive use was in Portland cement concrete blocks for the foundations of the great iron coast forts of Plymouth Breakwater, Spithead (Portsmouth) and Portland Breakwater. These foundations were massive rings of stone work in the sea bed executed by engineering contractors and filled in with concrete blocks by the Royal Engineers afterwards.[45] In the foundations of Horse Sand and Norman forts at Spithead, for example, 15,000 tons of concrete blocks weighing 3 to 7 tons each were used.[46] Horse Sand Fort foundation was planned and constructed under the direction of John Hawkshaw and his assistant Harrison Hayter.[47] The contractor was J.T. Leather, who also built Gilkicher and St. Helen forts foundations as well as the superstructures of the Spithead forts (completed 1872) directly under Royal Engineer supervision.[48] Leather was also contractor (in partnership with G. Smith) for the great extension works at Portsmouth naval dockyard (1867-1870's) under Lieutenant-General Clarke where Portland cement concrete was used extensively.

One of the notable Royal Engineers directly involved in the construction of these works was Captain William Innes (1841-1875). Commissioned in 1858, Innes worked initially under Du Cane on the Commission Forts at Dover (1859-1862) and designed Fort Burgoyne there. He spent the next five years in Halifax, Nova Scotia, where he designed harbour defences at Point Pleasant and George's Island which were regarded as much in advance of the time. Portland cement was used in part of the works. In 1867 he was assigned to the construction of the Spithead forts and later to similar works at Portland the next year. As a result of his experience with these works, Innes contributed an article to the Royal Engineer Professional Papers in 1873 on the supply, storage and testing of Portland cement. He had been appointed Assistant Colonial Engineer of Straits Settlement the year before. Innes was elected an Associate of the Institution of Civil Engineers in 1869 and was a regular attendant at the Institution's meetings. He was considered a most promising professional by both civil engineers and the army but he met an early and tragic death while leading an attack during the Malay uprising of 1875.[49]

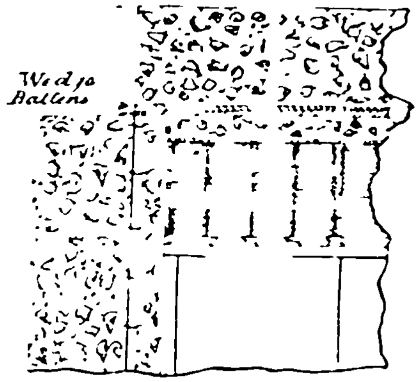
The Corps' first large scale use of Portland cement concrete for fortification superstructures in the British Isles appears to have been in the defences of Cork Harbour (c.1873).[50] It was used there, for example, in sea walls, casemated batteries and in dwelling houses.[51] These houses or huts were constructed with concrete in hollow walls. In 1874, Major J.P. Maquay, who had been involved with the works at Cork, illustrated in the Royal Engineer Professional Papers a method of making hollow walls and an arch of concrete for a powder magazine (see Figure 30).[52] The Chatham ring of land forts, begun in 1876 but not completed until the mid-1890's, were built primarily of Portland cement mass concrete. Casemates and tunnels still had conventional brick walls but with concrete arches.[53] It was not until 1877 at Shoeburyness that the British military undertook the first trials of mass concrete's resistance to rifled ordnance but General Joseph Totten of the U.S. Corps of Engineers had performed artillery fire tests at West Point, 1852-1855, on targets simulating casemate embrasures of concrete and his report was published in the Royal Engineer Professional Papers in 1860.[54] By 1885 concrete was preferred over granite masonry

SKETCH SHEWING METHOD OF MAKING HOLLOW WALLS AND ARCH FOR AN EXPENSE POWDER MAGAZINE.

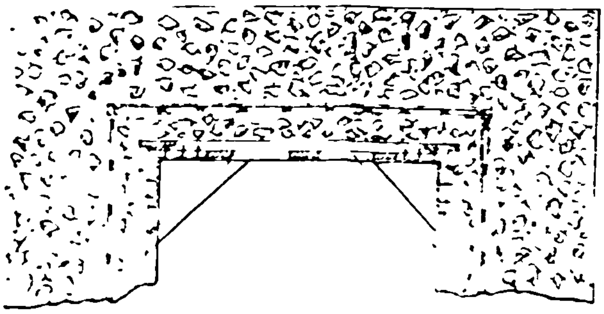




Detail of Hollow Wall in progress Scale ½"=1'.



Section shewing casing [illegible] for inner arch, and wedge [illegible] hollow space [illegible]



Plan of Panelling for inner walls and planks for hollow spaces

Figure 30 Concrete Magazine Construction, c. 1870 in fortifications because it confined damage of high velocity projectiles to the impact point whereas granite shattered and its courses dislodged.[55]

The adoption of mass concrete by the Royal Engineers in fortification works was certainly not a pioneering achievement. Indeed, they were slower to embrace the new material than the U.S. Corps of Engineers who had used natural hydraulic cement concrete for both foundation and superstructure work in forts Richmond and Tomkins in New York harbour from 1859.[56] By 1870 General Quincy Adams Gillmore was using Portland cement concrete for magazines and other fortification works on Staten Island, New York.[57] Mass concrete for fortifications was also introduced at that date in Denmark.[58] Essentially, the Royal Engineers followed the cautious approach to mass concrete manifested in the construction of civil works by the private sector in Britain, during the late 1860's and early 1870's.[59] Moreover, the War Office was no more conservative about concrete than civil authorities. The Metropolitan Board of Works did not include formal references to the material in its bye-laws until 1885.[60]

Asphalt in Military Works

Asphalt is one of the unsung new materials of the early nineteenth century. It was used in building as a waterproof material for roofing, flooring and for coating and bonding brickwork. The Royal Engineers were reasonably quick to recognize its potential merits, experiment with it and then put it to regular use in fortifications. Prevention of dampness was critical for both the storage of munitions and the health and comfort of soldiers.

Asphaltic rock deposits had been known in France from the early 1700's but until the end of the century they were generally mined only for the extraction of bitumen.[61] There were a few exceptions, however, and in 1743 Buffon used asphalt for lining large basins in formal gardens, including one for the gardens of the King of France.[62] Nevertheless, it was not until the outset of the nineteenth century that a material known as 'asphaltic mastic' began to be manufactured in the Pyrimont district of France near Lyssell.[63] This material was produced from a naturally occurring asphaltic rock, a pure carbonate of lime impregnated with bitumen. It was pulverized into a powder and mixed with heated mineral tar and clean gravel to reduce it to a suitable state for pouring into moulds where it was formed into blocks for sale. The initial use of the product was in paving footpaths. Blocks of asphalt were broken into pieces and melted in an iron pot. When it had attained the proper constituency, the molten asphalt was ladled out and poured on the spot to be covered, and small stones or powdered lime or chalk sifted evenly over the surface while the material was still hot.[64] The French asphalt industry was well established by the early 1830's and the product was soon taken up by the nation's military. In 1838 Pasley noted that the Director of the Royal French Atillery at Douai and several officers of the French Engineers had testified to the efficiency of asphalt for paving and floors. He also indicated that asphalt had been used in the extensive roofs of buildings in the Artillery Arsenal at Douai. A plain tile roof covering had joints filled and tiles bonded together by asphaltic cement. The tile roof was then covered with canvas, a coat of asphalt applied over it and sifted gravel beaten on top.[65]

The best known of the early nineteenth century asphalts in England was Claridge's Patent Seyssel Asphalte. Claridge obtained a British patent for his product in 1837 after a trip to France to investigate the novel asphaltic mastic used in that country. Claridge imported the asphaltic rock from Seyssel in the Jura Mountains. The patent was for "a Mastic Cement or Composition applicable to Paving and Road making, covering buildings etc", and the product manufactured at Claridge's works in Stangate, London, came in three different grades.[66]

In 1838 an article in the Minutes of the Proceedings of the Institution of Civil Engineers described asphalt's weatherproof qualities: "It may be considered as a species of mineral leather. The sun and rain do not appear to have any effect upon it."[67]

Apparently, at that time it could be laid for 8p to 9p per square foot.[68] Pasley reported in the same year that asphalt was being used on part of the Greenwich railway and as a foot pavement in many metropolitan parishes as well as in Liverpool.[69] He also indicated that Robert Smirke had given asphalt a trial and considered it better for covering vaults, protected from the sun by a sufficient thickness of rubbish, than for the flat roofs of dwelling houses which did not admit of being so loaded.[70] Pasley's own view of asphalt was that it would no doubt prove useful but that further experiments were needed lest over enthusiasm lead to its application in circumstances where other materials were better, and like concrete some years earlier, it prove not to be as suitable as traditional brick and stone.[71]

In 1839 Captain Denison, in his capacity as editor of the Royal Engineer Professional Papers, commented on an article in the journal describing the use of asphalt by the French military to cover the roofs of two model towers for defensive guard houses in coast batteries:

> "The material lately introduced into this country will probably be found of great service in covering the platforms of bomb-proof towers and the arches of powder magazines. It is perfectly waterproof, and its elasticity will enable it to resist the shock of a shell, which the best cement can hardly be expected to do."[72]

Denison was displaying here his typical enthusiasm for novelties. As mentioned in Chapter 4, four years later, while in the service of the Admiralty, he proposed to let a contract to the Asphaltic Company to cover some shed roofs at Woolwich naval dockyard but changed his mind after inspecting the performance of the material on some roofs at the Deptford yards where asphalt presumably had been specified by his predecessor, G.L. Taylor, Civil Architect to the Admiralty.

The Royal Engineers probably used asphalt from the late 1830's but the first documented evidence of its employment by the Corps found in this study was by

Surveyor-General of Prisons, Lieutenant-Colonel Joshua Jebb, in Pentonville Prison (1840-1842), for floors, footpaths and roads.[73] Its initial use in fortifications appears to have been in the roofs of casemates, and the earliest experiment was in Canada. In May 1841 the Board of Ordnance approved a proposal for covering the terreplein of casemated ramparts at Fort Henry in Kingston, Ontario. It called for the space over the casemate to be filled in with rubble stone and over this fine stone covered by asphalt. Thirty-five tons of asphalt with implements for applying it were dispatched to Canada later that year. The supply was Bastenne Mineral Bitumen or Mastic from the Bastenne Company and it cost £4.8.0 per ton. This was unusual since Claridge's Patent Seyssel Asphalte was used almost universally by the Royal Engineers in Canada in their later work.[74] The engineer officer responsible for this experiment was Colonel John Oldfield (1789-1863), Commanding Royal Engineer in Canada, 1839-1843. Oldfield explained in a memorandum of 1848 which was later published in the Royal Engineers Professional Papers that he had heard of the use of asphalt in covering arches and for other purposes and decided to give it a trial at Fort Henry to remedy a dampness problem in the rampart casemates. According to Oldfield, the work was executed in the autumn of 1842.[75] In this experiment the asphalt was exposed directly to the atmosphere and during the following winter it cracked in the frost. The new material had failed its first test in Canada as a cure for casemate dampness. Royal Engineers were to continue to experiment with asphalt in British North America throughout the 1840's and 50's in an attempt to find successful methods of applying the material in a country with decidedly colder winters than England. This story is an outstanding example of the Corps' transference and adaptation of building technology to colonial environments and is discussed fully in the penultimate chapter.

Oldfield had not been unfamiliar with the climate of British North America. Commissioned in 1806, he had served in Halifax, Nova Scotia (1807-1809) and as

Commanding Royal Engineer in Newfoundland (1830-1835) amongst his several postings prior to becoming Commanding Royal Engineer in Canada in 1839.[76] Oldfield's unsuccessful experiment with asphalt at Fort Henry did not discourage him from trying it again, but this time it was after his return to England. As Commanding Royal Engineer of the Western District (1843-1848), Oldfield made extensive use of asphalt for waterproofing in the Plymouth Citadel and harbour defences in a variety of applications. His first experiment was in June 1846 to damp-proof some one hundred year old casemates in the citadel. Asphalt was used to cover the casemate arches and the trial was considered a complete success.[77] As Oldfield explained, these casemates were "previously uninhabitable *from damp*" but since the application of asphalt "not a drop of water has been admitted through the arches."[78] The material for this initial experiment and all subsequent work was supplied by the Asphaltic Company, the same firm which Denison considered for a roofing contract at Woolwich naval dockyard.[78] In 1848 Oldfield undertook further experiments on asphalt pursuant to orders from the Board of Ordnance. These concerned the strength of fort embrasures where the brickwork was bedded and jointed in fluid asphalt. Thirty-two pounder guns were fired at an experimental battery of asphalted brickwork and it withstood the bombardment, unlike an old rubble masonry embrasure also tested which was completely shattered.[79] Both asphalt covering for arches and asphalted brick were used by the Corps in casemate construction in the 1850's (see Figure 31).

Oldfield's Memorandum on the Use of Asphalte of 24 March 1848 was adopted by the Board of Ordnance as the model for the application of the new material in fortifications. Copies were sent to the Commanding Royal Engineers in the Medway District, in Ireland and in Nova Scotia and, as mentioned earlier, the memorandum also appeared in the Royal Engineer Professional Papers in 1853.[80] In the preface to the memorandum Oldfield remarked: "... almost every District having brought forward different methods of staunching arches of Towers etc ... it appears

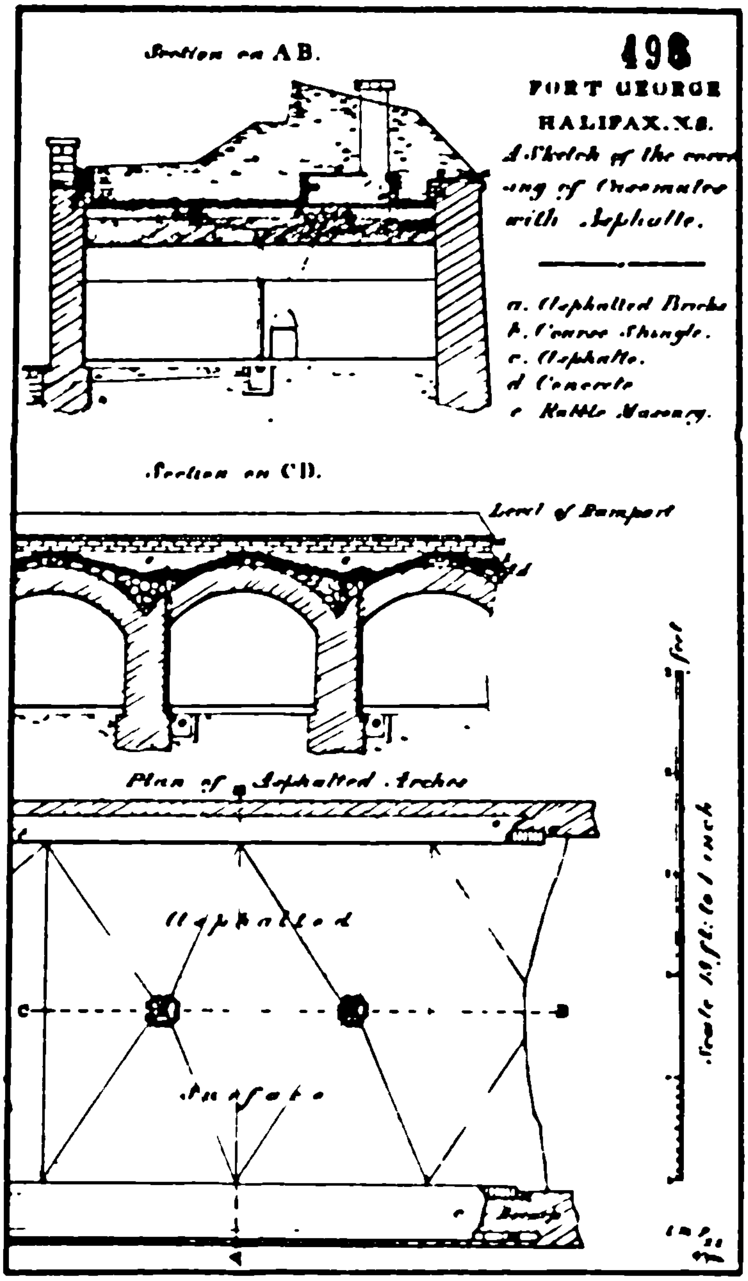


Figure 31 Asphalt in Casemate Construction, 1850's

desirable that a system which has been found to answer should be as far as possible adopted."[81] He outlined the range of applications for the new material and in a fashion characteristic of engineer officers cautioned that the key to success in the use of asphalt was rigorous supervision, discerning choice of materials and thorough testing:

> "From what I have seen of the use of the Seyssel asphalte, I am of the opinion that, if the materials and workmanship are unexceptionable, it is most efficient for covering of arches, and the floors of tanks, abulation rooms, stores and many other barrack buildings; but the slightest deficiency in workmanship or materials will cause a failure. The efficiency of the asphalte should be *severely* tested in every possible way before it is extensively adopted *in service*."[82]

Oldfield deserves credit for his perseverance in experimentation with asphalt and his insistance that a 'scientific' approach be employed. Whilst asphalt was an important new product for waterproofing masonry construction, it was not foolproof. The engineer officers in British North America were to experience especially difficult problems with it and the material was to have some undesirable side effects in England in subterranean powder magazines.

By the era of the Commission Forts it had become common practice to seal from rain casemates, magazines and some other fortification buildings by applying a coat of asphalt over the roof and covering it with a thick layer of earth. The material was also used in the floors of these buildings over concrete filled brick arches as a rot-proof alternative to wood and to provide additional head room by the elimination of wall plates, joists and floor boards.[83] Nevertheless, the Royal Engineers continued to struggle with the dampness problem in magazines and casemates, particularly those in subterranean conditions. The cause was condensation. Various techniques were tried to cure condensation by improving ventilation, including hollow brick walls, ventilating passages to normalize temperature by the inflow of outside air or simply opening the doors.[84] Lieutenant Innes undertook extensive experiments at Halifax, Nova Scotia, in 1867, on the ventilation of magazines by the systematic opening of ventilating passages during the summer months.[85] Lieutenant Home in his study of the construction of magazines in 1863 concluded that the impermeability of asphalt roof coverings was a contributing factor to dampness caused by the drying out of green brickwork in newly built magazine chambers. He proposed the construction of brick cavity walls along with perforated bricks and ventilators as a solution. Home also thought the use of Scott's cement for mortar and concrete would help because it became dry very rapidly.[86] Some Royal Engineers objected to asphalt floors in subterranean magazines because moisture condensed on the surface. In a memorandum of 1869 Lieutenant Ardagh, then secretary of the Committee Appointed to Enquire into the Construction, Condition and Cost of the Fortifications Erected or Under Construction, argued in favour of asphalt, notwithstanding its problems:

> "It has been objected to, on the ground that moisture condenses on the black surface, but if it be whitewashed, and the ventilation of the magazine properly attended to, this will not be the case; and taking the most unfavourable view, it is preferable that moisture should be deposited on asphalte, which it cannot injure, and where it can be easily dried up, than on timber, in which it soon induces decay. It would therefore appear desirable to use asphalte in lieu of timber floors, in all subterranean buildings."[87]

Asphalt was certainly not a panacea but the Royal Engineers demonstrated a progressive attitude in its use, fully recognizing the material's limitations.

Iron in Fortification

The use of iron in fortifications was not particularly significant in structural history and had very little, if any, impact on civil architecture. Iron was used as armour for coastal forts against powerful projectiles from the rifled guns of ironclad, screw propelled warships. It was employed in two forms: in shields for masonry fort embrasures; and in situations where it was necessary to place a fort in a strategic waterway where shore batteries' fire could not close the gap, in iron superstructures consisting of a skeleton frame clad in an iron skin supported on a solid masonry foundation ring of stone and concrete. The former was arguably not a part of the story of building technology at all; the latter was a highly expensive business and was restricted to four totally iron works (Plymouth Breakwater Fort, No Man's Land and Horse Sand forts at Spithead and Portland Breakwater Fort) and three cross breeds of masonry landward and iron seaward (St. Helen's and Spitbank forts at Spithead and Fort Cunningham, Bermuda). Both shields and iron forts were related directly to the development of armour in warships and this effected a close working relationship between the Admiralty and the two branches of the army 'scientific corps' - the Royal Artillery and the Royal Engineers. Indeed, the ever advancing power of rifled ordnance forced the Royal Engineers to play a game of technological leapfrog with the Royal Artillery and the Royal Navy. This contest also enlisted the skills of ironfounders and civil engineers and was influenced by the experience of foreign military engineers.

Wrought iron was the material employed and the military use of it was informed by thirty years of development in railways and civil construction which produced improvements in its manufacture and reduced the cost sufficiently that it was possible to consider it as a substitute for stone in some fortifications work. Some Royal Engineers felt that the collaboration of the military with the manufacturers in producing wrought iron plates for armour of forts and warships helped to raise the quality and size, and decrease the cost of the material.[88] Nevertheless, the use of iron in fortifications was a latecomer by the Royal Engineers' own estimation. As their leading expert on the subject testified in 1862:

"... fortification is about the only branch of engineering in which the use of iron has until now been completely neglected."[89] What is interesting and important, however, about iron in fortification is the process of technological adaptation in a highly specialized and very short lived form of building in the late nineteenth century.

The Royal Engineer most responsible for the development of iron technology in fortifications was Lieutenant-Colonel Thomas Inglis (- 1888). Commissioned in 1843, Inglis served at Woolwich and in Ireland until 1847 when he was posted to South Africa where he fought in the Kaffir War (1850-1853). On his return to England in 1853 he was put in charge of works at the new arms factories at Enfield and Waltham Abbey. In 1857 Inglis was appointed Inspector of Works of the Manufacturing Departments in the office of the Inspector General of Fortifications. His responsibilities included Woolwich Arsenal, Waltham Abbey Powder Works, Enfield Gun Factory, Pimlico small arms and clothing establishment and works at the experimental stations at Shoeburyness and Purfleet. Inglis served the Special Committee on Iron appointed by the War Office in 1859 to investigate the question of armour for forts and warships. He investigated several subjects for the Committee at Woolwich Arsenal and arranged many of the Committee's experiments at Shoeburyness.[90] From 1857 to 1884 he was present at nearly every experiment conducted on guns versus armour at Woolwich, Shoeburyness and other army and Admiralty facilities. In 1867 he was appointed Inspector of Iron Fortifications in the War Office and was in charge of all work that was done in that field. Inglis decided designs of shields and the iron forts at home or foreign stations, superintended their construction and dispatched iron materials to their destination. He was assisted throughout his career in iron fortifications by Lieutenant Thomas English who succeeded him upon his retirement in 1884 as Inspector of Iron Fortifications.[91] In 1881 The Engineer said of Inglis that on armoured defences he was "probably the best authority on the subject in this or any other country."[92]

The first recorded experiment in Britain on iron in fortifications was by Royal Engineer Major-General Ford at Woolwich in 1827. Ford encased a granite wall in iron bars and subjected it to 24 pounder cannon shot. The next experiments were not until 1846 when Colonel Colquhoun and Major-General Sandham tested wrought iron plates on fortifications at Woolwich Arsenal. During the period 1850-1854, the Admiralty undertook tests on wrought iron armour for warships using the '*HMS* Simmon'.[93] From 1852 to 1855 General Joseph Totten, Chief Engineer of the U.S. Corps of Engineers, performed experiments at West Point firing heavy ordnance at target embrasures with various facings and throatpieces of wrought iron (thin offset plates and thick single plate) and concluded that a thick single plate offered the best resistance.[94] In 1856 Sir John Burgoyne, Inspector General of Fortifications, recommended to the War Office that tests be undertaken on iron for both the external openings of fort embrasures and for warships.[95] Two years earlier Burgoyne had issued a circular calling for suggestions for improvements to embrasure design to better protect coast batteries from enemy fire. One of the responses was from Colonel Francis Ringler Thompson, Commanding Royal Engineer at Malta. He proposed a cast iron shield but did so with "some diffidence", expressing the view that experiments were needed "in order to obtain data for guidance in bringing forward schemes involving the use of iron in works of defence..."[96] Brittle cast iron was, of course, a dead end. In 1857 artillery fire experiments at Woolwich Arsenal shattered 8 ton cast iron blocks which had been tongued and grooved together and this convinced the military that this material was unfit for fortifications.[97]

Following Burgoyne's recommendation to the War Office in 1856, various armour plate experiments were undertaken over the next five years at Woolwich Arsenal by the Royal Engineers and Royal Artillery and at Portsmouth and Shoeburyness by the Admiralty. Tests were made by firing rifled ordnance projectiles at a variety of wrought iron and steel plate targets. These targets represented an extensive range of designs which employed different thicknesses of metal, some in single plates, others in laminated construction and one of rolled iron bars, tongued and grooved in horizontal layers. These were developed in collaboration with a number of different manufacturers and engineers including, for example, William Fairbairn and John Scott Russell. Perhaps the best known of the fort armour targets was the Gibraltar Shield, introduced in 1861. Two of the targets were model fort shields designed by Inglis and these proved satisfactory in the trials.[98] The Special Committee on Iron appointed in 1859, for which Inglis performed a number of tasks, reviewed the results of these experiments and reported in February 1863. It comprised William Jervois, Assistant Inspector General of Fortifications, and five others including William Fairbairn and William Pole from the private sector. In its report the Committee endorsed wrought iron over steel because it was softer and could absorb the impact of projectiles rather than crack or shatter: "We are still of the opinion that wrought iron of the softest quality is as yet the best material adapted for armour-plates; but as great progress is now being made in the manufacture of iron, it is possible that a superior quality of metal may eventually be produced."[99] Inglis was even more positive about wrought iron: "There is no material of such uniform and reliable strength, and so easily applied in any forms or dimensions, as good wrought iron..."[100] He felt an iron fort could be made "perfectly invulnerable", unlike traditional masonry ones, and that iron forts would be a saving because the material allowed a "reduction of bulk" and was lighter than masonry making it easier to establish foundations in problem soil conditions.[101]

By 1862 proposals for the design of iron forts began to emerge in the Corps. Inglis appears to have been the first off the mark. He suggested that in principle an iron fort should comprise a skeleton consisting of piers or columns of wrought iron boiler plate filled with concrete on which would rest wrought iron built up girders with wrought iron curved plates and concrete arch floors.

The roof would be a bombproof structure of wrought iron ribs with a skin of wrought iron plates and earth covered. In a fashion characteristic of the Corps, Inglis added a caveat about the need for further research:

> "Now, although so decided an opinion is here advanced as to the feasibility of these iron fortresses, it is not to be expected that any well-matured scheme can at present be given for one of them. It will be enough if a few general ideas upon the subject be thrown out for consideration of those who may be interested in it. The elaboration of these ideas must not be attempted without long and attentive study, guided by experience of a far more extensive set of experiments than has yet been made in this or any other country."[102]

One of those who took up the challenge of iron was Captain E.F. Du Cane, the officer under Jervois who had a hand in the design of the Commission Forts. In 1863 Du Cane proposed a structure consisting of iron pillars about 4 feet apart formed on the principle adopted in tubular girders composed of iron plates from 1 to 1 1/2 inches thick and 18 inches deep, connected by means of angle iron. Against this would be placed the iron facing which would be connected to the tubular girders by iron ties. He discussed the problem of bolt holes weakening the plates and called for experiments to determine how much play should be allowed in fastening the bolts to keep deflections under the force of projectile impact within safe limits. He also favoured interlocking plates to mitigate the problem of bolts.[103] Du Cane was clearly drawing on the legacy of the great experiments of the 1840's for the Britannia and Conway tubular wrought iron bridges and on over a decade of further experience using this technology for railway spans.

By 1864 little progress had been made in the construction of the Commission Forts. The lessons of the actions against coast forts in the American Civil War caused a brief re-examination of the concept of using masonry and iron. It was questioned whether it might not be a better idea to build earth covered forts since the

American experience tended to show their superior shot absorbing properties. However, the British military pressed on with its original idea. In the same year a Committee was appointed to examine the defence of Spithead and changes to the siting of coast and waterway installations were made. The War Office, however, continued to vacillate on the question of the design of iron in superstructures for the Spithead Forts mainly because of cost considerations. The Engineer commented: "If these forts are to fight iron ships ... they must be constructed either of iron or clothed with iron."[104] This journal expressed a preference for the latter. Meanwhile, Inglis was working with Messrs. John Brown and Company at the firm's Atlas Works at Sheffield in rolling large wrought iron plates for fort shields. On 30 September 1864 Brown succeeded in rolling a plate 6 feet wide, 7 feet long and 13 1/2 inches thick. The Engineer in noting this achievement commented: "The idea of manufacturing so enormous a plate originated with Captain Inglis, of the Royal Engineers, with a view to ascertaining if it would be desirable to protect casemates with such a powerful covering."[105] Five years later the Royal Engineers were to collaborate with Brown in an even greater achievement in plate rolling.

Sir John Brown (1816-1896) was a pioneer of rolled armour plate manufacture. In 1860 Brown had seen the French ironclad warship 'La Gloire', which had hammered plates, and he came to the conclusion that rolled plates may prove better. He soon attracted government support for his armour plate rolling experiments and by 1867 three-quarters of Royal Navy warships were fitted with Brown's plates. His works,covering nearly 30 acres, employed 4,000 men and his business turnover was £1 million. Brown had also been one of the first to try the new Bessemer process for steel manufacture. He introduced to Sheffield the production of Bessemer steel rails, the first of which was rolled by the Atlas Works in May 1861.[106]

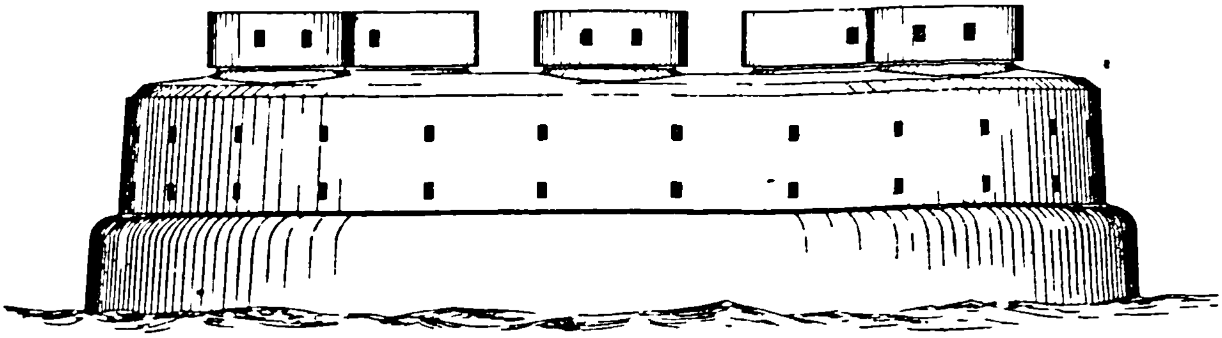
The issue of shield design had become a major concern for the Royal Engineers by 1865. Debate centered on the economy and effectiveness of various designs using the laminated plate approach which had emerged as the preferred method at that time. The Royal Engineer Professional Papers published shield projects by Inglis, his colleague Lieutenant English and by Lieutenant-Colonel Collinson as well as by a Captain Schumann of the Prussian Engineers.[107] On occasion there could be healthy professional disagreement between engineer officers. For example, Jervois and Inglis had a difference of opinion on the cost of thick versus thin iron plates. Both referred to their respective experience with ironfounders. Jervois claimed that "one of three great iron rolling firms" told him that the price per ton of 6 inch as compared to 9 inch plate was "no great difference" but Inglis replied: "I do not see how they will do it."[108]

In the late 1860's the gun fire trials on shields were renewed as the technological leapfrog game between armour and artillery continued apace. Trials at Shoeburyness in 1865 and 1868 tested various shield designs as well as different kinds of shield backing (iron concrete consisting of iron borings, asphalt stone, bitumen and pitch or Portland cement concrete). The two major designs tested were the War Office Shield, manufactured by the Millwall Iron Works in 1867, and the Plymouth Shield, a model of the type used in the Plymouth Breakwater Fort. Model casemates using these two systems were also tested with different plates employed in them (hammered plate by Thames Ironworks or rolled plate by Brown).[109] The Engineer, in commenting on the Shoeburyness trials of 1868, gave victory to the Royal Engineers in the contest with the Royal Artillery: "... the Royal Engineers have, so far, beaten the artillerists in a most conclusive trial, and the country may rest content that, as far as the iron shields go, the money spent on the Plymouth Forts has been judiciously employed."[110]

The Royal Engineers completed their final design for an iron shield and tested it in 1869 and 1870. The breakthrough came with the development of a rolled plate wide enough to cover the entire face of a shield and therefore avoid the problem of weakness caused by bolt holes in multipiece fronts. The process was developed by Brown at the Atlas Works in Sheffield, working from a suggestion by Lieutenant English. A normal 6 foot width mould holding molten iron was taken straight out of the furnace and rolled out for width and then was turned half round to roll it as usual for length. On 19 February 1869, the firm succeeded in producing a plate 8 feet wide by 16 feet long and 5 inches thick, weighing 10 3/4 tons. Out of this was cut the plate for the size required in the official Fortification Department shield - 8 feet by 12 feet. The design drawings for the shield were signed by Jervois and Inglis 31 December 1869. Brown won the contract for supplying the shields the next year and made delivery in thirteen weeks.[111]

British ironclad coastal fort designs were largely based on Russian precedents.[112] They were expensive and extremely controversial. The Plymouth Breakwater Fort provides an example of this distinctive and rare form of defence work. Built on a masonry foundation ring, it had a front iron wall separate from the front piers by which the roof was carried. Two thirds of the iron wall was composed of 15 inches of iron in three plates each 5 inches thick; the other third was 20 inches of iron in four thicknesses. The iron wall rested on iron uprights fixed into oval plates at the bottom and at the top which ran around the circumference of the fort and were supported by masonry arches which comprised the inner core of the structure.[113] Jervois thought the great advantage of the design was "that we can add strength to it which cannot be done in the case of granite."[114] He preferred iron shields with plates backed with concrete as opposed to unbacked ones. Jervois was particularly concerned with economy. Some argued that the outer walls of an iron fort should be made strong enough to be invulnerable to immediate frontal attack by a warship but Jervois disagreed saying the fort itself would have guns which could inflict more damage on the ship than the ship on it because the ship's armour was thinner. For Jervois, it was critical to have forts which were well armed so as to present a threat to warships, and he argued vociferously for economy in the use of iron.[115] (See Figure 32)

Most of the works on iron shielded coastal batteries and the iron forts were completed 1872-1873. In some cases Portland cement was used in concrete backing between the shields' armour plate layers (Horse Sand and No Man's Land at Spithead) but in others iron concrete was used. Portland cement was also used in concrete to fill the wrought iron pier casings which supported the armour shields in the Spithead Forts. While concrete and iron were both used by the Corps, no reinforced concrete construction was discussed or attempted at this time. The principal virtue of the iron forts was their adaptability to strengthening. As Inglis said near the end of his career in a paper given to the Royal Artillery Institution, throughout the construction process, the Royal Engineers had to be ever mindful of the need to make provision for change "taking the shape of continual increase in scale, and that in a rapidly increasing ratio."[116] The Engineer commented that this made the engineer officers' job very difficult and said they deserved great credit for making the works adaptable.[117] Nevertheless, the iron forts were certainly not completed without criticism from politicians and the public, including civil engineers. George Burnell, for example, thought that the wrought iron in these forts would rust severely unless extraordinary and expensive measures were employed to protect it from the chemical ravages of seawater. Moreover, he reflected a common complaint when he commented in 1862: "... though granite is itself a costly material, it must be less so, even in the first instance, than any form of metal."[118] If on balance these peculiar structures can be considered a qualified success, recognizing their rapid obsolescence, the achievement rested on a long process of experiment by the Royal Engineers in collaboration with the private sector as well as other branches of the British armed forces and with knowledge of the advances of foreign military engineers in contemporary fortifications design and construction.



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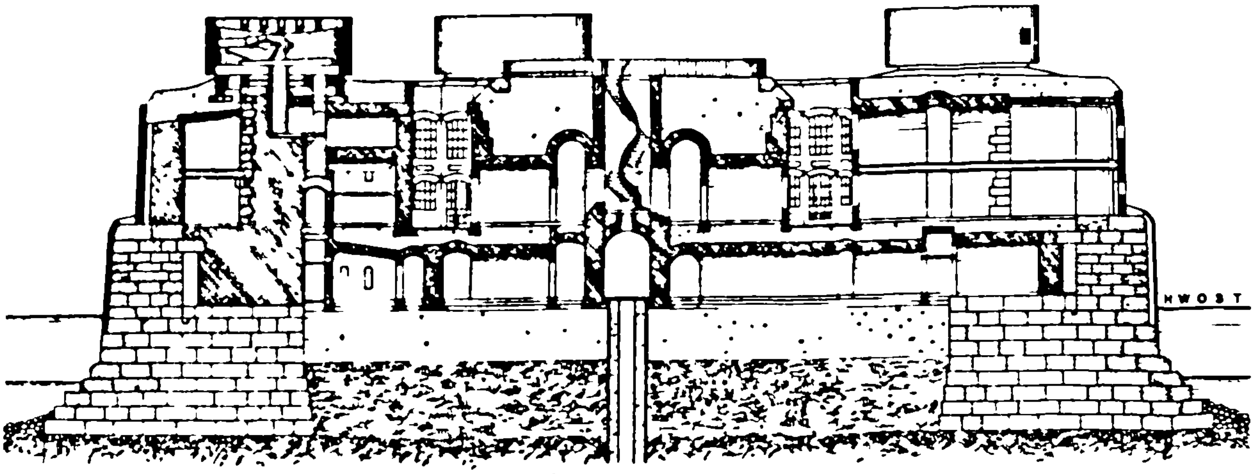


SECTION

Scale 40 Feet = 1 Inch

5 10 20 40 50 00 50

Figure 32 Design for a British Iron Fort, 1869

While the Royal Engineers' foremost responsibility in the employ of the War Office was the design and construction of fortifications, they were also in charge of barracks and military hospitals, a task which focussed on the provision of desired conditions of health, comfort, convenience and control. In exercising this duty, the challenge was not so much to produce great feats of advanced structural engineering or to explore adventurous applications of new materials, but rather to innovate and adapt with building plans, services and construction details. Some principles of design specifically related to barracks and hospitals were shared by another building type for which the Royal Engineers took responsibility not only for the military but also in the service of civil authority - prisons. The next chapter explores how the Corps met this challenge.

6. DESIGNING HEALTHY PRISONS, BARRACKS AND HOSPITALS

The achievements of Royal Engineers in the planning, servicing and construction of prisons, barracks and military hospitals were an important part of social reform in nineteenth century Britain. A healthy society, in terms of both physical well being and moral order, was the ultimate objective in designing accommodation for prisoners and soldiers. Criminal reformation and army sanitation were critical concerns for Victorian social reformers. The way to reform for them was to further the advance of science and reason while maintaining a firm belief in progress. Building technology was a vital instrument in the service of this fundamental doctrine.

It is significant that the contribution of the Royal Engineers was restricted almost entirely to two outstanding engineer officers - Sir Joshua Jebb in prisons, and Sir Douglas Strutt Galton in barracks and military hospitals. The Corps was severely criticized on barrack and hospital accommodation by the post-Crimean War army sanitary reformers, one of whom was Galton. In prison architecture, the reformed penal system which dictated Jebb's model design for penitentiaries also prevailed over his Royal Engineer successors to the extent that they had little to add to the established architectural solution. The attitudes and achievements of Jebb and Galton are especially revealing when examined in the context of their relationship with other professionals for whom architecture was a crucial vessel of social reform.

Architecture and Social Reform

From the eighteenth century, doctors had advocated greater attention to cleanliness and social reformers called for more humane treatment of prisoners, the poor and the mentally ill. By the 1820's these movements, along with expanding concerns about rising crime, high mortality from epidemic disease, hazards and unhealthy conditions in workplaces and other evils of industrialization, provoked a broadly based social reform impulse. Improved design of prisons, asylums, workhouses and later of barracks and hospitals became one of the reformers' objectives. This was often allied to their efforts to provide effective sewage disposal and drainage, treatment of air and water pollution and especially better housing and slum clearance.[1]

Prison reform, while concerned for the physical well being of convicts, was engrossed with moral order and the control of human behaviour. Tomlinson has shown how the transformation of prison architecture in the period 1835-1877 was part of the struggle against crime and criminals as well as a pivotal component of the growth of government centralization of social control.[2] Evans has argued that the design of Victorian prisons, based on Jebb's Pentonville model penitentiary, had nothing directly to do with kindness or severity. The exacting architecture of prisons was founded on two ideas: the concept that evil communication corrupts; and the notion that buildings could fix the shape of experience, thereby moulding social behaviour. This was a radical change from the earlier idea which conceived of prison architecture as simply representing virtue in its visible form.[3] Evans further contends that the techniques of isolation, sanitation, pacification and observation developed in prison architecture spread to embrace other kinds of abnormality in asylums, workhouses, hospitals and barracks.[4] Whether or not prison design experience had an influence as pervasive as Evans suggests, all these building types share the same basic principle of planning - separation of functions and of different categories of inmate.[5] This principle was to be a formative factor in the Royal Engineers' designs for reformed prisons, barracks and military hospitals, not only in building layout but also in the choice of ventilation and heating technology.

Army barrack and hospital reform adopted many of the salient features of the earlier movement for healthy housing, one of the cornerstones of the Victorian sanitary reformers' philosophy and programme. In the 1830's the primary concern of sanitary reformers was for sewerage and drainage, not the construction of houses or the prevention of congestion within them. Nevertheless, Edwin Chadwick's Report on the Sanitary Condition of the Labouring Classes (1842) provided the initial impetus for a housing reform impulse in the mid-1840's. Broadly speaking, it focussed on two major though not always related themes - dwellings unfit for human habitation and overcrowding.[6] From the outset, a key issue common to both concerns was ventilation. Indeed, the freshness and circulation of air became something of a national obsession. This prevailing attitude was articulated succinctly in 1844 by Dr. David Boswell Reid (1805-1863), perhaps the foremost expert in Victorian Britain on the subject of ventilation:

> "Mental anxiety may, perhaps, be considered the most powerful enemy to the duration of human life, and next to it, defective nutriment, whether in quantity or quality. But after these, no other cause, at least in modern times, appears to have inflicted so great an amount of evil upon the human race as defective ventilation..."[7]

Ventilation was to be a dominant concern in the army sanitary reformers' programme. It had also been an important factor in Jebb's model prison design almost two decades earlier.

Army sanitary reform was a direct response to the excessively high rate of disability and death from disease suffered by British soldiers in the Crimean War. A healthy army was of considerable significance to Victorian society. The army comprised a sizeable body of young men and played an important role in Britain economically as a source of employment, and at times was the focus of public concern as a political issue.[8] Improvement of barracks and military hospitals began in the late 1850's and benefited from nearly two decades of sanitary reformers' work for public health and better housing. Between 1856 and 1899, using crude mortality rates as the indicator, the health of the army was worse than the civil population at the beginning of the period but better at the end. This was only partly due to improvements in the health regime of civilian life which in turn influenced the army.[9] Better barrack and hospital accommodation was a major contributing factor to the improvement of the Victorian soldiers' health in the late nineteenth century. Indeed, it could be argued that after 1860 soldiers were progressively better housed than the British working class. Contemporary government reports and health statistics repeatedly condemned the widespread abuses of closed court terrace housing, back-to-backs and especially cellar dwellings, well into the latter decades of the century. Notwithstanding legislation, employer housing and company towns, philanthropic housing schemes and model dwelling associations, workingmen's housing remained inadequate. In the end, reformers realized that it was only the possibility of rising economic fortunes for the working classes that could solve the problem, particularly given the Victorian prejudice against state intervention in the marketplace and decided preference for self help.[10] In the case of soldiers' dwellings, it was greatly increased capital investment by the state in barrack and military hospital schemes that made the difference.

The development of new asylums, workhouses, prisons, barracks and hospitals in Victorian Britain witnessed the emergence of the state as the patron of these building types and its alliance with new professional groups in medicine, architecture and engineering as well as with social reformers.[11] Tomlinson has shown how Jebb worked closely, although not always harmoniously, with prison reformers and inspectors William Crawford and The Reverend Whitworth Russell.[12] Forty has argued in a discussion of the development of the pavilion plan hospital that the perceived sanitary and hygenic advances in this novel design veiled the motives of professional advancement of doctors, architects and nurses, especially Florence Nightingale.[13] Galton was married to Nightingale's cousin. He collaborated closely with Nightingale in the improvement of army barracks and hospitals as well as with a number of doctors with whom they were both allied in the sanitary reform movement.[14] Galton saw co-operation with other professionals as vital to the design and construction of healthy dwellings:

> "The researches of the physiologist and of the medical man into the laws which govern the prevalence of disease have enabled them, by gradual accumulation of information, to lay down the principles upon which the healthy construction of houses should rest. It is the duty of the architect, the builder, the engineer, and the surveyor to apply these principles, and their correct application is as essential to the efficient construction of a dwelling as is the quality or strength of the materials which are used to build the dwelling."[15]

Indeed, both Jebb and Galton were in the interesting position of being not only the employees of the state in furthering social reform through architecture but also the allies of doctors, nurses, architects, engineers and others in promoting professional interests.

As agents of the state and allies of the professions, Jebb and Galton joined prevailing opinions on the requirements of physical well being and moral order in prisons, barracks and military hospitals to their own assessment of available building technology, its cost and reliability. The evidence suggests that for them the overriding imperative in architecture was satisfying human needs and comfort. Their approach was perhaps best articulated by Galton in 1880 when he discussed ventilation and building design:

> "The laws regulating the movement of air should govern the form of buildings...; in both private and public buildings architects should conform their architectural design to the internal requirements, and not, as is too often the case, make the internal arrangements conform to the design of the facade."[16]

Building services engineering was a field in which both engineer officers excelled. Their contributions support Bruegmann's arguement that, contrary to popular impression, the Victorians were not universally uninterested in environmental control in architectural design.[17]

The Royal Engineers and Prison Administration and Architecture

Royal Engineers, most especially Joshua Jebb, played a pivotal role in the design of new and remodelled buildings to accommodate the separate system of penal confinement which affected a transformation of British prison architecture in the period 1835-1877. They advised on the design of 127 local prisons and were mainly responsible for the design of 13 convict prisons. Moreover, these engineer officers, as servants of the Home Office, took an active part in the process of gradually resting control of prisons from local authorities and placing it directly under the central government, a process which was completed in 1877.[18]

The proponents of the separate system rediscovered the idea of the reforming effect of solitude which dated to the ecclesiastical prisons of the middle ages and joined it to the concept of total supervision and control from a central vantage point developed by Jeremy Bentham in the Panopticon (1791).[19] It was the ultimate system of the categorization of prisoners and their separation. In 1845 Jebb described why he thought the individual separation of one prisoner from another was the only basis on which a sound system of prison discipline could be formed:

> "Among other advantages, it prevents the possibility of contamination; it is a severe punishment to be alone, and it affords the well-disposed prisoner the opportunity of reflecting on his past life, and its consequences, and of forming some rational resolutions for the future."[20]

The major influence on British separate system prison design was Cherry Hill, Philadelphia Penitentiary (1821-1829), by John Haviland (1792-1852), an Englishman who had emigrated to America in 1816.[21]

In 1835 a new central government body was established in the Home Office called the Inspectorate of Prisons. Its responsibility was to help control local prison design, conditions and operations. In November

1837, on the recommendation of prison inspector William Crawford, Captain Joshua Jebb was appointed to assist the inspectorate with architectural matters. Initially he was put in this position for six months whilst he continued on military duty at Birmingham, but by 1839 his post had been made permanent and he was seconded for civil service entirely. Jebb's job was to advise on local prison design, and in executing his duty he consulted local magistrates and architects, visited building sites and certified plans. By 1843 he had a permanent architectural assistant. In August 1844 Jebb was appointed Surveyor-General of Prisons and in the same year added the post of Inspector-General of Military Prisons. Soon after he was charged with the responsibility of expanding convict prison facilities in response to the increased number of criminals and changes in the system of penal transportation whereby the initial period of imprisonment was in Britain. Jebb became Director of Convict Prisons in 1850.[22]

Joshua Jebb (1793-1863) had been commissioned in the Royal Engineers in 1812. He was stationed initially in Canada during the War of 1812-14. Jebb remained in Canada after the war and made a survey of a proposed route for the Rideau Canal in 1815 which was not adopted. He returned to England five years later and subsequently spent some time in the West Indies (1827-1829). From 1831 to 1837 he was adjutant of the Royal Sappers and Miners at Chatham where he no doubt was associated with Charles Pasley, Director of the Royal Engineer Establishment. Nothing is known, however, of his experience in building prior to his appointment to the inspectorate of prisons. Jebb retired from the army in 1850 and died in civil service office.[23]

In 1838 and 1839 Jebb published designs for a separate system prison in his joint reports with inspectors Crawford and Russell to Parliament. By 1839 the New Gaol Act explicitly prescribed separate confinement and prohibited solitary confinement of the old type, thus removing the legal obstacles to new prison design.[24] A central government financed and operated 'model' prison, Pentonville, was designed by Jebb and built from 1840 to 1842. Jebb credited Crawford and Russell with the basic principles of design and said his association with them provided valuable assistance. He acknowledged that Pentonville was not a new idea but a model with novel details: "... in order to simplify, improve and economise the construction of prisons... and for the purpose of practically working out the separate system of discipline..."[25]

After 1839, all new local prisons had to be approved by Jebb. In the first six years, fifty new buildings were constructed on the Pentonville model prison plan. There were many variations but always in the direction of Jebb's model. The most notable departures were by Jebb himself at the convict prisons of Portland, Dartmoor and Brixton where cells were only for sleeping and convicts were employed in day labour on public works.[26] Portland Prison, the first to be constructed, became an alternate model for convict prisons to Pentonville. The separate system of penal confinement spread all over Europe in the 1840's and 50's. By 1846 there were thirty new French prisons in progress and Moabit Prison (1842-1846) in Berlin was an exact replica of Pentonville.[27] Jebb's model prison design principles were also prescribed for the British colonies, most notably in Australia. The interaction of ideas and practices between Jebb and Royal Engineers in foreign stations is an interesting case study in the process of building technology transfer, and this matter is taken up in Chapter 8. After mid-century, the hope of reforming prisoners through the separate system evaporated and the system's purpose was redefined as a convenient way of exacting punishment and deterring crime. Jebb himself held this view by 1854.[28]

Following Jebb's death in 1863, Royal Engineer, Sir Edmund Yeamans Walcott Henderson (1821-1896) was appointed to the post of Surveyor-General of Prisons. Henderson had been commissioned in 1838 and served initially in Canada (1839-1848). In 1849 he was made Comptroller of Convicts in Western Australia where he designed Freemantle Prison (1851). He was replaced in 1856 but stayed on as the colony's head of public works until 1863. Henderson served as Surveyor-General of Prisons until 1869 when he was appointed Chief Commissioner of the Metropolitan Police. He made no notable contribution to building technology in prisons while Surveyor-General and essentially completed Jebb's unfinished projects.[29]

Also, after Jebb's death, Major-General Sir Edmund Frederick Du Cane (1830-1903), who had served under Henderson in Australia (1851-1856) and in the War Office under Jervois on the construction of the Commission Forts (1856-63), succeeded to the post of Director of Convict Prisons and Inspector of Military Prisons. He administered the new Prisons Act of 1865 and in 1867 made arrangements for additional prison accommodation following the abolition of transportation. By 1869 he was Chairman of the Board of Directors of Convict Prisons, Surveyor-General of Prisons, Inspector-General of Military Prisons and had responsibility for colonial convict prisons as well. His main achievement in prison administration was the reorganization of county and borough prisons which under the Prisons Act of 1877 were put under central government control through three commissions for which Du Cane served as chairman. Du Cane designed Wormwood Scrubs Prison (1876-1883) built to replace Millbank Prison, and a discussion of its salient features is presented at the end of the following section.[30]

Jebb and the Model Prison

When completed in the autmn of 1842, Jebb's Pentonville Prison occupied an area of 6 3/4 acres in Islington, London. It had a curtain wall with massive posterns in front where stood a large entrance gateway whose arches were filled with portcullis work. A large Italianate clock tower rose from the main building. Four radiating wings as well as a long entrance hall were arranged about the central point beneath the clock tower. The interior of each of the four wings was fitted with 130 cells, arranged in three galleries or storeys, one above the other. (See Figure 33). In February 1841, Jebb proposed that Sir Charles Barry (1795-1860) should be employed to design features of the prison where a decorative architectural character was desirable. Barry prepared drawings of houses for the governor and chaplan, the gateway and terrace walls, and porter's lodge, archway, and gates and walls in the courtyard. The actual work for these features fell under Jebb's supervision as in the rest of the prison. Messrs. Grissell and Peto were the contractors for the building, the total cost of which was £84,164.[31]

As Jebb himself admitted, there was nothing new in the principles of design in the model prison at Pentonville. His contribution was therefore not one of innovation but of the adaptation of established design principles and available technology to the details of plan, heating and ventilation, lighting, plumbing and materials of construction. Architecture and building services engineering had to serve the requirements of the separate system. As Jebb explained his brief: (1) each prisoner must have his own cell where he is kept day and night which must be light, well ventilated and warmed, and of sufficient size to admit the introduction of small machines for part-time manual labour; (2) prisoners must not be able to communicate with one another but must be able to summon a prison officer in case of illness or emergency; (3) each prisoner must be subject to unobserved inspection; (4) separate stalls were needed in chapel as well as separate yards for open air exercise, with four or five prisoners in each maximum; and (5) cells must be fitted with means for sleeping, washing, using the lavatory and eating, making it unnecessary for a prisoner to leave his cell unless ordered to do so.[32] Jebb devised interesting solutions for each of the items in this design discipline, the salient features of which will be examined from the perspective of the present study of building technology development.

The plan adopted for Pentonville was the radial.

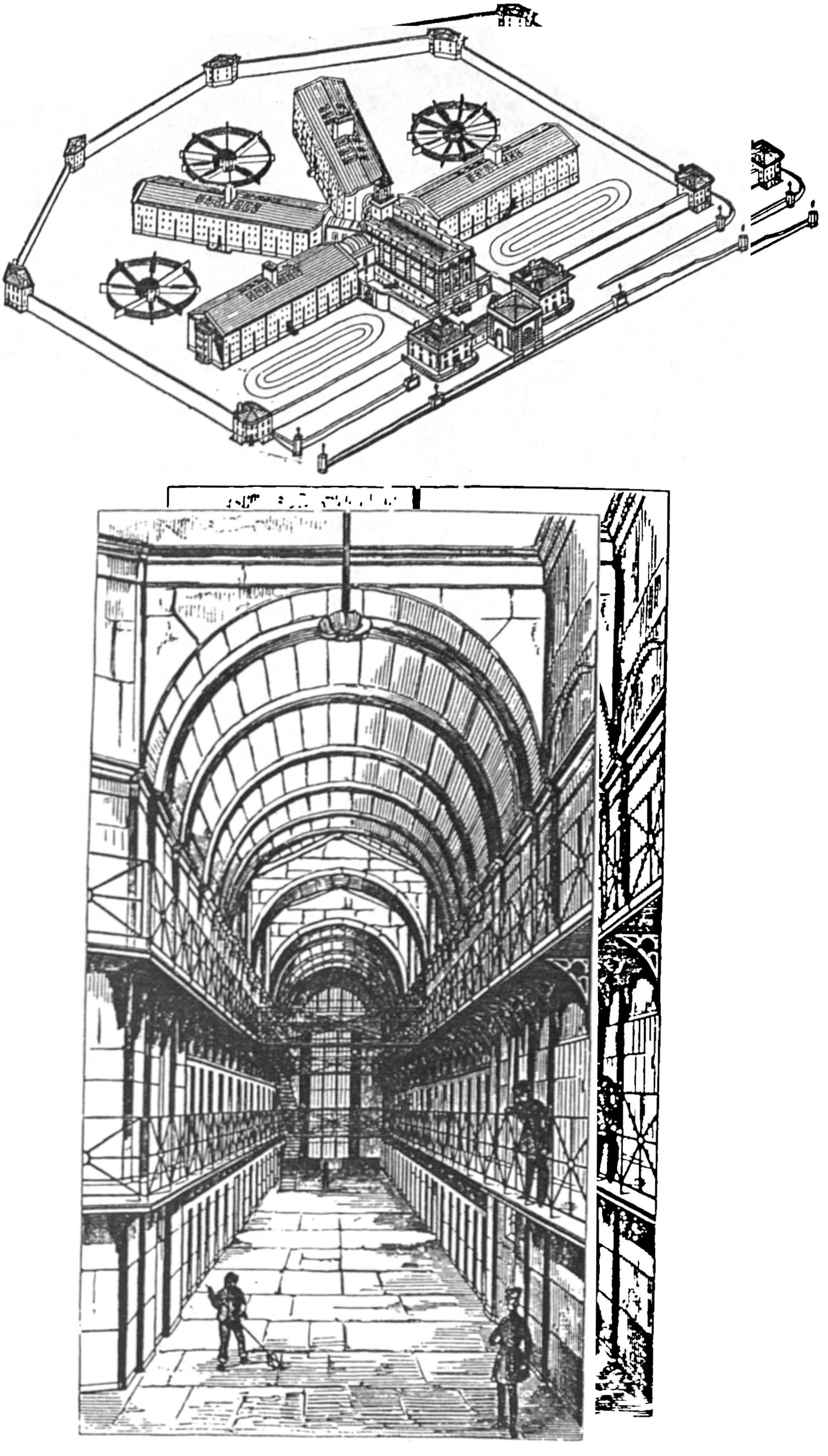


Figure 33 Birdseye and Interior Views of Pentonville Prison, 1840-42

It had been employed in prison architecture since the late eighteenth century along with its chief rival, the polygonal plan.[33] The radiating arrangement of detached wings was preferred in the early nineteenth century over the polygonal plan because of its superior surveillance, accessibility and lower cost. Its disadvantage was problems with security. Detractors thought low boundary walls and flimsy railings could not prevent escape and did not trust preventive inspection without unbroken solid containment.[34] In Jebb's opinion, the radial plan best achieved the objects of security, facility of access, discipline and control with a limited number of prison officers. The critical feature was surveillance. As Jebb explained:

> "Experience has shown ... that these important objects cannot be obtained by any simpler mode than by laying out the different buildings and distinct portions of which a prison is comprised so that they shall diverge or radiate from a common centre, which if kept in view in regulating the internal construction, becomes a point of observation commanding a view and from which access is afforded in all direction."[35]

The crucially important surveillance advantage of detached wings radiating from a common centre was achieved by opening up the central hall and wing corridors from floor to roof with cells placed on either side of the corridor so that the doorway of every cell could be seen from nearly the same point (see Figure 33).[36] In order to enhance security, Jebb specified for radial plan prisons, 18 to 20 foot high boundary walls with deep foundations, a clear space of 15 to 25 feet with a smooth surface around the boundary walls and prison wings, officers' houses in the angles of the boundary walls and only one gateway in the external boundary (see Figure 33).[37] It is clear that Jebb had given considerable thought to maximizing the surveillance advantage of the radial plan and minimizing its security problems.

It was the cell, however, which comprised the most significant story of prison building technology.

The specification was for a space 13 feet long, 7 feet wide and 9 feet high with an arched ceiling, containing some 820 cubic feet.[38] In Jebb's opinion:

> "Cells of this size admit of the introduction of small machines for the employment of prisoners, give space for exercise, are wide enough to sling a hammock, and allow an active ventilation to be maintained without subjecting the occupant to draught that would be prejudicial to his health."[39]

Healthy ventilation and heating presented a great problem. In keeping with the separate system of confinement, the technology employed must prevent audio or visual communication between inmates. Conventional windows, doors and individual fireplaces in each cell would not be acceptable. As Jebb put it:

> "The ventilation of a cell cannot fail to have a direct influence on the health of a prisoner and it is therefore one of the most important objects connected with the construction of prisons... The necessity of resorting to an artificial system for a regular supply of fresh air at all times and seasons will be apparent when it is considered that, with a view to prevent communication between prisoners in adjoining cells, it is necessary that windows should be fixtures, and the doors generally closed."[40]

The conclusion was clear - Jebb needed a forced ventilation and central heating system.

In 1840 the choices available to Jebb for ventilation and heating from existing technology were extensive and complex. There were essentially two approaches to ventilation: natural or gravity ventilation where lower density warm air moved through open windows and doors or up the chimney of a fireplace or stove when a fire was burning; or forced ventilation which could be either heat-aided, where the drawing power of a heat source is used to extract air from a room, or mechanical, where a fan, screw or pump and bellows is used to extract the air, or more commonly to force air into a room. Heating could be arranged utilizing one of three basic heat sources and a choice of a number of methods for generating them, used in combination with the appropriate ventilation system. Hot air could be used, distributed by convection or forced from a central furnace or central steam or hot water apparatus. Direct radiant heat from hot water or steam might be employed instead. Both used pipes threaded through the building and radiators in each room, with central and sometimes supplementary boilers.[41]

Prior to the model prison at Pentonville, most prisons were ventilated by windows and heated by open fireplaces in day rooms or in cells. Dr. Neil Arnott's patent stoves were sometimes placed in corridors with some heat making its way into the cells.[42] Nevertheless, there were a few experiments with more sophisticated methods.

In a number of multi-storey prisons, Dr. Reid used heat-aided ventilation with hot air heating from a central hot water boiler and pipes located in the basement. Outside air was conveyed to a central channel in the basement containing the hot water pipes where it was heated and then gained access to a great corridor in the centre of the building. From the corridor, the air rose and entered cells at the floor level and exited at the ceiling from whence it travelled by a shaft to a horizontal vitiated air chamber in the roof and then via another shaft to the outside atmosphere.[43] Reid's ventilation and heating system, whereby fresh, heated air entered a room at the floor level and exited at the ceiling, was known to contemporaries as the 'ascending' principle. It was the reverse of the arrangement of air flow used by Jebb at Pentonville which was called the 'descending' system. The merits of the respective approaches were vigorously debated in the mid-nineteenth century, and this matter is discussed further below. Reid was an advocate of heat-aided ventilation. He argued that mechanical ventilation should be used only when natural and heat-aided ventilation were "not sufficient, or too expensive and complicated from peculiar circumstances that do not admit of the introduction of large and commodious channels for the ingress and egress of air."[44] For Reid, when a force was needed to sustain a more uniform and determined movement of air, and where the form of the structure allowed it, a fire or heating power to increase the ordinary tendency of vitiated air to escape was best because it was "convenient and requires so little attention and management."[44] Reid's opinions were important, recognizing his high standing as an expert on ventilation and heating technology for buildings. His best known works were in the temporary House of Commons (1835) and in St. George's Hall (1841-1854), Liverpool. In the former he used a heat-aided system and in the latter a mechanical forced air arrangement.[45]

Another heating system which had been tried in prisons was Jacob and Angier March Perkins' patented (1831) high pressure hot water system which employed one inch pipes threaded through the building and one or more central boilers. The first installations of Perkins' system were in 1832 and it evidently was used in Newgate Gaol sometime before 1837 and in King's Lynn Borough Gaol before 1840.[46] Charles Richardson extolled the virtues of the Perkins system in his A Popular Treatise on the Warming and Ventilation of Buildings (1837):

> "The apparatus combines before all other, the great requisites of compactness, utility and frugality, and possesses the power of adaptation to all situations, interfering in no respect with any architectural arrangements."[47]

The Perkins system, although widely used in Britain, was dangerous. It had a tendency to char and sometimes ignite adjacent wood because of high temperatures under high pressure.[48] Apparently, the Perkins system installed at the King's Lynn Borough Gaol was abandoned because the pipes exploded.[49]

In developing a ventilation and heating system for Pentonville, Jebb adopted a heat-aided arrangement on the 'descending' principle using hot air generated by a central hot water apparatus. Jebb turned for advice not to Dr. Reid, the recognized expert on heat-aided systems, but to the less well known George Haden of Messrs. Haden, Trowbridge, Wiltshire. As early as 1837 when the subject of a model prison was first being discussed, Jebb consulted the firm which was then engaged in warming and ventilating a new wing of the county gaol at Shrewsbury.[50] Jebb explained later: "... their practical acquaintance with the subject enabled them to render valuable assistance in the arrangement of the necessary flues and details..."[51] Although not stated explicitly, it appears that while the system was Haden's, Jebb modified it: "Some important improvements, however, suggested themselves during the execution of the works; among which those of placing the main foul air flues and the fire for summer ventilation in the roof instead of in the basement have had a very beneficial and economical effect on the working of the system."[52]

George Haden (1788-1856) apprenticed under Boulton and Watt and later worked for them at Manchester, Leeds and Glasgow. He subsequently settled in Trowbridge where he became an agent for Boulton and Watt for thirty-four years and was primarily engaged in erecting steam engines in cloth factories of the region. Haden eventually established business on his own and took up the ventilation and warming of buildings of all kinds and gained a good reputation, being entrusted with many large structures in all parts of the country. He was to be much employed in prison work since he held the patent for the apparatus used at Pentonville for heating air via hot water.[53]

The Pentonville central heating and ventilation arrangement was the prototype for all the new separate system prisons erected to 1847 and many thereafter.[54] In the centre of the basement of each wing was located a case or boiler designed and patented by Haden for heating air by hot water. It was a double iron case with the space between the two cases filled with water. From the top of the boiler rose a main pipe which connected to several pipes which returned to the bottom.

The external case was cast iron and was covered with a zig-zag pattern of plates to distribute heat to the air passing over. A large open flue communicating with the external atmosphere was connected with the heating apparatus. Fresh air introduced through this flue passed over the surface of the boiler and was heated. The heated air was then conducted by way of flues along the corridors under the floor and then up the corridor walls in flues which terminated in a grating placed close under the arched ceiling of each cell. For the extraction of foul air from the cell, a grating was placed close to the floor on the side next to the outer wall and diagonally opposite the fresh air grate. The foul air was conducted through the grate by way of a series of flues and out of the building through a vertical shaft some 20 to 25 feet above the ridge of the roof. During the summer months, a small fire was maintained in a fireplace at the base of the foul air shaft located within a massive chimney leaving the roof. The fire raised the temperature of the column of air within the shaft above that of the external air causing the foul air to rise and creating a partial vacuum which was filled by air from the foul air flues and thence the vitiated air from the cells. In winter months when fires were lighted in the boiler apparatus in the basement, disposable heat and smoke exited via the foul air ventilating shaft sufficient to create an updraught for ventilation. Jebb explained that hot water instead of steam was used to heat the air because it was "essential to health that the increased temperature be derived from a moderately heated surface..."[55] Dr. Reid preferred hot water too. This derived from the notion that heat consumed or burnt oxygen. The system was completely out of the prisoners' control except that in a few select cells where work differed from the normal situation regulators were installed in fresh air flues to permit the inmate to let in warm or cool air from the corridor.[56] By 1847 Jebb was recommending regulators for general use and suggested as well a special triple glazed ventilating pane in the cell window or an extra grate in the foul air flue with sliding cover for additional summer ventilation if desired.[57] (See Figures 34 and 35)

The Jebb/Haden system shared some features of other contemporary heat-aided ventilation and heating arrangements in large buildings but was much more complex, particularly in its use of complicated flue and shaft work. In the prisons ventilated by Reid, the fresh, warm air was simply allowed to make its way into the cells from flues all connected to the central corridor. Given Jebb's design brief for absolute prohibition of communication between prisoners, each supply and extract duct had to be isolated from all others. Moreover, the total length of each pair of flues for fresh and foul air respectively was designed to be about the same "thus promoting uniformity of action" and this further complicated the arrangement.[58] It was notable that Jebb disagreed with Reid on the placement of fresh and foul air ingress and egress. In using a 'descending' rather than an 'ascending' system, Jebb reversed Reid's (and others) arrangement by letting the fresh, warm air in at the ceiling and extracting vitiated air at near floor level. Jebb said he adopted this arrangement to prevent draughts for prisoners and to discourage them from obstructing the fresh, warm air inlet.[59]

As suggested earlier, the matter of the 'ascending' versus the 'descending' principle was one which provoked considerable controversy. Perhaps the best summary of the debate is to be found in Charles Tomlinson's A Rudimentary Treatise on Warming and Ventilation (1850) and it is worth quoting at length:

> "... at first view, it appears to be strange and unnatural; namely that by which fresh warmed air is admitted into the room by openings near the ceiling... With upward ventilation, a great part of the vitiated atmosphere of crowded rooms is liable, by the slightest check or condensation, to be thrown down and mixed with air, which is already partly unfitted for the purposes of respiration. But let the ventilating current descend, we have a

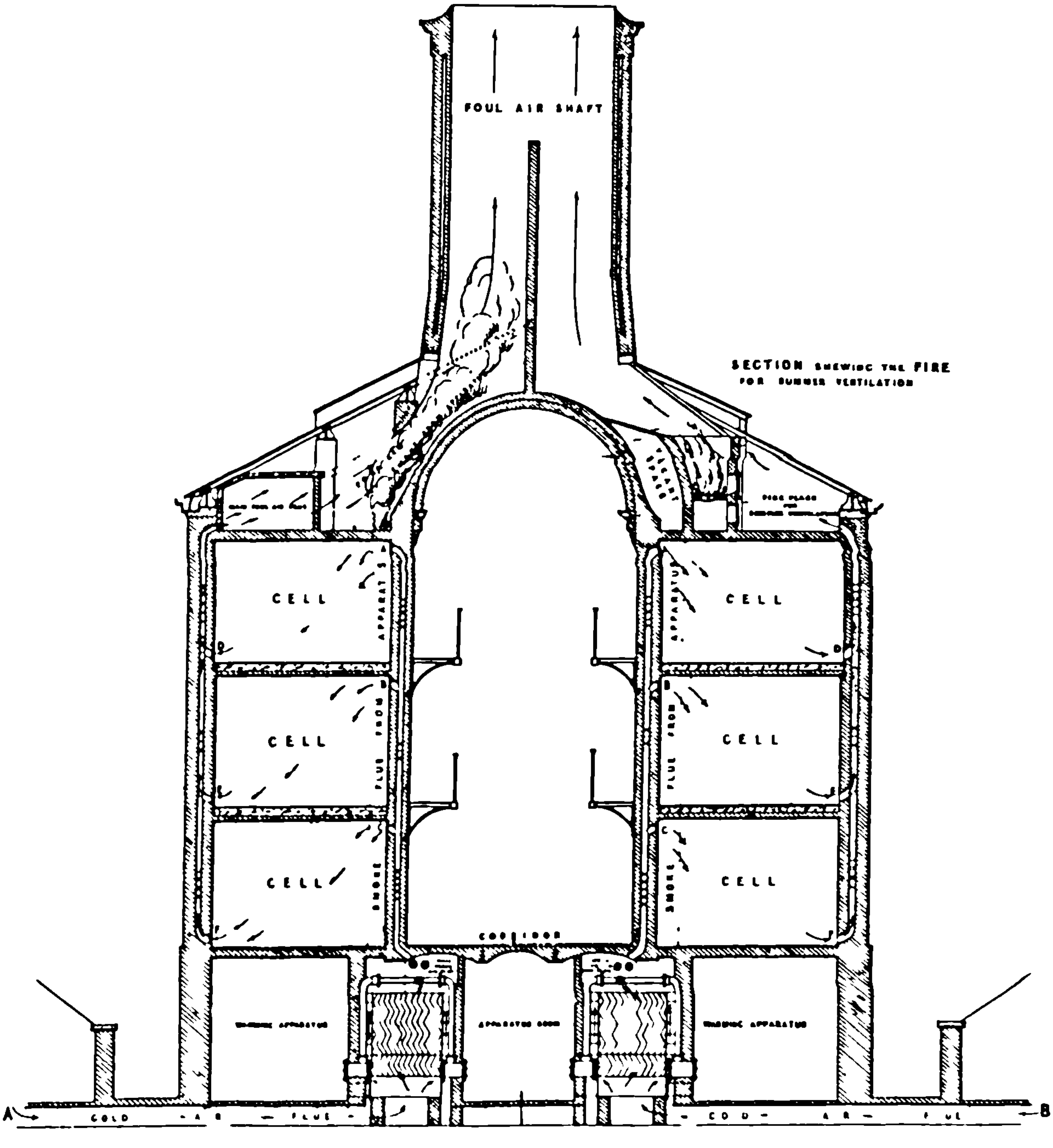


Figure 34 Pentonville Prison : Transverse Section Showing Ventilation and Heating System

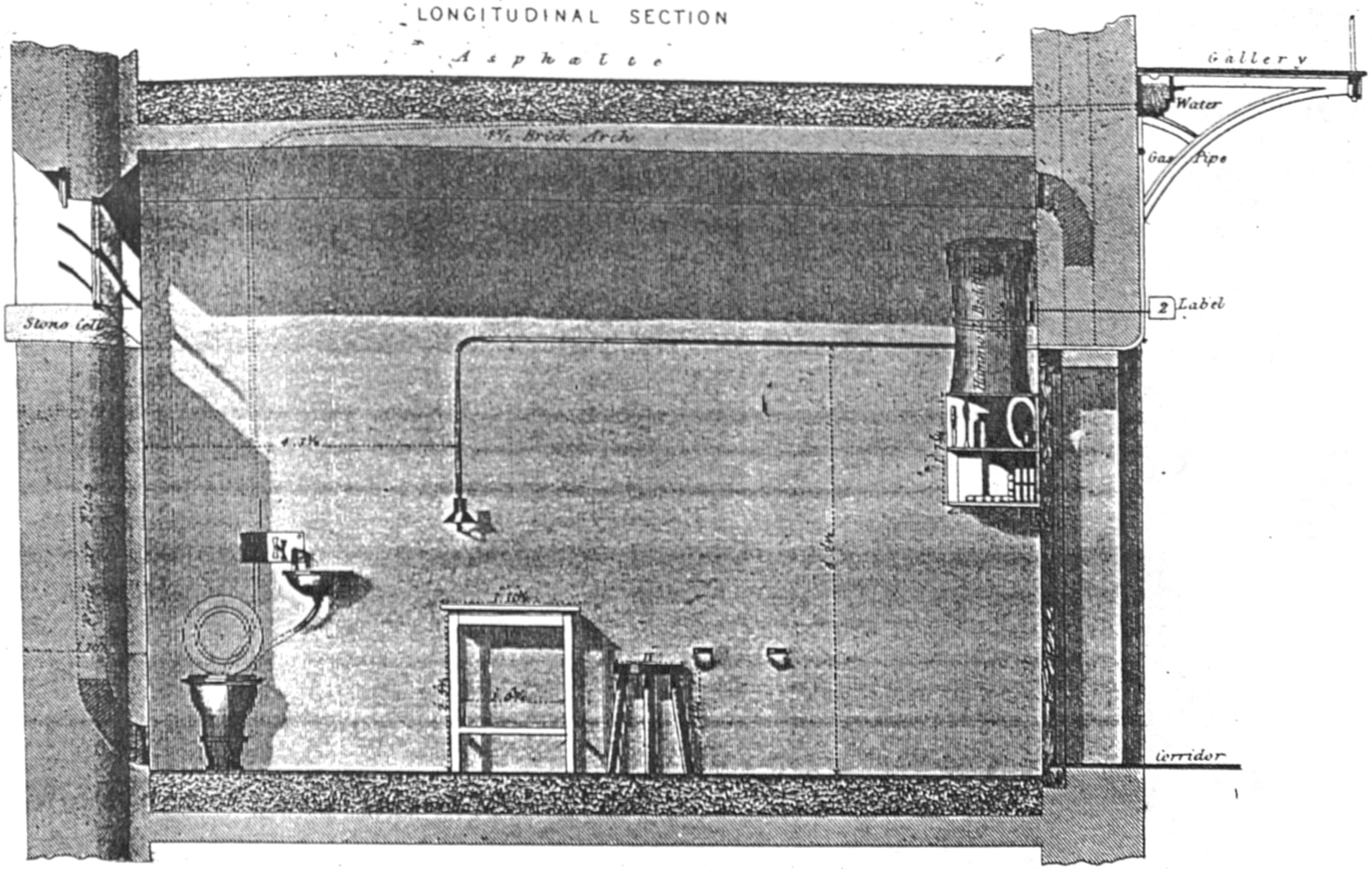


Figure 35 Pentonville Prison : The Cell

> bright atmosphere of pure air, which, as it becomes contaminated by respiration, is drawn downwards and discharged. On the other hand, this method of ventilation by descent has been denounced as a "noxious fallacy", because the vitiated air from the lungs having a temperature of 98°, naturally rises through the air of the room, which is of the temperature of 60° or under; and if forced downwards by any means, must be breathed over again by the occupants of the room, before it can be discharged at the level of their legs and feet, in opposition to the laws of gravity."[60]

Tomlinson was inclined to agree with the critics of the 'descending' system saying that only if "the velocity of the outgoing current be so considerable as to amount to a strong wind" would the arrangement provide a healthy room atmosphere; but that would defeat a prime objective of good ventilation - the prevention of draughts.[61] Indeed, the 'ascending' system was preferred by most writers from the late 1830's to mid-century.[62]

One of the most vociferous critics of Jebb's 'descending' arrangement was the Mechanic's Magazine. This important technical journal condemned the Pentonville Prison ventilation and heating system as unhealthy and wasteful because it introduced an artificial power source to overcome the natural force of rising air.[63] The Mechanic's Magazine later printed Jebb's defence of the system which had been given in the Second Report of the Surveyor-General of Prisons in 1847. Jebb claimed that his ventilating and heating arrangement actually maintained the 'ascending' principle on the whole:

> "... the ascending principle of ventilation of the entire system is preserved and ... the extraction of foul air from the cell is partly to be referred to the superior altitude of the extracting flues and shaft, which are in and above the roof. If the foul air were required to pass downwards, below the floor of the cells, into flues situated in the basement, a power must be maintained in constant operation to overcome the tendency of air at a higher temperature to remain at a higher level. The

> ventilation in such case would be entirely <u>forced</u>; whereas, by the arrangements which have been described, it only requires to be assisted."[64]

Jebb's arrangement of the openings for the ingress and egress of air in a room was in fact based on a principle that was at least thirty years old. In 1880 Galton said that the ventilation of cells in prisons by Jebb was practically the same as the system originally proposed by Charles Sylvester and William Strutt for the Derby Infirmary (1806-1810) - extraction of air at the lower part of the cell and its admission near the ceiling.[65] Tomlinson has suggested that Mr. Sylvester worked on Haden's system for Pentonville because they were each given half of the prison to under*take experiments* on ventilation and heating.[66] However, Jebb made no reference whatsoever to Sylvester's activities in acknowledging Haden's contribution to the model prison. Nevertheless, the connection is interesting.

The question of how well Jebb's system worked was also a matter of some controversy. In collaboration with the Pentonville Prison medical officer of health, Jebb had some experiments made on the cell environment in the winter of 1844. They found that 30 to 45 cubic feet of air was entering each cell per minute and concluded from this that "abundant ventilation goes on with great regularity."[67] Their report claimed that a temperature of 52 to 60° F could be maintained in the cells "during the coldest weather, at an expense of less than 1/4d per cell for twenty-four hours, and in summer ventilation by means of a fire lighted in the extracting shaft has been kept up at half the expense."[68] The temperature in the summer reached a maximum of 78° F.[69] In 1850 further tests were conducted, this time using "an ingeniously constructed anemometer" fixed to the extraction plate which measured the amount of air withdrawn from the cell.[70] In his report, medical officer of health Charles L. Bradley said that the system was working well and praised "the remarkable power possessed by the apparatus of equalizing the temperature of the cells, and maintaining a range independent of all sudden fluctuations of the external temperature."[71]

Supporters and critics of Jebb's system expressed their views in the technical press. Dr. Owen Rees, principal medical officer at Pentonville, explained in The Builder, 30 November 1844, that opinion was divided on the efficiency of the system - some condemned it outright, others called for modifications, and a few thought it the best possible. He claimed that prisoners had praised their cells as a workshop even in the warmest months of summer, although there were occasional complaints about excess heat in winter but not owing to ventilation. His own view was that "the system's objective had been most effectually attained during every season of the year."[72] The Mechanic's Magazine condemned it as "... one of the most absurd and inefficient that could possibly be devised..."[73] In 1845 Thomas Laurie, Clerk of the Works at Pentonville, responded to mounting criticism in the technical press:

> "The ventilation of Pentonville prison has been noticed more than once in the Builder, but not favourably. We have, however, excellent health here, there being little sickness amongst the prisoners, which would not be the case under a bad system of ventilation."[74]

Jebb's heating and ventilating system did run into trouble. It took at least two weeks to raise the temperature in the cells at Pentonville and ten to fourteen days to lower it again once the fires were extinguished.[75] The Mechanic's Magazine attributed the problem of slow cooling to the system of carrying hot water warming pipes in the fresh air flues running under the corridors and no independent fresh, cool air source.[76] Temperature in the cells varied between 50 and 78° F and there was only one way of making the extracting flues work - open the doors. Hot air persisted in rising and evaded the foul air flue near the floor. Sometimes problems were due to the bad practice of prison maintenance staff in failing to light fires at the base of the chimney to create draught in the summer.[77] The vulnerability of ventilating and heating systems to human error, neglect or tampering was a persistent concern for Jebb and other Royal Engineers.[78]

Evans and Tomlinson, scholars of nineteenth century prison architecture in Britain, both agree that the model prison ventilation and heating system, while being no great innovation, was certainly better than earlier efforts to ventilate and warm this building type, especially considering its complications following from the need for absolute isolation of each cell.[79] Evans maintains that it seems to have worked marginally better than the system in John Haviland's Cherry Hill penitentiary, the American source for the Pentonville model prison design.[80] Tomlinson and Evans also argue that, combined with its various other servicing elements, the model prison was not only the most advanced prison but also one of the most advanced buildings of its time, in terms of environmental controls.[81] While it is difficult to disagree with this assessment, it is important to point out that Jebb's heating and ventilation system in the model prison had one serious architectural disadvantage. The building plan and construction were subordinate to it to the extent that the system could not easily be installed in already existing structures or other building types. This problem was specifically identified by Galton and the Army Sanitary Commission in 1861 when considering Jebb's system, amongst other available technology, for new barrack designs.[82]

Nevertheless, it is important to emphasize that Jebb's solution in the model prison at Pentonville was governed by the demands of the separate system. His general opinions about ventilation and warming were revealed more fully in his designs for other convict prisons on the Portland model and in his testimony to the Parliamentary Committee on Barrack Accommodation for the Army in 1855. The latter reveals some particularly interesting comparisons between prisons and barracks on the matter of environmental controls in design.

Portland Prison (1847-1849) was the alternate model to Pentonville for convict prisons. It was conceived as a temporary or moveable design. The main building consisted of four large open halls with four tiers of small cells on each side. It had a framework of wood for cells and external walls and corrugated iron internal partitions. Portland Prison had a heat-aided system of ventilation but it differed from Pentonville's. Cold air was brought into contact with a heating apparatus in the basement passage from which warm air rose by convection into the open hall by way of a flue and thence made its way into prisoners' cells. Fresh air was introduced into each cell by openings over and under the door or by gratings placed in the door, and the foul air was extracted at floor level and passed into the roof through a flue from whence it passed into the atmosphere outside by way of louvres in the gables. Prisoners were able to introduce additional fresh air to their individual cells by way of a controlable ventilator beneath the cell window situated near the ceiling. It is interesting that, while introducing greater facilities for the ingress of fresh air into cells, Jebb remained wedded to the 'descending' principle with respect to the extraction of vitiated air, notwithstanding the fact that he did not have to maintain the rigorous isolation of cells demanded at Pentonville.[83] (See Figures 36 and 37)

In his testimony before the Committee on Barrack Accommodation for the Army, 11 May 1855, Jebb extolled the virtues of the English open fireplace, saying that it was the preferred method of heating and ventilating and that "no artificial warming, whatever may be the greater degree of comfort attained, will compensate for its loss."[84] He recommended that the passages in barracks be warmed "by common stove or coil of hot water pipes", in addition to open fires in rooms.[85] Fresh air should be introduced to the passages in winter by a large flue from the exterior connected to the stove or coil, and in summer through special openings made in doors, windows or walls. Jebb explained that in the large

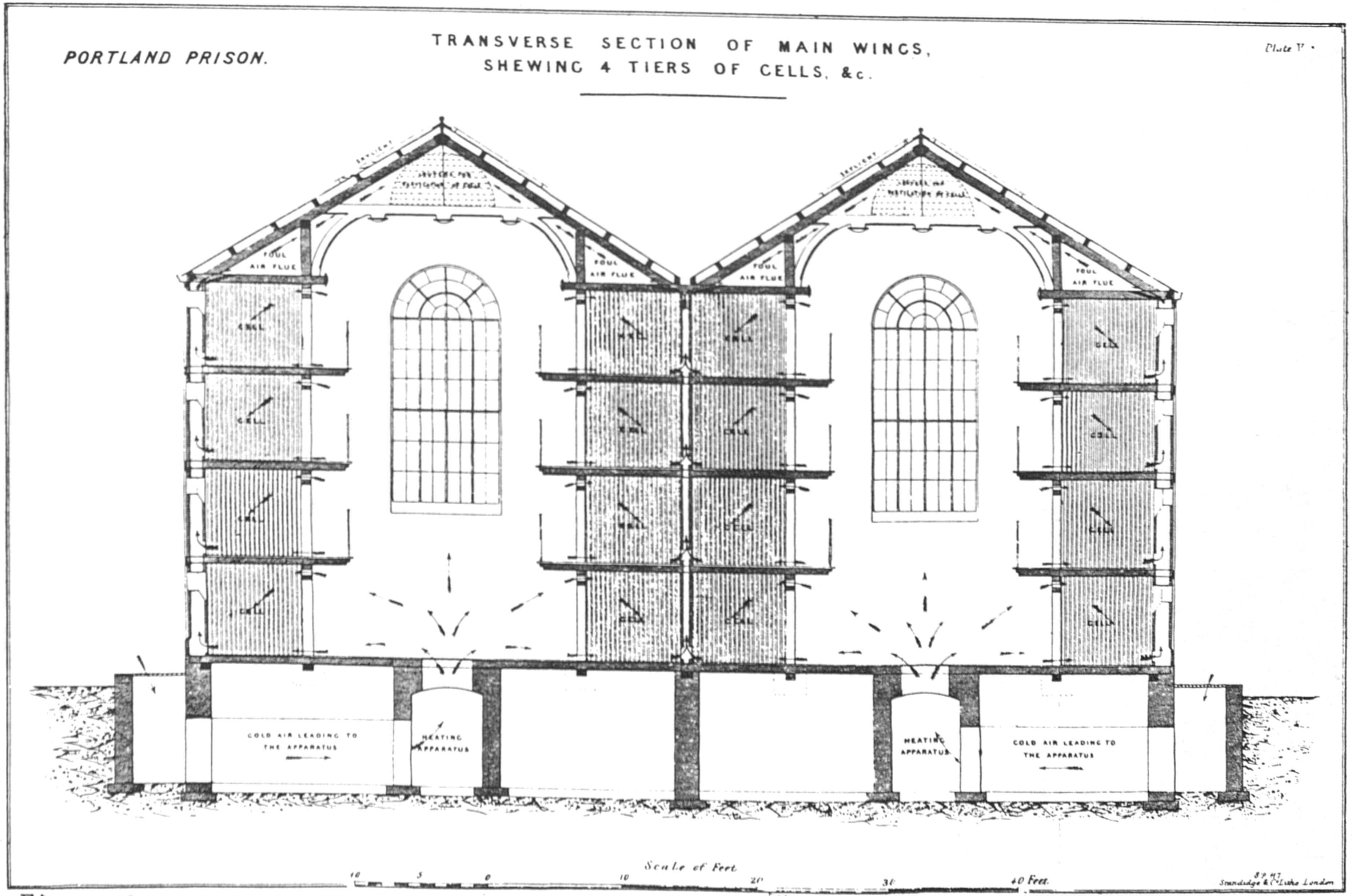


Figure 36 Portland Prison : Transverse Section Showing Ventilation and Heating System

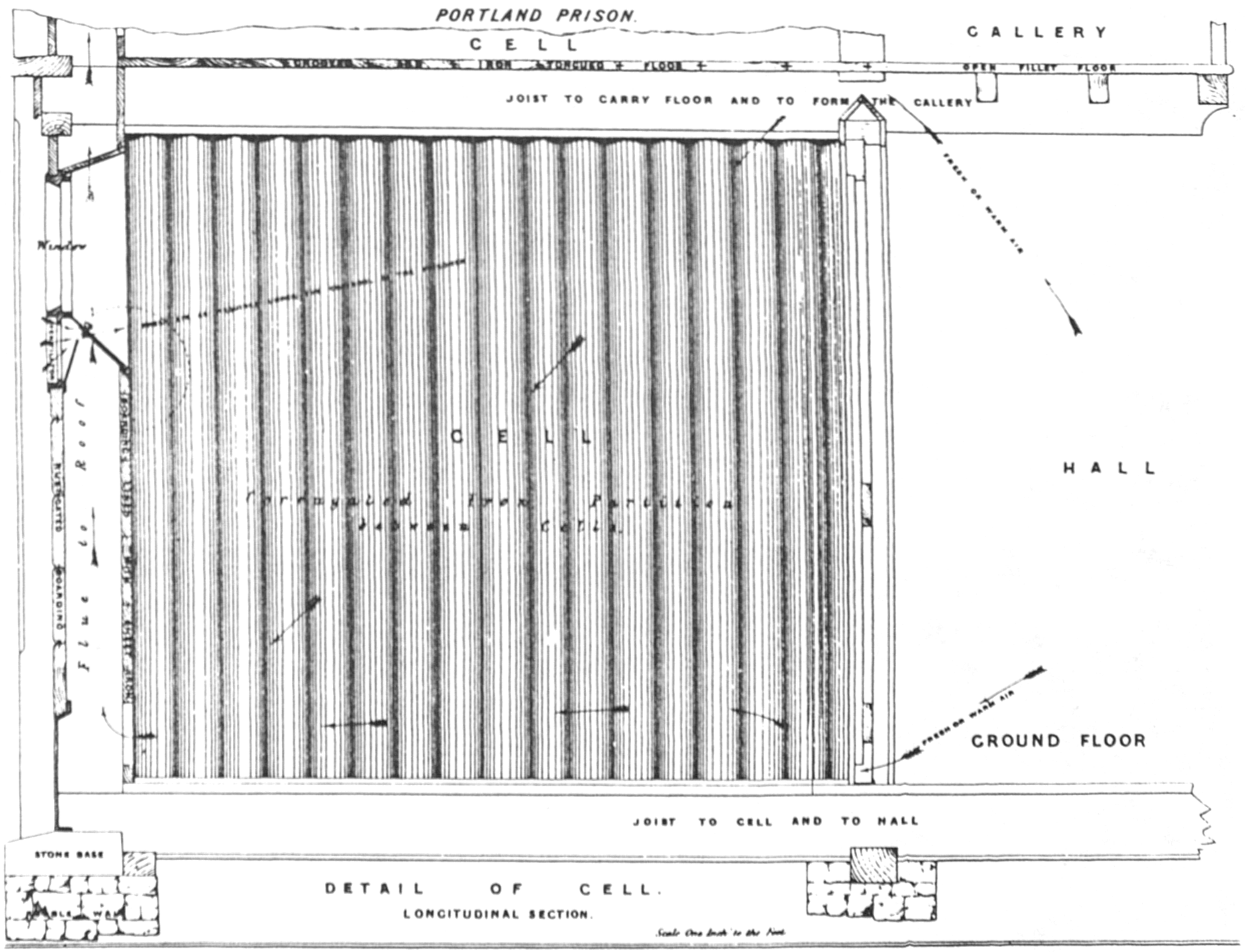
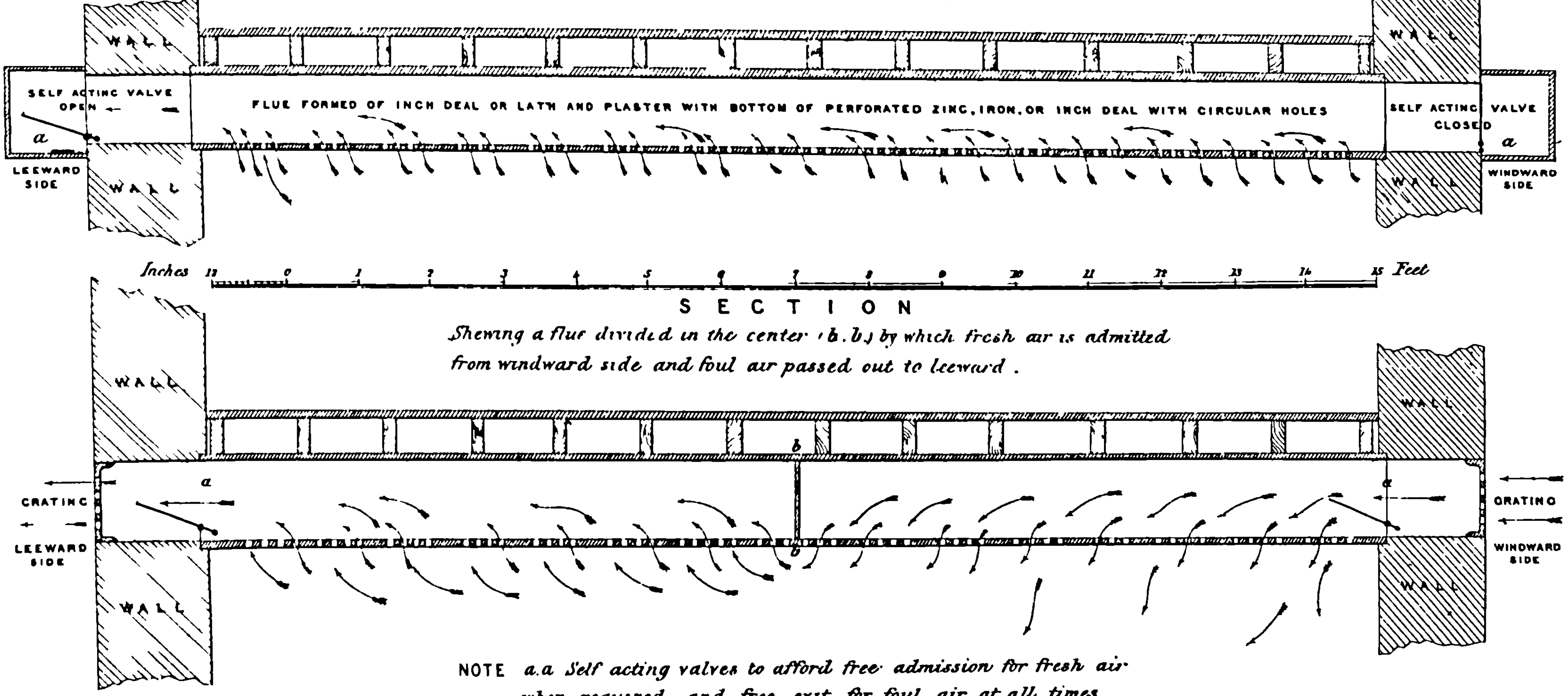


Figure 37 Portland Prison : Detail of Cell Ventilation and Heating

corridors of Portland and Portsmouth prisons, he had installed an iron grate in addition to each external door so that the doors could be left open all night for free circulation of air without diminishing security. He did not think an open fireplace alone was sufficient to ventilate a barrack room properly by convection by drawing foul air up the chimney, but he eschewed forced ventilation saying "under ordinary circumstances, the health of men may be preserved without resort to scientific measures."[86]

As an alternative means of ventilating barracks short of the introduction of forced air by way of either a heat-aided or mechanical system, Jebb submitted to the Committee a sketch of the system used at Dartmoor Prison where a natural ventilation concept was adopted "to provide for very moderate velocities, such as can be secured by taking advantage of the prevailing winds, or accidental variations of temperature within and without the building."[87] This device was a ventilating beam or flue under the floor, passing through the side walls and with self acting valves to control the ingress and egress of air. There were two models - one to evacuate foul air only and another to let foul air out one side of the building and fresh air in the other. (See Figure 38) The apparatus was later used in some barracks and military hospitals and was seen as an improvement on the ordinary ventilating beam employed in those buildings before the 1860's.[88]

According to Jebb, it was more important for a person in a prison cell or a barrack room to have fresh air all the time, without exposure to draughts, and sufficient space to move around, than to have a specified size of space either in floor area or cubic content.[89] Also, it is interesting that he preferred open fireplaces for rooms and supplementary to these in building passages hot water circulated in large pipes or large air stoves (a stove with a warm air chamber) lined with firebrick, as an economical substitute. He objected to iron furnaces because they got too hot and absorbed oxygen in the air making it "unfit for respiration."[90] Although he did not



SECTION

Shewing a ventilating flue open to leeward and closed to windward, with self acting valve for excluding fresh air and permitting the escape of foul air.

SECTION

Shewing a flue divided in the center (b.b.) by which fresh air is admitted from windward side and foul air passed out to leeward.

NOTE *a.a Self acting valves to afford free admission for fresh air when required, and free exit for foul air at all times. The Valve to windward to be fixed when necessary.*

Figure 38 Dartmoor Prison Ventilating Beams say so, Jebb was also implicitly rejecting Perkin's high pressure hot water system as well as various steam heat arrangements. His concern with a moderately warm heating surface had been important in his choice of Haden's apparatus for Pentonville. Jebb's preference for open fires, hot water, firebrick lined stoves, and natural ventilation were all to be taken up by Galton in the 1860's in his work on barracks and military hospitals.

Before leaving Jebb and the model prison, it is necessary to describe briefly the other aspects of building technology employed by him at Pentonville. The cells were lighted by inoperable windows high up, made of heavy iron bars on the outside with a lighter frame of mullions and transoms inside, enclosing small, fixed, fluted glazing to prevent seeing out but allowing sunshine in. Later Jebb recommended one pane in the frame should be glazed triple with ventilation through the panes to the inside. The night light was gas which Jebb considered as the best for "comfort and economy."[91] Gas was supplied by Pentonville's own gasometer. Tomlinson has questioned whether gas lighting was a humanitarian expression or a measure to keep prisoners at work longer, and points out that gas was costly and that prison authorities sometimes turned it off early to economize.[92] Water supply was from taps feeding into a copper wash basin and a glazed earthware toilet which had a water sealed trap. Acoustical design was concerned with preventing intelligible communication, not with controlling noise. Robert Smirke and later Abel Blouet, Michael Faraday and Dr. D.B. Reid had experimented on building sound diffusing walls at Millbank Prison in collaboration with prison inspectors Crawford and Russell. Ultimately, the inspectors decided upon 18 inch walls, double doors, arched ceilings and concrete floors to prevent the penetration of any comprehensible sound.[93] The walls for the model prison were brick, reinforced with hoop iron bond in the outer walls and in the ceilings of the upper cells. Ceilings were brick arches covered with cement. Floors were concrete with asphalt covering. Jebb's design also prevented audio communication by inoperable windows placed high up, heavy iron grills on ventilation duct openings, water sealed traps in toilets, and narrow, sheet metal covered timber doors with a spy hole and a trap door for meal trays.[94] Finally, Jebb made good use of fireproof, waterproof and sanitary materials - brick arch floors, concrete in corridor and cell floors, asphalt floor coverings, iron galleries, stairways and fittings and fixtures, and sheet metal on doors.[95] Indeed, Jebb's model prison was what the twentieth century might call 'a machine for living' but with life being sustained entirely in the cause of moral reform.

As a postscript to the present discussion of Royal Engineers' contribution to the design of Victorian prisons, brief mention must be made of Edmund Du Cane's Wormwood Scrubs Prison (1876-1883). In Du Cane's own view, the most notable feature of this prison was that it was constructed entirely by the use of convict labour, a procedure with which he was very familiar from his earlier career in Western Australia.[96] Du Cane abandoned Jebb's radial plan and adopted instead the pavilion plan which he considered a decided improvement. (See Figure 39) As Du Cane explained:

> "All the cells under this arrangement can have sunlight on them at some time of the day; there are no dank, dark courts and corners, as there must necessarily be on the radiating plan, and all the cell windows of one block do not overlook the yard attached to another block."[97]

By the 1870's the pavilion plan was well established in asylums, hospitals and barracks, and after Du Cane's introduction of the plan at Wormwood Scrubs, it gradually replaced the radiating wing arrangement for prisons.[98] Nevertheless, Wormwood Scrubs was the last major prison of the nineteenth century. Moreover, although Du Cane had substituted the pavilion plan for the radial plan, thus abandoning the concept of central inspection which had been a crucial principle in Jebb's design, the cells at Wormwood Scrubs were hardly distinguishable from those of the separate system prison of the 1840's and 50's. As

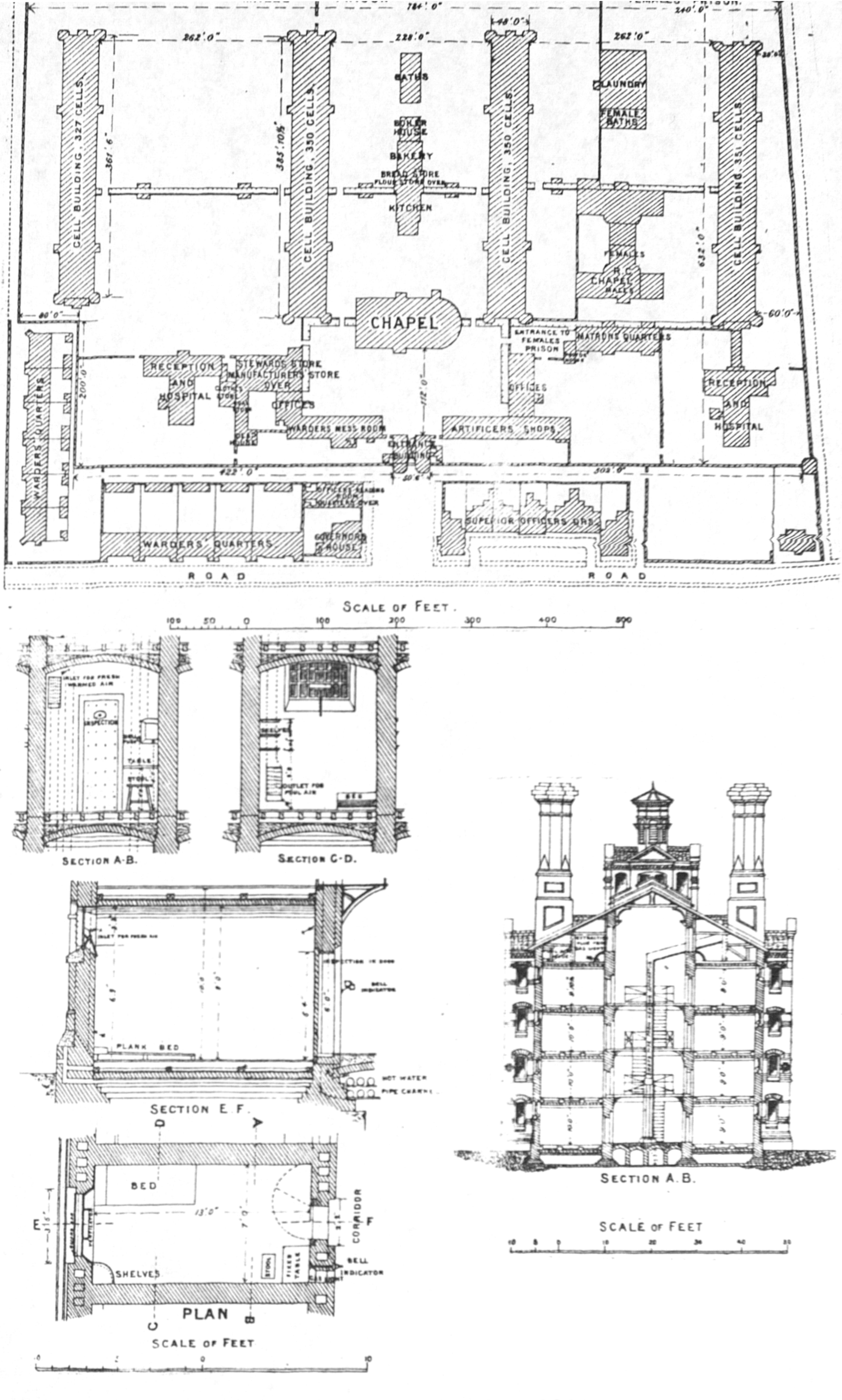


Figure 39   Wormwood Scrubs Prison, 1876-1883

Evans has observed, this demonstrates well how the idea of reform had been divorced from the prison architecture.[99]

The Corps, Barracks and Army Sanitary Reform

In the late eighteenth century barrack design and construction, which included military hospitals, was the responsibility of the Board of Ordnance, and work was carried out under the direction of the Chief Royal Engineer. However, in 1793 a new department called the Barrack Board, which reported directly to the War Office, was created in the midst of the French Wars to construct a large number of barracks and it took over this function completely except for Royal Engineer and Royal Artillery barracks. The Barrack Board was operated entirely by civilians. In 1822 barrack responsibility was handed back to the Board of Ordnance and the Royal Engineers who worked under the Inspector General of Fortifications, and the Barrack Board abolished. The Inspector General of Fortifications and the Royal Engineers reported directly to the Secretary of State for War after the discontinuance of the Board of Ordnance in 1855.[100] Royal Engineers also built barracks for the Royal Marines after 1837 as part of their responsibilities in the Admiralty Works Department. Civil architects were employed in barrack construction occasionally, but mainly for the design of elevations and decorative details, and usually with respect to officers' accommodation.[101]

The question of the role of the Corps in barrack and military hospital construction was given particular focus by the army sanitary reform movement following the Crimean War. Douglas Galton was to be a central figure in the movement and he would emerge as a distinguished expert and promoter of sanitary engineering in late Victorian Britain. Several Parliamentary select committees and a Royal Commission reported during and after the Crimean War and they were overwhelmingly critical of the standard of barrack and hospital accommodation and sanitary provisions. Distinction must be made between barracks for soldiers and those for officers, which were decidedly better. Barracks for the rank and file built from the 1790's to 1856 were almost all inadequate in design, faulty in construction, overcrowded, poorly ventilated, heated and lighted, and had defective sewage disposal and drainage.[102] In 1856 the soldiers' environment more than any other factor contributed to the extraordinary amount of sickness in the armed forces.[103] Sleeping quarters were particularly cramped and poorly ventilated. The minimum amount of space allocated per soldier by regulation was 450 cubic feet, 30 cubic feet less than a pauper was given in a Scottish workhouse.[104] The reformers advocated a minimum of 600 cubic feet per man and through ventilation of barrack rooms, amongst their several prescriptions for improving the sanitary condition of army accommodation. Their recommendations were accepted by the government and implemented after 1860.[105] It is with the matter of improving the ventilation and heating of barrack rooms that Galton and his colleagues were to make a notable contribution to the technology of building.

Reform of barrack accommodation involved establishing a watchdog agency, formulating an improvement programme and allocating more money for construction, rehabilitation and repair. In 1857 the government created the Barrack and Hospital Improvement Committee to implement reform which, four years later, became the Army Sanitary Commission. Galton was appointed to this body in 1858. His chief colleague on the Commission was Dr. John Sutherland. Douglas Galton had been commissioned in the Royal Engineers in 1840 and early in his career made some important contributions concerning the application of iron to railway structures while in the employ of the Railway Department of the Board of Trade (1847-1857). He served on the Army Sanitary Commission until his death in 1899. Galton was appointed, in 1860, Assistant Inspector General of Fortifications at the War Office, in charge of barracks. Two years later, Galton reluctantly resigned his army commission to become Assistant Permanent Under

Secretary of State for War, a post which only civilians could hold. Cook has claimed that Florence Nightingale arranged this to serve her objective of reorganizing the War Office towards sanitary reform.[106] Galton remained in the position until 1870 when he became Director of Public Works and Buildings for the Board of Works. He retired in 1875.[107] John Sutherland (1808-1891) was a physician and promoter of sanitary science. While practising in Liverpool in 1846, he edited The Liverpool Health of Towns Advocate and two years later became an inspector in the General Board of Health. In 1855 he was appointed to head a commission to investigate the sanitary condition of the army in the Crimea and in 1858 was also appointed to the Barrack and Hospital Improvement Committee on which he remained until his retirement in 1888.[108] Sutherland and Galton were close associates of Nightingale. Smith has argued that Nightingale used them in her quest for power and influence in the cause of sanitary reform.[109] Between 1861 and 1863, the Army Sanitary Commission, led by Galton and Sutherland, surveyed 111 major barracks and 59 military hospitals in implementing accommodation and sanitary improvements.[110]

While pre-1860 barracks were almost universally substandard in planning and services, two examples have been found where more advanced design and technology were employed. Significantly, these were the work of two Royal Engineers who figure prominently in this thesis - William Denison and Francis Fowke. Brief discussion of their respective projects serves as a useful context for an examination of the contribution of Galton and the Army Sanitary Commission.

In 1844-1845, Denison designed the Royal Marine Barracks at Woolwich for 960 men with 48 sleeping rooms. He supervised construction of the project until he was transferred to Portsmouth in June of 1845; the building was completed two years later. The contractor was Messrs. Rigby. This three storey brick structure with stone dressings had iron girder and brick arch floors covered with asphalt. The Builder said the whole was fireproof.[111]

It will be recalled that Denison had visited Liverpool to inspect fireproof mill construction with the object of applying it in buildings at the Woolwich naval dockyard where he was in charge of construction for the Admiralty. The most interesting feature of this building, however, was a mechanical forced air central heating and ventilation system. In the basement, a revolving fan worked by falling weights, forced air conducted from outside into two copper boxes containing the heat source (presumably hot water) and thence into a tunnel running longitudinally down one side of the basement from which flues ascended into rooms. Warm, fresh air entered the rooms near floor level, and each room had two flues near the ceiling from which foul air was conducted to the attic and then out via a foul air flue in the ridge of the roof inside a false chimney.[112] (See Figure 40) Denison was very critical of the conventional design for barracks in the 1850's which was to construct a single barrack with 18 to 20 men per room heated by a fireplace and ventilated by windows only. He strongly favoured a central heating system to distribute heat more equitably and some form of mechanical forced ventilation because soldiers had the habit of keeping the windows shut. For Denison, improving the salubrity of barracks was vital to the moral condition of the soldier.[113] His choice of central heating and mechanical forced air ventilation using a fan apparatus powered by falling weights was not new; the technology was at least forty years old. A system somewhat similar in principle to Denison's had been developed in 1813 by Benford Deacon, but it is not known if there was any connection between them.[114] Unfortunately, nothing has been found on how Denison's system worked. It was an important indication of his progressive approach to advanced building services, and his choice of a 'high technology' approach to ventilation and heating was to be a marked contrast to Galton's preferred arrangement for barracks nearly a decade later.

In 1850-1851, Francis Fowke produced a design for the new Raglan Barracks at Devonport naval dockyard

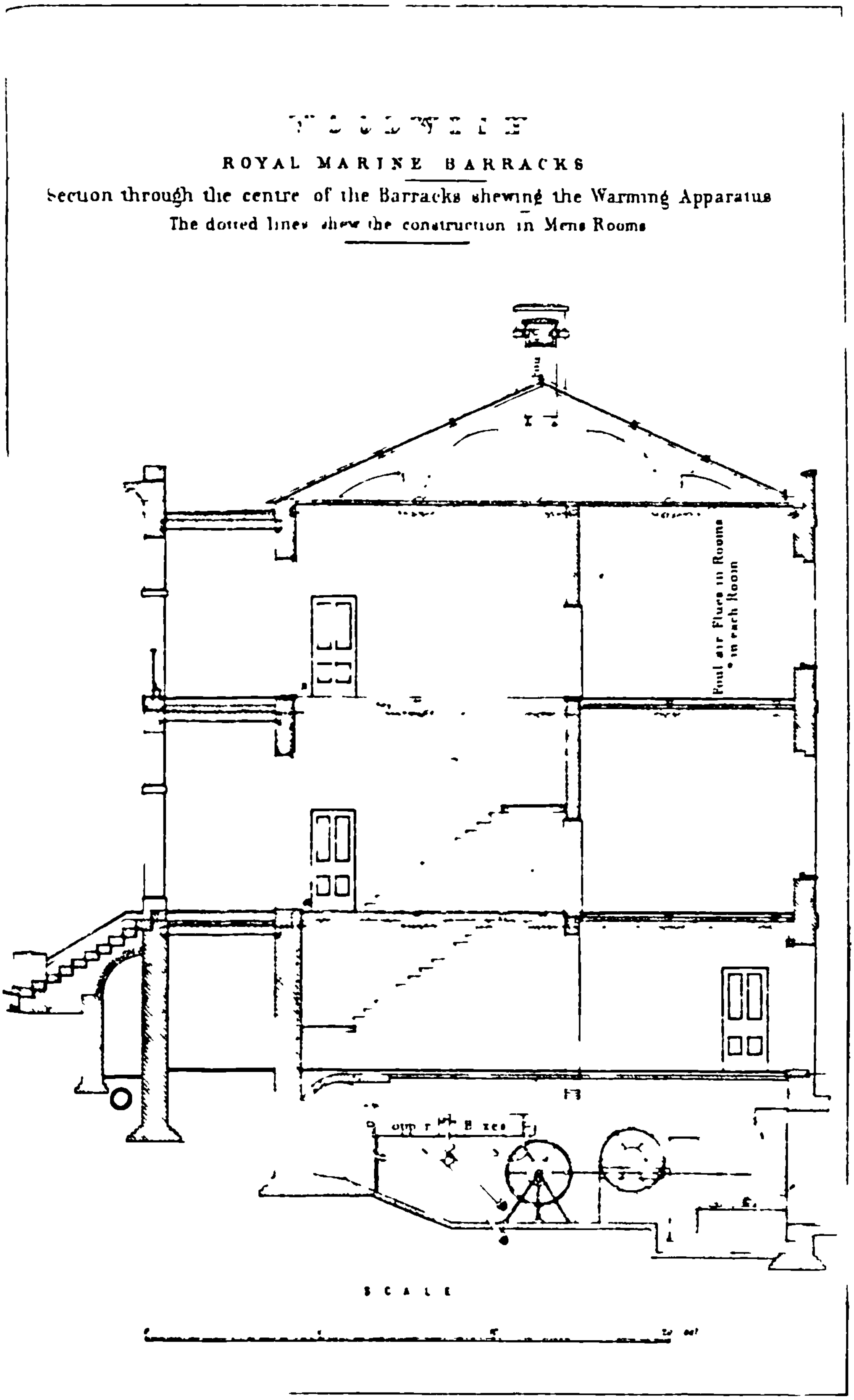


Figure 40 Royal Marine Barracks, Woolwich, 1845-47

to accommodate 2,000 infantry. The project was executed 1854-1856. Porter claims that Fowke "introduced novelties which were since incorporated in all new barracks" and the Dictionary of National Biography credits this noted engineer officer with "originating the many sanitary improvements introduced there."[115] Galton and the Army Sanitary Commission, however, were not so completely kind. Although Fowke's design was credited for avoiding the widely condemned arrangement of back-to-back rooms and for adopting instead single room blocks, the Commissioners criticised it because: "The windows are at the ends of the rooms instead of being along its sides, and the rooms are deficient in light and in means of natural ventilation in consequence."[116] The Commissioners preferred pavilion plans for barracks as they did for hospitals.[117] Although Fowke had complied with their wishes in his choice of plan, he had not met their expectations with respect to the details of natural ventilation and lighting. Galton was to become one of the foremost exponents of the pavilion principle in hospitals and of the application of its detailed design code for the construction of healthy dwellings generally. This topic is taken up in the next section.

The Army Sanitary Commission was particularly concerned with the ventilation and warming of barracks, a matter readily amenable to improvement in existing structures, which building plan generally was not. It was not the first, however, to examine this issue. As early as 1855, the Committee on Barrack Accommodation heard expert testimony from Joshua Jebb who, it will be recalled, expressed a decided preference for the open fireplace and natural ventilation in barrack rooms, while allowing that it should be supplemented with other non-forced air or central heating systems to increase effectiveness. Moreover, in 1857 the Commissioners Appointed to Inquire into the Warming and Ventilation of Dwellings reported to the General Board of Health on its findings concerning the best approaches to providing non-smoking, efficient fireplaces and stoves for the civilian population. The Commissioners were Sir William Fairbairn, James Glashier and Charles Wheatstone.

They had been asked in November 1856 by Inspector General of Fortifications, John Fox Burgoyne, to examine the warming and ventilation of barracks as part of their investigations, with the result that extensive experiments were performed by them at Wellington Barracks, London. The Commissioners subsequently concluded:

> "... we have to observe, in regard to the sanitary condition of the army, that a more defective system of warming and ventilation could not be devised than that exhibited at the Wellington Barracks, and assuming that those in other parts of the kingdom are not superior, if as good, we would beg to direct attention to the evils and defects which exist, not only in the construction, but in the management of these important establishments."[118]

The Commissioners called for more room for soldiers in barracks as well as a more economical and healthy system of heating and ventilating including improved firegrates and better chimney flues.[119] This matter was to be taken up by Galton and the Army Sanitary Commission.

Prior to 1860, barracks were generally equipped with the common fireplace, fitted with the regulation War Department grate; sometimes stoves were used as an alternative method of heating. Ventilation was normally by way of windows only. Barrack rooms were notoriously draughty and unevenly heated. The Barrack and Hospital Improvement Committee, as one of its first tasks made experiments on ventilation requirements for the newly specified regulation of 600 cubic feet per man and concluded that a barrack room's air needed complete renewal twice an hour.[120] Following this, the Army Sanitary Commission took up the issue of ventilation arrangements and examined systems in Parisian hospitals and in London. Galton and his colleagues looked at virtually every form of existing technology including: methods of propelling air by fans and screws driven by steam or other mechanical means; apparatus for extracting air by the draught of a heated flue or by mechanical contrivances; and devices for removing air by shafts and openings, variously planned and arranged to take advantage of natural air movement.[121] As discussed earlier, Jebb's heat-aided system for prisons was amongst the systems examined, but the Commissioners made no reference to Denison's remarkable forced air mechanical arrangement in the Royal Marine Barracks at Woolwich. Interestingly, the Commissioners concluded that mechanical means of ventilation was too expensive for barracks and lamented: "... in all these systems of ventilation, the open grate, with its cheerful fire, must disappear ... the two are incompatible."[122]

After much consideration, the Commissioners adopted the principle "to keep each barrack room independent of every other in respect to ventilation; and to depend for the movement of air in barrack rooms upon the fireplace and upon the element of the difference of temperature between the air outside and the air within."[123] The sectional areas of ventilation shafts were to be governed by the cubic contents of the room. Fresh air inlets were to be placed near the ceiling to prevent draughts. The construction of air inlets was to be of iron or perforated air bricks of different sectional areas. In principle, the Commissioners had not departed from Jebb's preference for natural ventilation of barrack rooms. Although informed by a legacy of experimentation and a process of extensive enquiry, one cannot resist the speculation that their choice rested as much on sentiment for the "cheerful" fireplace as on economy, effectiveness and reliability. The matter of economy and effectiveness was the motivation for Galton's development of a remodelled firegrate. Reliability depended, in the Commissioners' view, on it being made "someone's business to see that it is not tampered with, nor allowed to get into a state of disrepair or inefficiency."[124]

Galton's invention of a novel ventilating firegrate was a crucial component in the Army Sanitary Commission's recommendations. The Commissioners' report of 1861 did not credit Galton specifically for the achievement nor did Galton claim responsibility for it in his publications on the subject, but it was common knowledge that the invention was his. He was the only Commissioner with expertise in mechanical engineering and building construction. General Arthur-Jules Morin of the French Artillery and head of the prestigious Conservatoire desArts et Metiers, himself an expert and noted author on ventilation and heating, considered Galton's apparatus the only device for perfect warming and ventilating with the open fireplace produced during the nineteenth century.[125] An adaptation of the original invention was developed for hospital stoves and applied first in Galton's Herbert Hospital at Woolwich. Another variation was developed for married soldiers' barrack accommodation which combined cooker and heater. All of the models were still being used in 1898.[126] (See Figures 41 and 42)

This remarkable apparatus was first used following a memorandum dated 3 February 1860, from Galton, Assistant Inspector General of Fortifications, to all Commanding Royal Engineers advising them of the new device and the War Office's supplier - Messrs. Kennard and Company of 67 Upper Thames Street, London.[127] Galton later explained that the invention was not patented. In his view, it was partly for this reason that the apparatus was not applied much outside the army because "manufacturers did not care to suggest its use."[128] By 1869 the firegrate was being installed for the army by Edward Deane of 1 Arthur Street East, London, E.C., and the devices for married soldiers' quarters were made for the War Office by Messrs. Benham of Wigmore Street, London.[129]

Galton's firegrate had two fundamental working principles: to economize and aid the combustion of fuel; and to utilize waste heat passing up the chimney to heat the grate which in turn heated fresh air drawn from the outside atmosphere to warm and ventilate the room. Galton described the operation of his invention:

> "The flame, heated gases from combustion, and such small amount of smoke as exists are compelled, by the form of the back of the grate and the iron part of the smoke flue, to impinge upon a large heating surface, so as to subtract as much heat as possible out of them before they pass into the chimney, and the heat thus

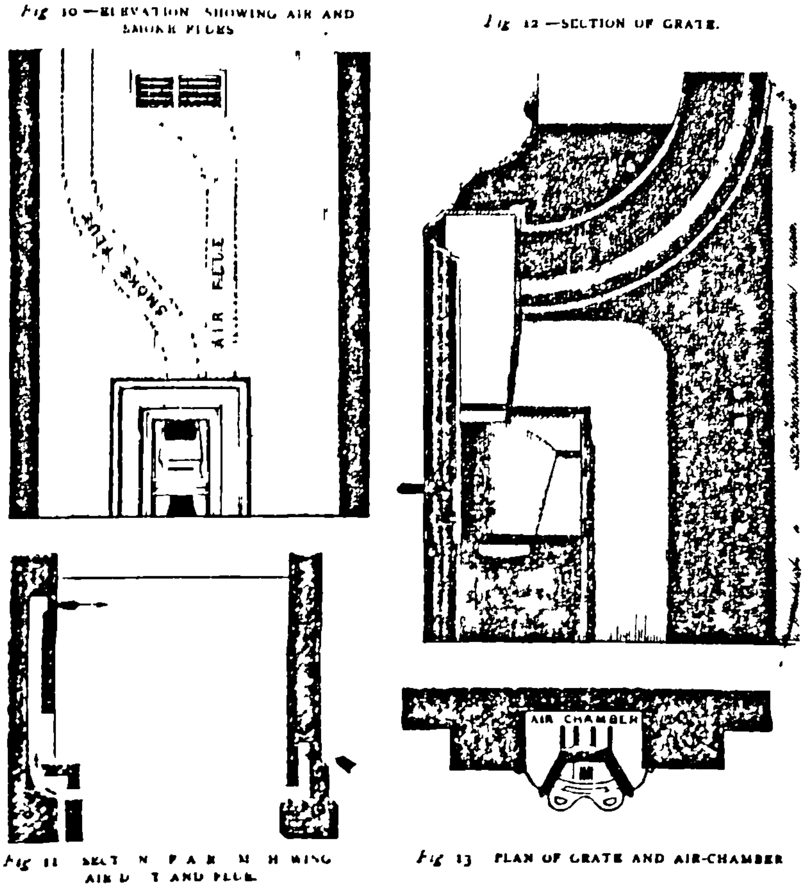


Figure 41 Galton's Ventilating Grate

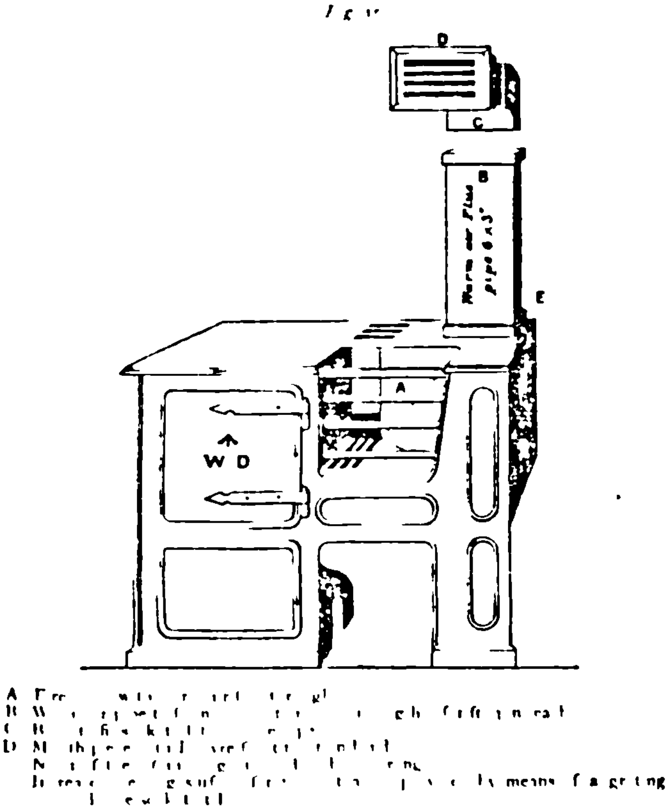


Figure 42 Cooker with Galton's Grate

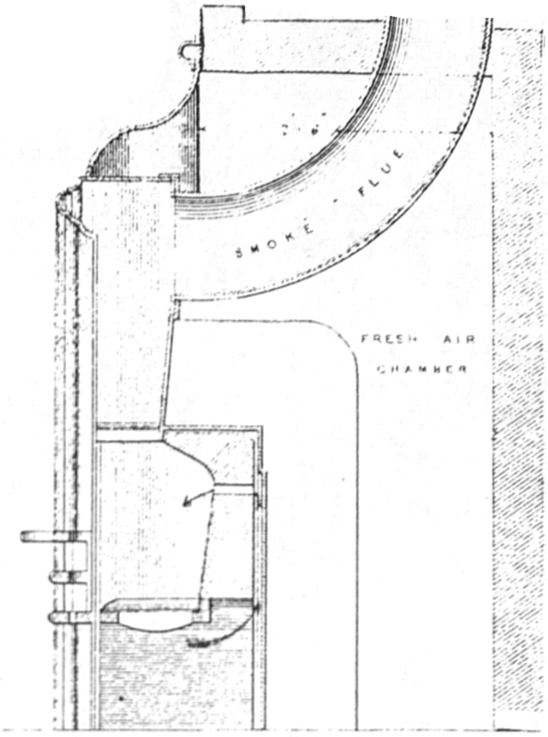


Figure 43 Galton's Ventilating Grate : Detail

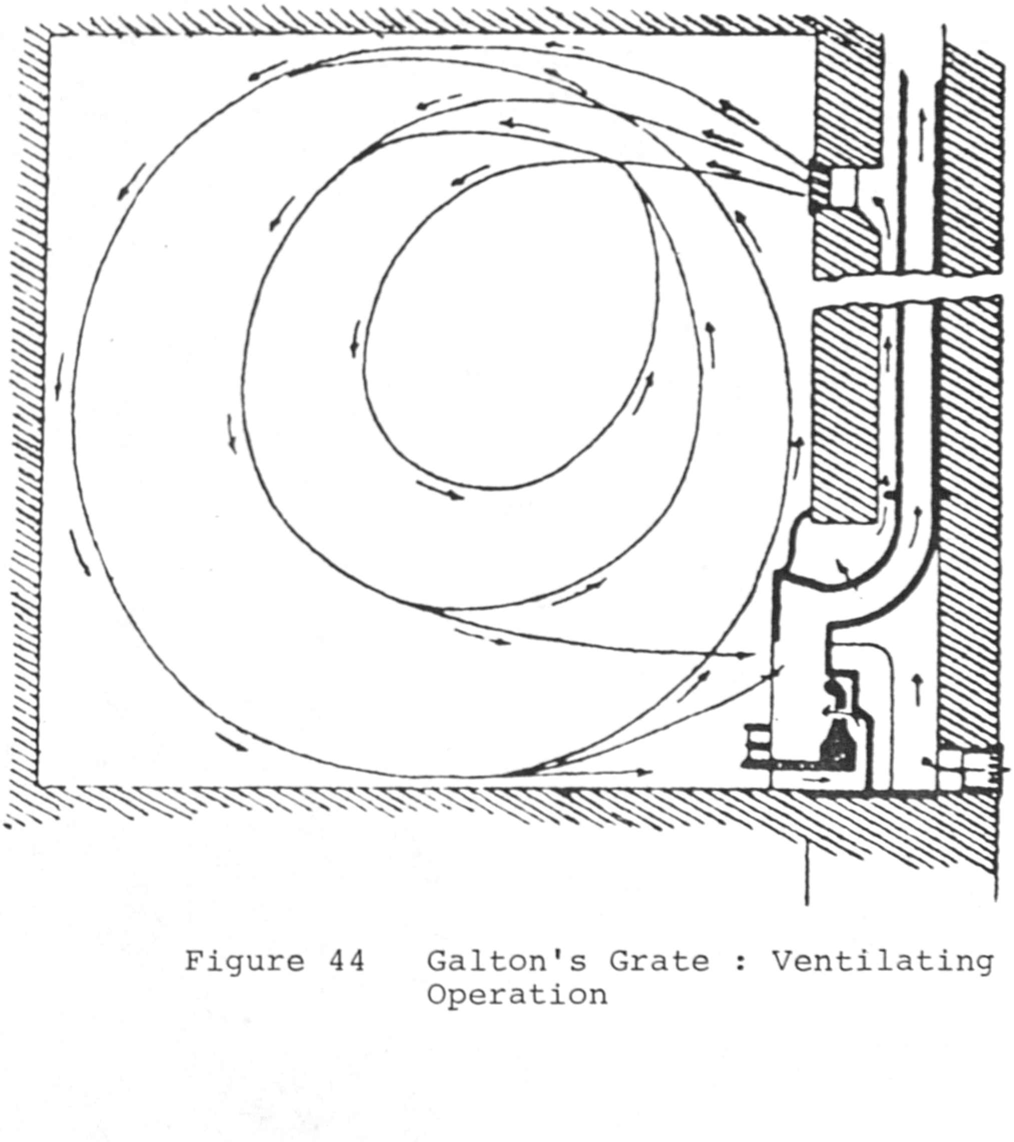


Figure 44 Galton's Grate : Ventilating Operation

> extracted is employed to warm air taken directly from the outer air. The air is warmed by the iron back of the stove and smoke flue, upon both of which broad flanges are cast as to obtain a large surface of metal to give off heat. This giving off surface ... is sufficient to prevent the fire in the grate from rendering the back so hot as to burn the air it is employed to heat. The fresh air, after it has been warmed, is passed into the room near the ceiling by the flue..."[130]
> (See Figures 43 and 44)

With this invention Galton essentially had perfected the traditional 'low technology' approach to heating and ventilating houses. It is interesting that he had proven wrong the opinion of such distinguished men of engineering and science as Fairbairn, Glashier and Wheatstone who had investigated several ventilating firegrates patented between 1781 and 1857 and pronounced against the concept of a grate constructed to warm and ventilate conjointly. These experts, in their capacity as members of the Commission Appointed to Inquire into the Warming and Ventilation of Dwellings, said in their 1857 report: "The Commission is decidedly of the opinion that as long as the firegrate is studied with a view to this twofold application, it will not succeed well in the performance of either."[130] Perhaps more significantly, Galton had managed to retain the pleasure of the open fireplace to which the English were so sentimentally attached while improving its practical performance.

Galton, the Pavilion Principle and Herbert Hospital

Military hospitals had also been the subject of the Army Sanitary Commission's investigations and improvement campaign. In 1860 military hospitals were of two kinds - the regimental hospital situated at barracks, and the general hospital. The former were by far the most numerous. The Army Sanitary Commission found that the usual form of barrack hospital was a barrack house consisting of a two or three storey building with a passage and staircase occupying the middle of it and with the rooms entering from right and left. More recent ones had a corridor down one side of the building with centre staircase and rooms running off the corridor. The nearest approach to the preferred pavilion plan in the house hospital type was Aberdeen Barrack Hospital where two large wards opened right and left out of a central passage and staircase. The Commissioners also described a few examples of the misapplication of the pavilion principle in England, including the General Military Hospital, Stoke, Devon. Space per patient compared unfavourably with London workhouses, and although most existing military hospitals recognized the need for ventilation, it too was deficient. The almost universal method of ventilation in use was that of carrying hollow beams above and across the ceilings of the wards, opening to the outer air at the ends where they were carried through the external walls and into the wards by auger holes or large circular apertures in the ceilings. They were intended to act as outlets for foul air but at most times, especially where fireplaces were operating in wards, acted as badly placed inlets for cold air to supply the draught of the chimney. Cold air poured directly down on patients' heads. Inlets therefore were usually closed by paper pasted over them to stop the nuisance. Windows were also used for ventilation but they were generally not high enough for foul air at ceiling level to escape. A few hospitals had Arnott's ventilators. For heating, the ordinary regulation grate with its large wasteful fireplace was in general use. Some recently built hospitals had Anglo-American stoves to increase heat but the apparatus' ventilating merit was doubted. The Commissioners recommended that heating and ventilating be improved in the same manner as with barracks, including Galton's ventilating fireplace grate. Existing hospital plans could not be improved since the Commissioners favoured the radically different pavilion principle; for this they would have to construct new buildings. Their recommodation was realized in September 1861 when work started on Galton's Herbert Hospital at Woolwich, a large general military hospital.

The Herbert Hospital was constructed to replace the Garrison Hospital at Woolwich which had become seriously overcrowded and which appeared impossible to enlarge and convert according to the pavilion principles of planning.[131] Galton's brief called for a hospital on the pavilion principle with 620 beds plus a ward of 28 beds for prisoners and a small ward for itch patients.[132] He designed an imposing complex of buildings in the Italianate style occupying an area of 523,500 square feet and with the structures enclosing some 74,450 feet in all, or nearly 115 square feet per patient.[133] The hospital complex included an entrance administrative block, nurses quarters, orderlies quarters and dining room, chapel, library and kitchen, in addition to the seven parallel pavilions which contained wards.[134] A water supply building and washing establishment were also constructed remote from the main hospital complex.[135] Herbert Hospital was completed in March 1865 and cost £220,884.[136]

Although costly to construct, high in maintenance costs and extravagant in the use of land, the pavilion plan was to dominate hospital design from its introduction in Britain in the 1860's well into the twentieth century. For Galton and other advocates, the pavilion principle was more than simply a plan; it was an entire design philosophy which expressed itself in every aspect of the planning, construction and servicing of a hospital. It was a marriage of architecture and medicine which embodied the interests of the professions associated with these respective disciplines.[137] Accordingly, the selection of building technology mirrored ideas, beliefs, and values. The Herbert Hospital was a case study of this important phenomenon in Victorian Britain.

At the root of the pavilion principle was a theory of disease contagion known as the miasmic or zymotic theory. It contended that disease was caused by noxious emanations from a diseased source which passed through the air, adhered to building surfaces and was present in the soil and stagnant water. Good ventilation and drainage therefore became the prime objects of the pavilion plan design discipline.[138] The use of the miasmic theory as a rationale for siting, planning and ventilating structures was not new to the 1860's. Royal Engineers had referred to it, for example, in their work on barracks for tropical climates in the 1820's and 1830's (see Chapter 8). Nevertheless, the experience of the Crimean War and Florence Nightingale's and others' campaign against bad air and soil in hospital environments, were the most immediate influences in the connection of the miasmic theory to pavilion design.[139] Galton's articulation of the miasmic theory and its consequences for design, although consistent with the conventional wisdom, is worth quoting:

> "... the causes of deteriorated health... arise from poisons in the soil we live on, the air we breathe or the water we drink *emanating from decomposition*... Practical sanitary science is thus embodied in the words pure air, pure water - these conditions include pure sub-soil."[140]

The siting of a building and its layout to achieve good drainage and air circulation were important, but even more critical was the arrangement of enclosed space to provide good through ventilation:

> "The purity of the air within an inhabited space, enclosed on all sides, is necessarily vitiated by the emanations proceeding from the bodies of those who inhabit it, and especially by the effect on it of their respirations. With persons suffering from disease, especially infectious fevers, or from wounds, or sores, these emanations are greater in quantity and more poisonous in quality, than from persons in health. Stagnation in the movement of air would lead to rapid putrefacation of these emanations."[141]

Galton clung to the miasmic theory even after it had been discredited in the 1860's and 70's by advances in the germ theory. In this he was inspired by Nightingale for whom the miasmic theory was a political weapon. Theories about specific causitive agents for specific diseases and the germ theory were detested by Nightingale because she perceived them as barriers to action, and each advance in the germ theory diminished sanitary reformers' opportunities to advocate work that won public esteem.[142] Galton quietly changed his mind in the mid-1880's, but in one of the last publications before his death, while mentioning Pasteur's and Lister's discoveries, he had not fully abandoned his old attachment to the miasmic theory - cleanliness and fresh air were still for him the most important factors in hospital construction.[143]

The origin of the pavilion plan hospital has been traced by Thompson and Goldin to France, specifically to the report of a commission which examined the matter of rebuilding the Hotel Dieu in Paris in 1788. Two of the commissioners had visited England as part of their enquiries and had seen the proto-pavilion plan hospitals of the Royal Navy at Plymouth and Portsmouth. These English navy hospitals influenced the Commissioners' design which was approved by the French Academy of Sciences but not built, because of the revolution, until 1821 at Bordeaux. The French pavilion was first used on a major scale in the Hôpital Lariboisière (1846-1854) in Paris.[144] Nightingale is usually given credit for being the earliest advocate of the pavilion principle for hospital design in England, but King has shown that she was anticipated in print, beginning in March 1856, by John Roberton, a surgeon at Manchester Lying-In Hospital, and by George Godwin, architect and editor of The Builder.[145]

At the time Roberton and Godwin first published articles advocating the pavilion plan for hospitals, Galton was in the United States on Railway Department business investigating American progress in railroads. In 1857 Galton was appointed a government referee on plans for the main drainage for London and it was no doubt in this capacity that he was given his first major exposure to sanitary engineering. The next year he was appointed to the Barrack and Hospital Improvement Committee, and was enlisted by Sidney Herbert, the chairman, to improve radically the ventilation system for the much criticised

Royal Victoria Hospital at Netley, a large general military hospital constructed from 1856 to 1861.[146] Galton gave credit for the promotion of pavilion principles in England to a committee of army medical officers which had been appointed by the Director General of the Army Medical Department in 1856 to report on a proposed hospital at Aldershot camp.[147] He further indicated that it was the Royal Commission on the Sanitary State of the Army (1857) which specified the pavilion plan for all future military hospitals and that the Barrack and Hospital Improvement Committee on which he sat worked out the details.[148]

The pavilion plan hospital proposal for Aldershot was approved by the Army Medical Department in November 1856 but evidently remained only a design on paper in the summer of 1857. The design had been submitted by F. Warburton Stent, clerk of the works in the Royal Engineer Department, and it incorporated the suggestions of Dr. Mapleton of the Army Medical Department.[149] Unfortunately, no evidence has been found to indicate whether or not Stent's Aldershot hospital design was executed. The first pavilion hospital actually begun in England was the Blackburn Infirmary. Construction started in January 1858. The Herbert Hospital though was completed before it, making Galton's building the first pavilion plan hospital to open in the country.[150]

Responsibility for the design of Herbert Hospital was not entirely Galton's, as he himself was willing to admit. Galton acknowledged the assistance of R.O. Mennie, Surveyor of Works to the War Department, in "designing the plans for the hospital and the contingent arrangements..."[151] Mennie was appointed Surveyor of Works in 1852, the first to hold the position. He had been clerk of the works with the Royal Engineers in the Ionian Islands for nearly twenty-two years at Corfu, and had been at Portsmouth for over two years before his appointment as Surveyor of Works.[152] Mennie designed the Royal Victoria Hospital at Netley in which Galton had improved the ventilation system.[153] It is likely that

Mennie was of considerable help to Galton on the practical details, especially given Galton's lack of earlier building experience. As Galton testified to the Barrack Works Committee in 1861, his knowledge of barrack design and construction was based on his limited work as Assistant Inspector General of Fortifications, a position which he held effectively from October 1859, and that he had no personal experience in the execution of barrack works.[154] Galton's two years'work on the Barrack and Hospital Improvement Committee no doubt made him knowledgeable about the theory of pavilion plan design and on ventilation and heating services, but he was very short on practical building expertise. Galton also acknowledged Nightingale "whose practical experience was of great assistance in the design."[155] Cook claims that Nightingale "*even drew up the heads of the specification* for it."[156] The works were superintended by Captain Newsome under Colonel Ford and Colonel Hawkins. Newsome was assisted by clerks of the works Mr. Parry and Mr. Tait. Contractors were Messrs. G. Meyer and Son.[157]

It is instructive to review in detail the plan, construction and servicing of the Herbert Hospital in attempting to interpret Galton's contribution to the development of the pavilion principle in hospitals. His work there heavily influenced his promotion of the principle throughout the balance of his forty year career as a sanitary engineer and reformer. It is particularly revealing to assess Galton's practical application of the pavilion principle and its detailed sanitary code in the light of the opinions of advocates like Roberton, Godwin and Nightingale, and from the perspective of Galton's later views. Furthermore, it is useful to compare Galton's solutions in the Herbert Hospital to contemporary approaches to design in British civilian hospitals and attitudes towards them especially as indicated in the report by Dr. John Syer Bristow and Mr. Timothy Holmes to the Medical Officer of the Privy Council in 1863 on the hospitals of the United Kingdom.[158]

Site selection and drainage were important starting points for the pavilion sanitary code.

The Builder had begun a feature series on hospital construction in 1858 with this topic.[159] Galton evidently had found that only two sites afforded the space and aspect necessary in the Woolwich area. The preferred one, with gravelly soil, the owner refused to sell.[160] The Builder criticised the selected site for its poorly drained boggy clay soil.[161] Galton drained the site with a complex network of agricultural drains below the layer of concrete and rubble forming the buildings' foundations. In 1865 the eastern pavilion and other portions of the hospital showed signs of subsidence which was attributed to laying of the drain pipe below the artificial foundation rather than above, and part of the hospital had to be underpinned and a more solid foundation built.[162] Galton used a damp-proof course of glazed perforated brick just above ground level and a granite surface drain all around the walls.[163] In later writings, Galton was to advocate asphalt as a damp-proof material for foundations.[163]

The block plan of a pavilion hospital was its most distinctive characteristic. In the Herbert Hospital Galton used seven pavilions of three storeys each arranged side by side and connected by a 715 foot corridor extending the whole length of the building on the basement floor and ground floor, and as an open terrace on the first floor. Pavilions were spaced 63 feet 9 inches apart. While this layout took up a large area relative to the enclosed space provided, it furnished unobstructed air circulation and light - two major objectives of the pavilion principle of design. Galton's pavilion arrangement was similar to the preferred block plan illustrated by Roberton and Godwin in The Builder in 1858.[164] The Builder commented in 1865 that the Herbert Hospital was "a model arrangement for that class of building" but that it "might have desired certain features of the plan slightly different, and certain of the decorative details more as the product of an artist's hand."[165] The limit of two floors above ground level was specified by the Barrack and Hospital Improvement Committee. In the Committee's opinion, more than two floors was unhealthy because of the difficulty of ventilation resulting from the tendency of impure air of the wards below to pass, by means of the staircase, into the upper wards.[166] Galton later argued that more than two floors was also undesirable because it increased the distance which pavilions had to be placed apart and took up correspondingly more site space. The rule of thumb was that pavilions should be placed at a distance equal to twice their height.[167] Not everyone agreed with the idea that more than two floors was unhealthy. As Bristowe and Holmes explained, this was contrary to their own observation and also to the almost unanimous opinion of hospital authorities, and that to conform to this idea would call for "an increase in the area of two thirds of the hospitals in the kingdom."[168] They saw the limit of two floors as purely a matter of convenience since it was hard to service floors above the second without lifts. Herbert Hospital had steam powered hydraulic lifts for goods and supplies but not for passengers.[169] St. Thomas's Hospital (1868-1871), London, designed by Henry Currey, was four storeys and had a hydraulic passenger lift in each of its six pavilions which were stretched out on a 900 foot continuous corridor.[170] (See Figures 45 and 46)

The ward plan was another critical aspect of the pavilion principle with each ward being in effect a separate hospital. Galton's Herbert Hospital met the specifications of what Thompson and Goldin have called the "Nightingale Ward".[171] Bath and water closets were separated from the ward by a ventilated lobby as were the nurses' office and scullery at the opposite end. The open ward had beds placed on either side with one window for every two beds. A ward measured 117 feet 4 1/2 inches long by 26 feet wide and accommodated 32 beds. Waste pipes were all trapped just under the outlet from the basin, and sewage was carried directly out of the building with no drain passing under it. Precautions were taken against drain smell entering the ward.[172] It is significant that Galton's ward design was virtually identical to the pavilion hospital ward layout published by Roberton and Godwin in The Builder, 25 September 1858,

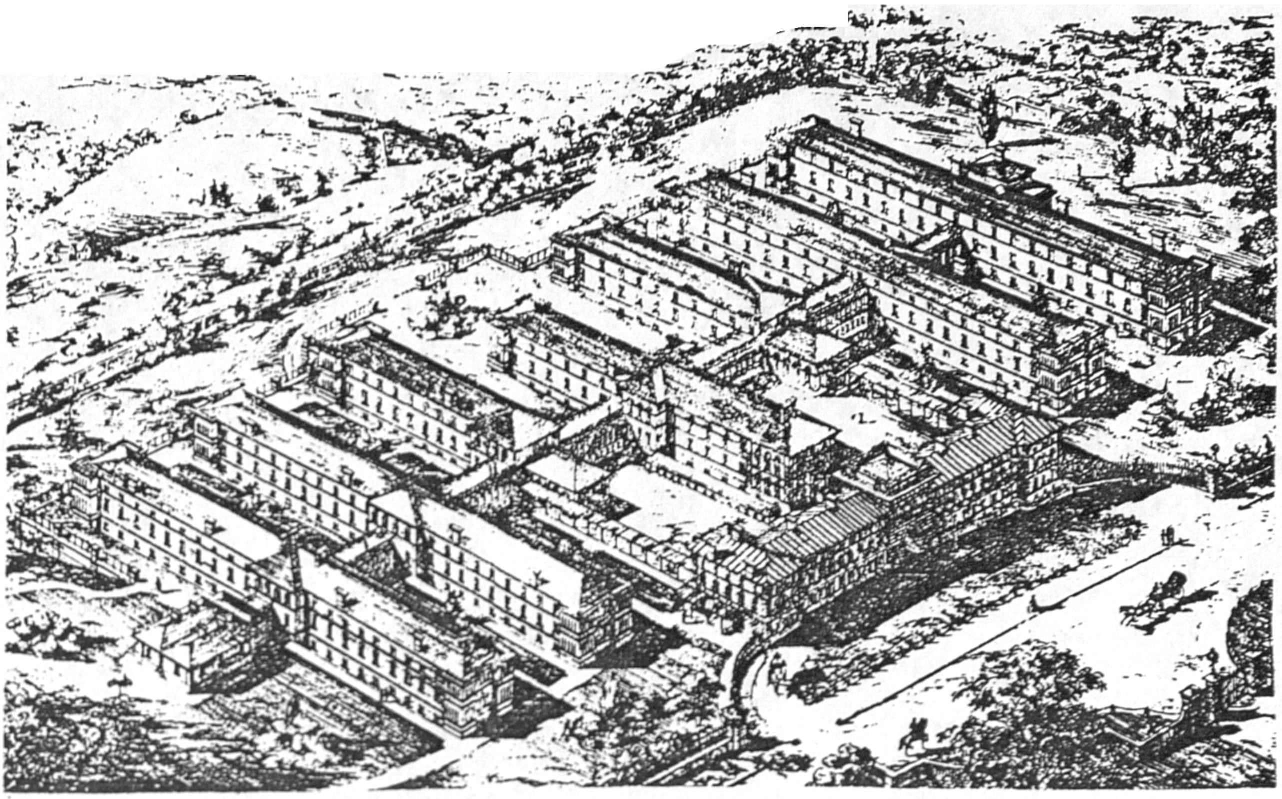


Figure 45 Herbert Hospital, Woolwich, 1861-65 : Birdseye View

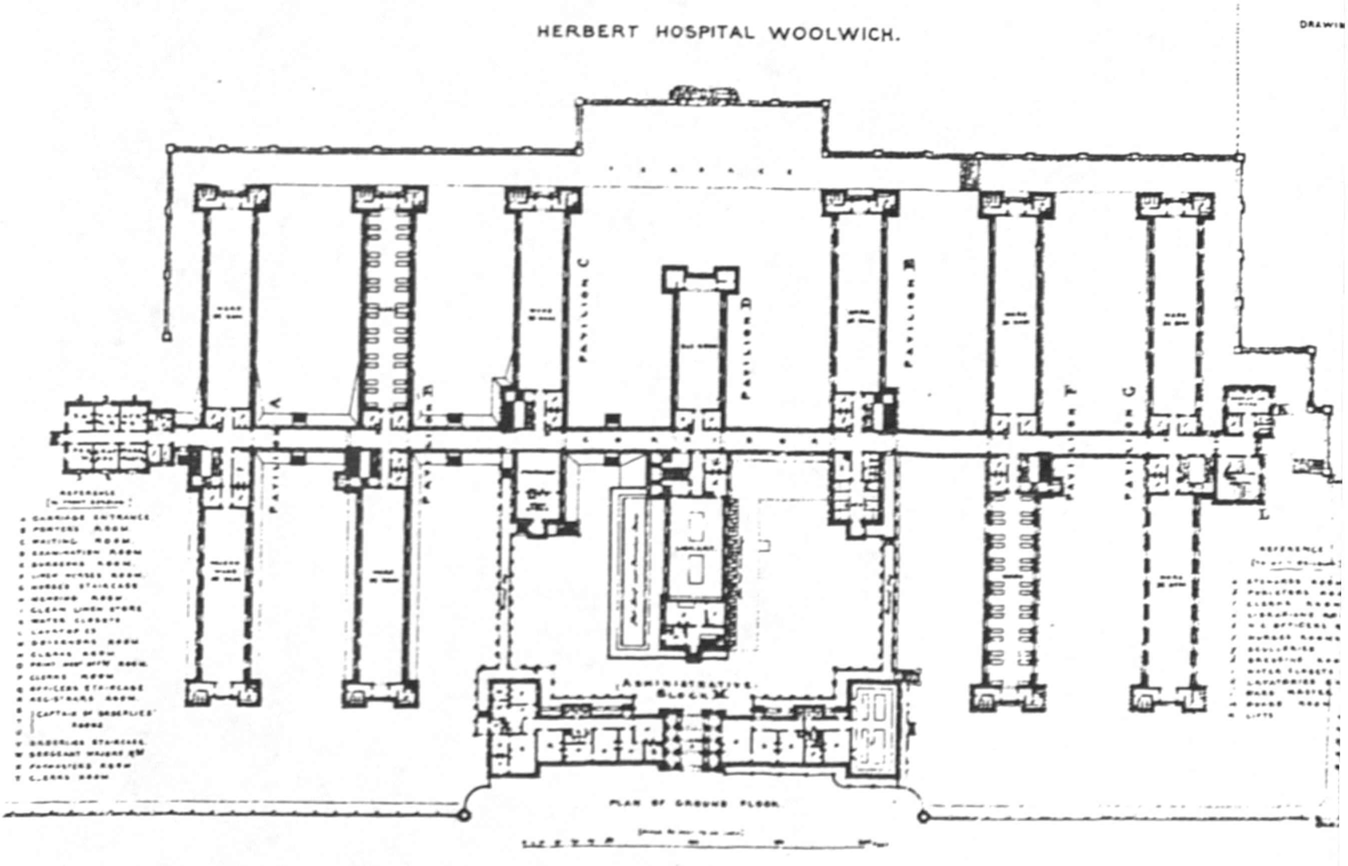


Figure 46 Herbert Hospital : Ground Floor Plan

except that the Herbert Hospital wards were marginally smaller.[173] (See Figures 47 and 48)

The construction techniques employed by Galton are also of interest. Hoop iron bond was used to reinforce the brickwork below window sills and under the ceiling line. In order to economize on warmth and ensure dryness, Galton employed cavity walls. The inner portion was 14 inches of stock brick, the ties were vitrified bonding bricks ('Jennings'), the air space was 3 inches, and the exterior was stock bricks faced with white Suffolk bricks. Plate glass was used for insulation. Fox and Barrett's patent floors of iron joists and concrete were used for fireproofing, soundproofing and airproofing. Iron was used for fireproof staircases and Galton left his engineer's mark on these by designing an interesting trussed girder to carry the stairs. Oak floor coverings, well waxed and polished, and Parian cement walls were used to provide non-absorbant, sanitary surfaces. Galton's choice of Parian cement plaster was in keeping with the accepted conventions for British hospitals of the time. Herbert Hospital was lighted by gas and had a hot and cold water supply.[174]

Galton's major contribution in Herbert Hospital, however, was in the heating and ventilating arrangement which was adapted from the basic system which he had developed for barracks. The warming and ventilation of wards combined windows, Sherringham ventilators, a ventilating shaft and ventilating stoves. Ward windows followed the conventional prescription for pavilion hospitals for plentiful fresh air and light, and were designed so that patients could see out and to add cheerfulness to the wards. They were 4 feet 6 inches wide, 9 feet apart, 2 feet from the floor, 1 foot from the ceiling and double hung. The wards also had an end window which was circular headed with the lower part a casement. It opened by falling inwards so as to direct incoming air towards the ceiling. Sherringham ventilators were located between the windows close to the

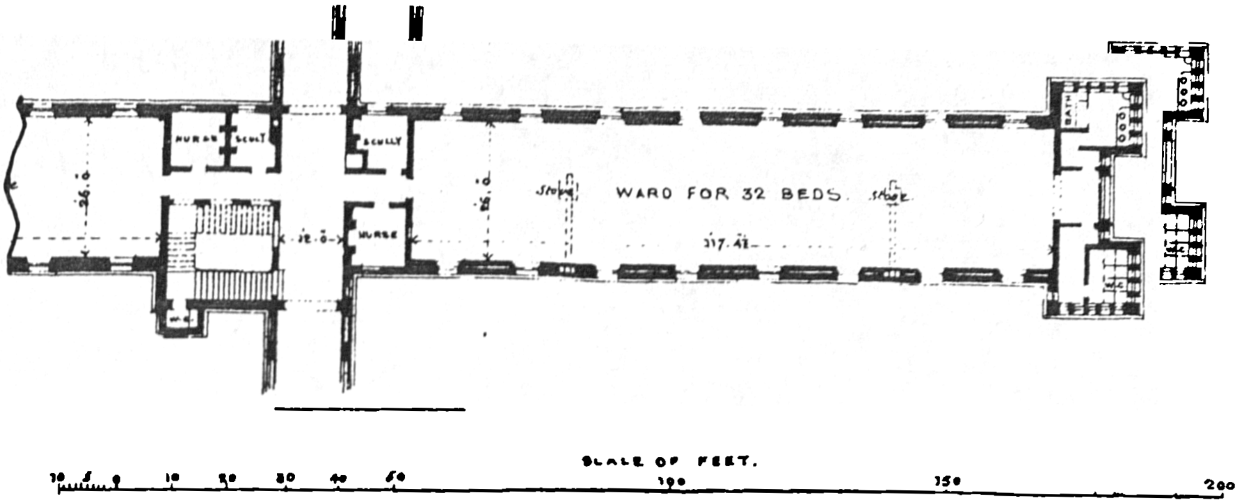
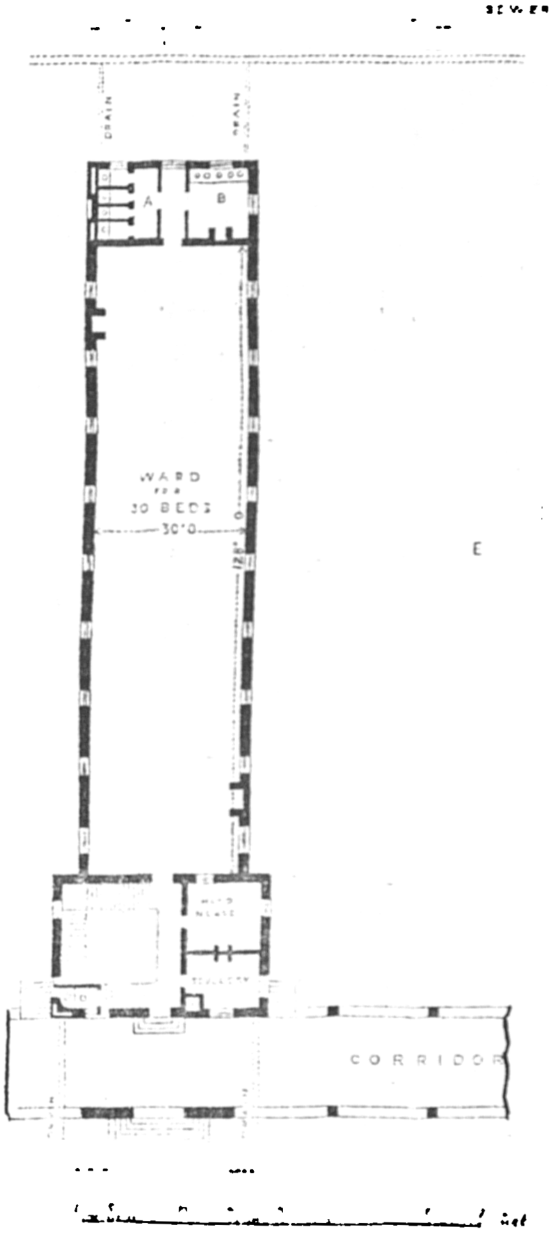


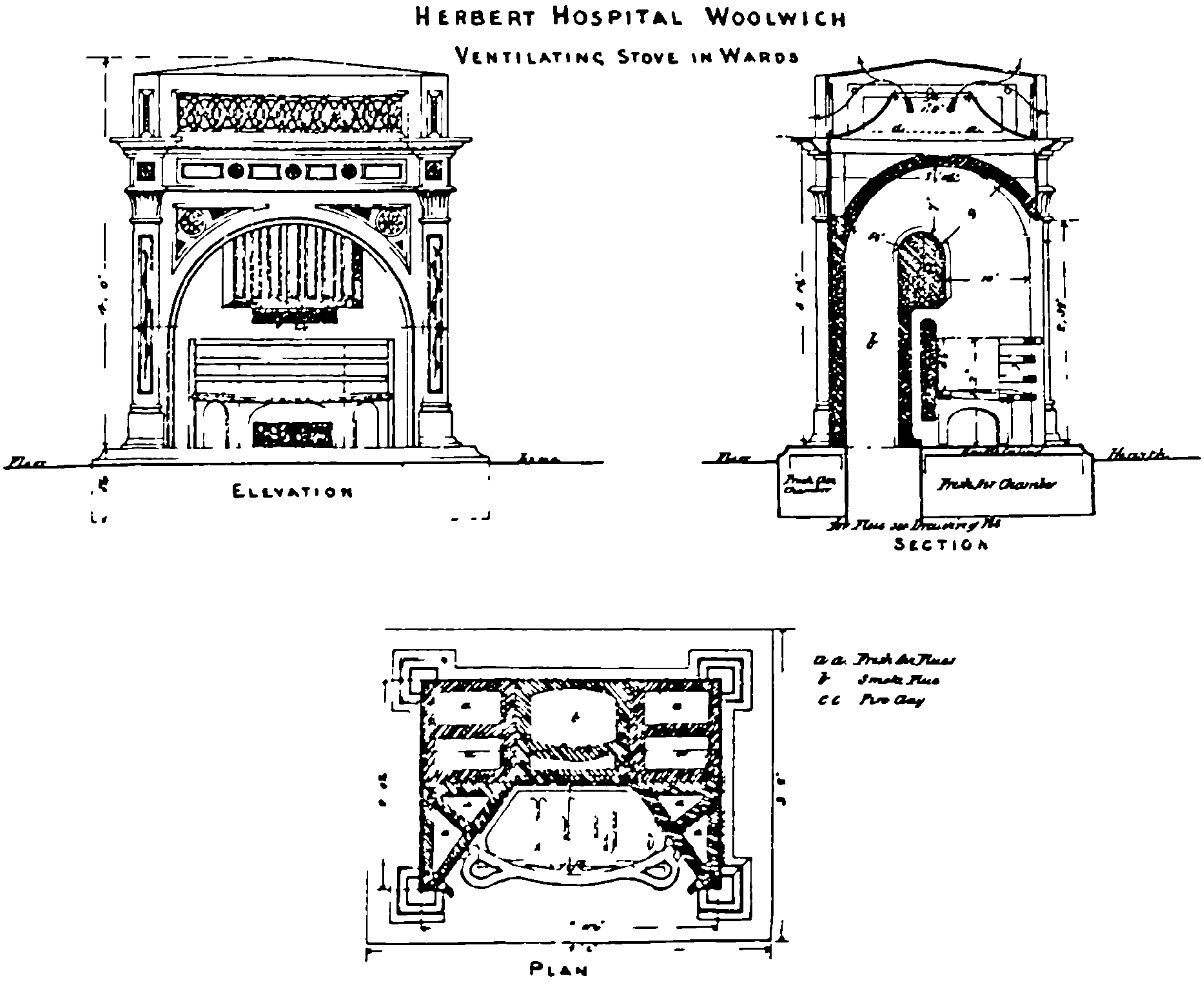
Figure 47 Herbert Hospital : Ward Plan



A. Ward Closets.
B. Bath and Lavatory.
C. Lift in Scullery.
D. Private Closet.
E. Ornamental Ground.
Ward Windows to be 4 ft. 8 in. in the clear.

Figure 48 Roberton's and Godwin's Ward Plan for a Pavilion Hospital ceiling on each side. The ventilating shaft was located at each angle of the ward, carried up above the roof for the escape of foul air. These devices produced the ventilation when heat was not required. In weather requiring warming, fresh air was also introduced from the specially constructed ventilating stoves located along the ward centre line. These stoves used Galton's grate. The fire rested in an iron cradle lined with fireclay back and side. Chimney flues passed under the floor within an air shaft bringing in from the outside fresh air to be warmed by the stoves. By this means more than 36 feet of heating surface were obtained for warming fresh air in addition to the heating surface in the stove. The stove thereby distributed warm, fresh air to the ward and warmed also by radiant heat.[175] (See Figure 49)

Experiments were undertaken on the efficiency of Galton's ventilating stoves by Dr. Parkes in a hospital ward at Chatham in April 1864, and by Arthur-Jules Morin from 1864 to 1866. Parkes found that the temperature in the room did not vary more than 1° F compared to a common fireplace grate's performance of 4 to 6° F. Morin found that Galton's grate required only a third of the coal used in a conventional grate while providing good ventilation and keeping an even temperature. Galton claimed the following advantages for his ventilating stove in Herbert Hospital: it ventilated the room, maintained equable temperature in all parts, and prevented draughts; radiant heat was better than from other grates; the firebrick lining prevented the fire from going out and prevented rapid changes of temperature in rooms during cold weather; it economized on fuel by making use of heat which would otherwise pass up the chimney; its construction ensured complete combustion, thereby diminishing smoke; and it prevented smoking chimneys by bringing an ample supply of warm air to the room and by the draught created in the neck of the chimney.[176] The Builder said the stoves were "very important contributions to good hospital construction."[177] In spite of this, the apparatus was not universally



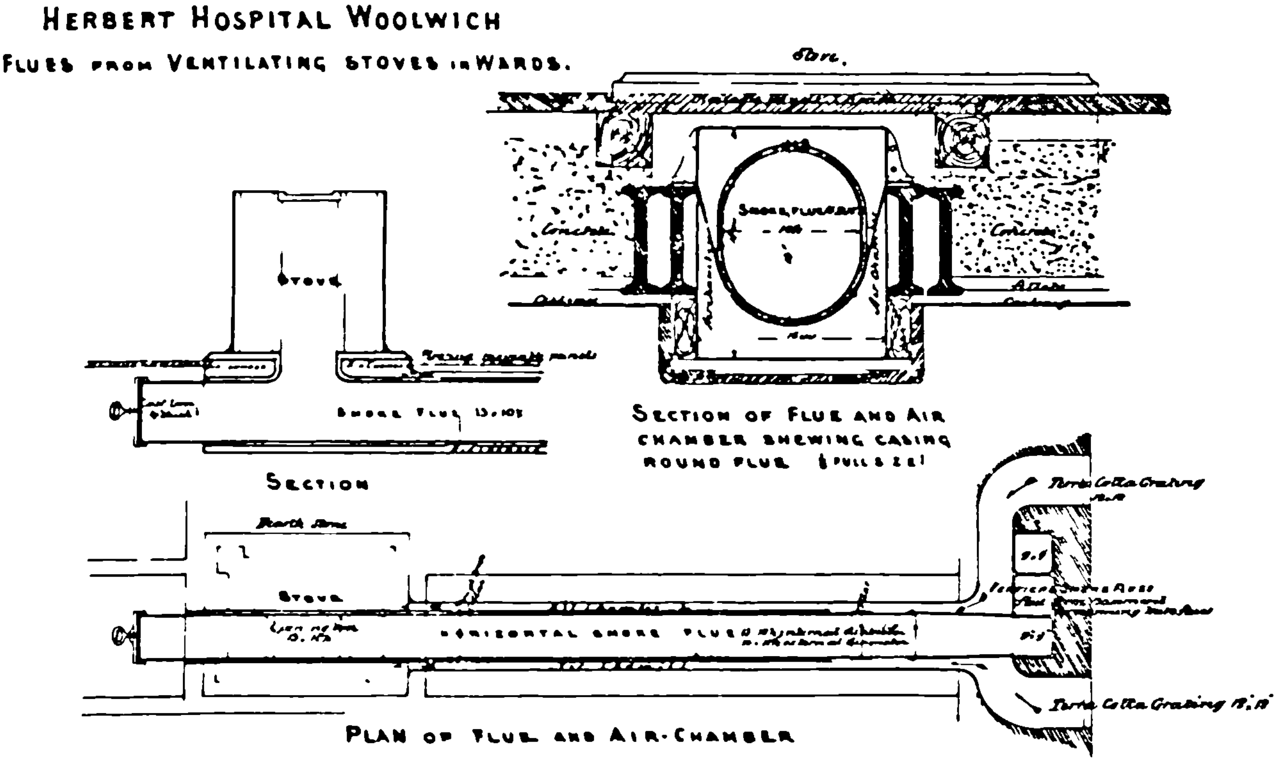


Figure 49 Herbert Hospital : Ventilating Stove in Wards

admired. In 1878 a heating engineer, Mr. Schonheyder, said in a discussion at the Institution of Civil Engineers that the "Galton stove" left impure air in some parts of the room and the heat unevenly distributed, and that he, like many others, preferred forced air ventilation.[178]

Galton's ventilating grate was used in open fireplaces in the Herbert Hospital offices, orderlies' quarters and hospital officers' rooms. The nurses' office at the end of the ward, the lobby between the water closets and the ward, corridors and staircases were warmed by hot water coils and ventilated by fresh air admitted through the coils. Every water closet had a separate window, ventilators and a foul air shaft. The patient area of the ward and its service and access appendages were therefore each separately heated and ventilated units in order to achieve sanitary isolation - the object of design directed by the miasmic theory of disease contagion.[179]

A 'natural' ventilation system using the open fireplace or stove, windows, ventilators and shafts was universally preferred by sanitary reformers. Other systems had been employed in hospitals but received negative criticism. York County Hospital had been ventilated by Arnott's pumps with windows and chimneys permanently closed and, according to Bristowe and Holmes, it was "so unhealthy that it was found necessary to close it, until the natural system could be replaced."[180] A new ward block at Guy's Hospital, London, in the 1850's was heated and ventilated on the heat-aided 'descending' system by John Sylvester. It was criticised by Godwin in The Builder and by Bristowe and Holmes in their 1863 report.[181] Bristowe and Holmes also condemned various artificial ventilation systems in other hospitals - Bristol General Hospital, West Kent Hospital, Maidstone, the Liverpool Royal Infirmary, and the Edinburgh Royal Infirmary. By 1863 artificial ventilation systems apparently had been greatly discredited in Britain for hospitals. As Bristowe and Holmes put it: "At no British hospital is artificial ventilation now used, except as an auxiliary to natural ventilation; and, we may be allowed to add, an auxiliary on which no great reliance is reposed."[182] Roberton was convinced of the superiority of the open fireplace and he reflected the view of many sanitary reformers when he remarked that he had "little faith in scientific ventilation ... whether the downward mode, the upward mode, or the circuitous mode."[183] For him, the main fault with scientific ventilation was its unreliability. The belief in the superiority of the open fireplace or stove and the unsuitability of forced ventilation for hospitals continued into the 1870's.[184]

Galton's heating and ventilation system at Herbert Hospital was not an unqualified success. In later years experience suggested that the ventilation had been overdone. The Report of the Army Medical Department for 1877 said that some of the wards were so breezy that patients were catching chills and were in danger of contracting pneumonia.[185] Even so, Galton's adaptive genius in devising a heating and ventilating system for Herbert Hospital, based on his work with the Barrack and Hospital Improvement Committee rested firmly on prevailing opinion in favour of natural over forced ventilation. He saw his choice of technology as not necessarily the most theoretically perfect but the most reliable:

> "The simple methods of admitting air into, and removing air from, wards which I have here described, are those which after much consideration I have preferred to more mechanical and complicated methods, which might possibly be shown to be theoretically more perfect. But the theoretically perfect method of supplying a known quantity of air hourly into the ward, and neither more nor less, requires, if its action is not to be disturbed, that the windows shall not be opened, and that an open fireplace shall not be used. I believe, however, that health will be best secured by using open fireplaces, and keeping the windows open when it is possible to do so, so as to sweep out the foul air

> than the quantity pronounced
> theoretically necessary."[186]

Notwithstanding the initial development of aerodynamically better designed fans and electrical power source in the 1880's which provided the impetus for effective mechanical ventilation, Galton stuck fast to his preference for 'natural' ventilation and to the pavilion plan to the end of his life. In an article on hospital construction in the Royal Engineer Professional Papers in 1898 he said: "... unless we are prepared to adopt a system of mechanical ventilation, the pavilion system cannot fail to hold its own in hospital design."[187]

Following his work on the Herbert Hospital, Galton became an energetic promoter of sanitary engineering and pavilion hospitals both in his capacity as Assistant Permanent Under Secretary of State for War (1862-1870) and in his later career. He gave public lectures and wrote several reports, articles and books on these subjects from 1865 until his death in 1899. Galton lectured to the Royal Engineers on sanitary engineering at the School of Military Engineering, Chatham, in 1876, and his notes were published the following year.[188] He considered that the Royal Engineers' training in that branch of the profession was inadequate, and advocated a more systematic approach to the subject be taken in their formal education.[189] Galton became a member of the Sanitary Institute of Great Britain and was chairman of its council from 1885 to 1887. He was a fellow of the Royal Society from 1859, a member of the British Association for the Advancement of Science from 1860 and one of its general secretaries (1871-1895), and a member and one time vice-president of the Society of Arts.[190] Galton used these learned and scientific societies as a forum and mouthpiece for his ideas on sanitary engineering and the construction of healthy dwellings. Furthermore, while Assistant Permanent Under Secretary of State for War, Galton was consulted by the Poor Law Board about the design and construction of workhouses and workhouse infirmaries.[191] Following the Poor Law Reforms (1867-1868), the Local Government Board prepared instructions that workhouse infirmaries be designed on the pavilion principle.[192]

In consideration of his achievements, it is probably fair to say that Galton was one of Victorian Britain's most distinguished and effective practitioners and promoters of the pavilion plan for hospitals, and a leading expert and advocate on the construction of healthy dwellings generally. His contribution was shaped by his joining forces with the medical profession and other sanitary reformers to express their collective aspirations in architectural design. Galton's special genius was in mechanical engineering which he skillfully applied to building services, especially ventilation and heating. He demonstrated an early aptitude for mechanical skills in his work on experiments for the Royal Commission on the Application of Iron to Railway Structures. In 1878 Galton undertook a series of experiments on railway train brakes and made an important contribution here as well. These activities were recognized in his being elected vice-president of the Institution of Mechanical Engineers in 1892.[193] It was ironic though that he eschewed mechanical ventilation. In the final analysis, his work was to serve rather than lead the prevailing forces of change in hospital planning and servicing in the 1850's and 60's to which he remained committed throughout his career, virtually unmoved by other emerging opinions in the late nineteenth century. It was probably Nightingale and the nursing profession whom he served the most. As Galton said in 1869:

> "... as economy of labour in administering the hospital is a main object to be sought in hospital construction, the hospital should be laid out as to enable the largest number of patients to be nursed by a given number of nurses... the form of the ward must be as much calculated to facilitate nursing as to ensure free circulation and change of air."[194]

Like Jebb in prisons, Galton's approach to hospital design was dictated by the functional requirements of social reform and reformers.

It is interesting to observe that, similar to the situation with the Royal Engineers' contribution to the planning, construction and servicing of prisons, barracks and hospitals, the Corps' principal achievement in the design of monumental public architecture in Britain was the work of two engineer officers only. In this case the challenge was to marry successfully innovative technology and Victorian taste. The Royal Engineers who took up this challenge are perhaps the best known of the army architects in the nineteenth century - Francis Fowke and Henry Scott.

7. INNOVATIVE TECHNOLOGY AND VICTORIAN TASTE IN WORKS OF MONUMENTAL PUBLIC ARCHITECTURE

The works of Francis Fowke and Henry Scott, undertaken while each was in the employ of the Science and Art Department, comprise a substantial part of the cultural complex at South Kensington, London. Their respective contributions to the district's familiar monumental public architecture, which were not restricted to the Department's buildings, are well known and have been discussed in considerable detail by a number of scholars.[1] Although building technology has not been ignored in previous studies, much remains to be described and interpreted. It is particularly revealing to examine the relationship between the use of new materials, structural forms and building services and the dictates of function and fashion in Fowke's and Scott's buildings. The achievements of these remarkable engineer officers were made in close collaboration with civilian colleagues in the Science and Art Department as well as with private sector engineers, architects and manufacturers. Together they met the challenge of marrying innovative technology and Victorian taste.

The Science and Art Department Architectural Atelier

The Science and Art Department was established in 1853 under the Board of Trade and three years later was placed under the Privy Council as a branch of the Committee on Education. From 1856 to 1870 the Department was responsible for the design and execution of its own buildings. In the last year the Office of Works assumed responsibility but the Department continued to originate designs until 1883. The really creative time, however, was the period before 1870 when a do-it-yourself design and construction programme was established at South Kensington in a Departmental architectural atelier.[2]

Francis Fowke and later Henry Scott were team leaders in this architectural workshop. Their contributions focussed on co-ordinating the skills of the decorative artists and draughtsmen in the Department together with their own special talents and those of consultant architects and engineers from the private sector. The two engineer officers were markedly different in background, though both possessed inventive genius. Fowke was a practical man with particular talent for ingenious mechanical contrivances, and had a flair for design and construction. Scott was a building scientist and entrepreneur with especial skill in directing projects.

Born in Belfast in 1823 and educated at Dungannon College and under a private tutor, Fowke entered the Royal Military Academy at Woolwich in 1839 and was commissioned in the Royal Engineers three years later. Evidently, Fowke was chosen out of his turn for the Corps. Having ranked sixth out of a class of sixteen and there being less than half a dozen openings in the Royal Engineers, he should have been commissioned to the Royal Artillery, but his drawing ability was so superior to that of his fellow cadets that normal commissioning procedure was put aside.[3] Fowke's initial posting was in Bermuda under brother officer William Reid, then governor of the colony. It has been discussed in Chapter 1 how Fowke taught himself to design barracks while in Bermuda. On his return to England, he served briefly at Devonport naval dockyard where he designed Raglan Barracks in 1851-1852 (see Chapter 6).

In 1854 Fowke left Devonport and was invited by Colonel Owen, then Secretary of the British delegation to the Paris International Exhibition of 1855, to superintend the Machinery Department of the Exhibition. Owen soon left for service in the Crimean War and Fowke succeeded him as secretary in January 1855, residing in Paris during the year of the Exhibition.[4] At the Exhibition, Fowke undertook experiments on the strength of colonial woods and wrote a report on exhibits concerned with civil construction. Results of his experiments and the report were published in the Parliamentary Papers in 1856, and the report was later reprinted as a pamphlet.[5] The Builder said of the report on civil construction that it was an "admirable document" and reprinted most of it in the journal in 1857.[6] Fowke's work at the Paris Exhibition was to be a critical formative experience for him, and many of the things he learned there were to be expressed in his architecture at South Kensington.

In the summer of 1856 Fowke was appointed an inspector in the Science and Art Department, and architect and engineer the following November.[7] He ceased to be an inspector in 1862.[8] Fowke was concerned with buildings for the Department's museum and schools beginning with the transfer of the Department from Marlborough House to South Kensington. His first assignment was to adapt for the museum's new home a prefabricated corrugated and cast iron building known as the 'Brompton Boilers' (1856-1857) plus some old houses and a series of wooden buildings. Erection of the controversial iron structure had been supervised by William Cubitt, but it had been designed by William Dredge and manufactured by C.D. Young and Company.[9] In 1861 Fowke told the Barrack Works Committee that, since 1854, he had been essentially an architect not a military engineer.[10] He was elected an associate of the Institution of Civil Engineers in 1863.[11] Fowke died in December 1865 and was succeeded by Henry Scott.

Scott's background and early working life have been discussed in Chapter 2. When he took over from his deceased brother officer, he had enjoyed a successful ten year career as a building scientist and instructor at the Royal Engineer Establishment, and was well established as an expert on limes, cements and concrete. Scott had also invented selenitic cement which he patented and marketed with good results. Even so, he appears to have had very little design and construction experience prior to his appointment at South Kensington. It appears that he may have participated in the building of fortifications while stationed at Gibraltar (1843-1848), but the evidence is insubstantial and inconclusive.[12] Scott was seconded from the Royal Engineers late in 1864 to help Henry Cole run the Royal Horticultural Society's garden at South

Kensington, and he became an administrative officer in the Science and Art Department.[13] He was therefore on hand when Fowke died.

It is perhaps significant that Scott's position on succeeding Fowke was called 'Director of Works' which later changed to 'Director of New Buildings', and that he was never known as 'Architect and Engineer', which had been Fowke's title. The record of his appointment in the 13th Report of the Science and Art Department stated: "We have not thought it necessary under the circumstances to re-appoint an architect, but Col. Scott RE, will act as Director of Works... "[14] Scott retired from the army in 1871 but kept his job with the Science and Art Department until his dismissal in 1883 as part of re-organization under the Office of Works.[15] He died shortly after losing his position in the Department.

Both Fowke and Scott had a number of close working associates in the Science and Art Department architectural atelier with whom they shared responsibility for the buildings of the South Kensington cultural complex. Fowke's office included a number of architectural assistants and draughtsmen: Thomas Verity, 1864-1871; H. Saxon Snell, 1860-1864; and John Liddell, 1864-1865; as well as Gilbert R. Redgrave, 1861-1865, who was to become better known as architectural assistant to Scott after Fowke's death.[16]

Fowke also had an engineer assistant, John William Grover (1836-1892), whose design activities were concerned mainly with works in structural iron. Grover had articled under Charles Fox of Fox, Henderson and Company, and was then employed by John Fowler. On the recommendation of Fowler, he was appointed draughtsman in the office of works of the Science and Art Department, and soon became head of the engineering and construction department as well as chief draughtsman and clerk of the works. Besides his building work at South Kensington, Grover conducted for the Department a series of experiments on iron floors and arch ribs in wrought iron and prepared reports on various buildings. In 1862 he left the Department and entered private practice as a civil engineer in Westminster and specialized in railway construction, including bridges. Grover assisted Scott with the new lecture theatre of the South Kensington Museum and the Albert Hall. In his later career, he abandoned railway work and took up water supply engineering both at home and abroad. Grover was elected a member of the Institution of Civil Engineers in 1867.[17] While in the Department, Grover was paid by way of deductions from Fowke's salary.[18] He was clearly the most important influence on Fowke's works in structural iron.

On the decorative aspects of Fowke's architectural designs, the key associate was Godfrey Sykes (1824-1866). He had been the master of the School of Art at Sheffield and was a proven designer and modeller. Sykes joined the Science and Art Department in July 1859. He soon commenced a series of designs for execution in sgraffito and terracotta for study in the Art Training School and in local schools of art as well as for use in the completion of South Kensington Museum buildings.[19] Sykes had demonstrated an ability to handle three dimensional forms superior to most architects.[20] Fowke and Sykes collaborated in expressing a distinctive Departmental style, especially in the use of terracotta. They died within three months of each other and the memorial to them in the <u>13th Report of the Science and Art Department</u> is worth quoting:

> "... we have to deplore the irreplacable loss to the Department of two of its most valuable officers... In various reports to the Department it has been pointed out how much was due to these gentlemen; how successfully the one by his scientific attainments, combined with a mechanical genius and a boundless ingenuity and fertility of resource, was grappling with the hitherto unsolved problem of a useful and harmonious employment of iron in architecture, and the introduction of new forms and new materials adapted to the atmosphere of London;

> how the other was impressing on those materials a decoration both of colour and of form, no less artistic than original... "[21]

Fowke and Sykes were close friends as well as professional colleagues.[22]

Although not of great consequence, a few other Royal Engineers were seconded to assist Fowke with projects at South Kensington. From about 1863, Fowke was aided by fellow officer Captain E. Robert Festing in the Science and Art Department's architectural and engineering office, but Festing appears to have been concerned mainly with administrative matters.[23] Lieutenant E.J. Brooke and Captain William C. Phillpotts helped Fowke with the 1862 Exhibition building project.[24]

Scott had a number of assistants too, and he tended to delegate responsibility to them more than Fowke.[25] Two of Sykes' pupils, James Gamble and Reuben Townroe, augmented Scott's limited experience in decoration in architectural design, using mainly Sykes' patterns.[26] Scott was also helped by architectural draughtsmen, including, for example, D.R. Dillon who served in the post of chief draughtsman from 1865 to 1878.[27] Scott's most important associate in architectural designs, though not a member of the Department, was James William Wild (1814-1892) who became his right hand man immediately following Fowke's death.[27] For example, Wild assisted Scott with much of the interior arrangements of the Science Schools (1867-1871) and in the adaptation of the 'Brompton Boilers' for the Bethnal Green Museum in 1873.[28] On the matter of building technology, Wild's influence seems to have been limited - he was essentially a decorative architect.[29]

Scott's most important associate within the Department was Gilbert R. Redgrave (1844-1841) who had joined the architectural atelier in 1861 under Fowke. Son of Richard Redgrave R.A., he was educated at Chester Training School, King's College, London, and the schools of the Royal Academy.[30] Redgrave was an architectural assistant to Scott and became chief draughtsman in 1878 on

Dillon's death.[31] His work included helping Scott on all aspects of building projects. Redgrave became a close colleague of Scott's, co-authoring with him the paper on Portland cement which won the Telford premium in 1880, and joining him as a partner in the sewage cement business. Redgrave published a book on calcareous cements in 1895 which went through several editions. It contained an extensive description of Scott's contributions to cement manufacture. In 1878 Redgrave was architect to the Royal Commissioners of the Paris Exhibition of 1878, and was awarded the distinction of Officer of the Legion of Honour for his work. He served as secretary to the Royal Commission on Technical Education (1881-1884), and after Scott's death became an inspector of schools in the Science and Art Department.[32]

Scott also had some help from a fellow engineer officer who had originally joined the Department under Francis Fowke. Captain Festing became Scott's Assistant Director of Works on Fowke's death in 1865. His duties appear to have remained largely administrative. Even so, Festing did carry out some experiments on the effectiveness of the heating and ventilation system at the South Kensington Museum in 1868.[33] More importantly, Scott made extensive use of consultants in the private sector, especially in the design and construction of the Albert Hall. This will be discussed in subsequent sections of this chapter.

Sir Henry Cole (1808-1882) was the civil servant at the controls of the administrative apparatus under which Fowke and Scott worked, and the principal arbiter of taste in the matter of architectural design in the Science and Art Department. Cole was Superintendent of General Management in the Department of Practical Art (1852-1853) and Joint Secretary (1853-1855), then Inspector-General (1855-1857), then sole Secretary (1858-1873) of the Science and Art Department.[34] His association with Fowke began in 1854 when they were both British officials at the Paris Exhibition of 1855.[35] They soon became close friends. Fowke's son Frank was married to Cole's daughter Isabella.[36]

Cole's relationship to Scott, though not unfriendly, was more of a business nature. He was in partnership with Scott in the sewage cement enterprise and acted as managing director of the company.[36]

Cole distrusted the architectural profession and promoted the Royal Engineers as civil servant watchdogs for government building projects. He felt that excessive costs of public buildings over original estimates were due in large measure to the lack of control of public departments over architects, and he objected to the prevailing system where the architect was paid a percentage of the building cost. He recommended instead a fixed salary over a definite period of time. In order to control architects, he recommended that public departments select an engineer officer to oversee the project, and preferably to have him draw up preliminary plans and sections and a block model which would form the basis of the project and the datum from which to measure the architect's progress. The architect would then be called on to enter upon the artistic completion of the exterior and interior.[37] This view was very much informed by his experience with the design process at South Kensington. In Cole's view, cheaper and better public buildings would result from employing the Royal Engineers to inspect all projects:

> "At the present time it may be said with truth, that great waste would be prevented, and saving of professional labour at out-stations effected, if all the public buildings of the country, those for the Post Offices, Custom Houses, &c, as well as the Public Offices in the metropolis, were placed under the inspection at least, of officers of the Royal Engineers. Had there existed the control of a Royal Engineer officer during the building of the Houses of Parliament, the badness of stone and many other deficiencies would probably have been found out, and again recently, the new Foreign and India Offices would probably have been far better in arrangement, far more useful, and far cheaper in cost."[38]

Cole took an active part in the working of the Science and Art Department's architectural atelier. He visited its offices daily and would make rough sketches for designs and inspect specimens of materials in use or proposed for use. Cole travelled to Italy and to other parts of Europe to observe historic architectural styles and current building practices as well as to collect building materials, especially those for decorative use, many of which he placed in the South Kensington Museum of Construction and Building Materials. He also visited important new projects in England, particularly those where significant issues of style versus technology were to be observed. For example, Cole inspected the University Museum (1855-1860) Oxford, which displayed an important decorative approach to structural iron. While in residence at South Kensington (1863-73), Cole did a daily tour of inspection round the buildings in progress as well as the carpenter's shop and the smith's workshop on the premises. His role in the development of the South Kensington buildings and in the promotion of the Royal Engineers, especially Fowke, was very important.[39]

The Science and Art Department fostered an alliance of architecture, engineering, painting and sculpture. This alliance led to the development of a teamwork design process, with Royal Engineers as co-ordinators, markedly different from the individualistic approach which characterized the major architectural practices of the 1860's. The team produced a distinctive style which combined up to date technology with a well articulated view of late Victorian architectural taste. As a matter of policy, the Science and Art Department first fitted a building for its purpose in plan and construction, and then decorated it. This had important consequences for appearance, in particular materials and methods for decoration.[40] The Department was convinced that its design process ensured the achievement of both economy and durability in the South Kensington construction programme:

> "The highly decorative buildings at
> South Kensington in terra-cotta and

> red brick have cost under 1 s the cubic foot exclusive of mosaics, decorative paintings, and the like. This is below the cost of an ordinary London house of the first class. After six years' duration it has been found that the surfaces and colour of terra-cotta, and brickwork are but slightly affected by the smoke and atmosphere compared with Portland stone, which is much discoloured."[41]

The production of buildings, many parts of which were considered objects in the South Kensington Museum's collection, as much as the artifacts housed in it, became one of the chief means of satisfying the Science and Art Department's purpose as a promoter of practical art and a shop window for enlightened manufactures and builders. It was ceramic ware that was featured in the experimental and exemplary role of the museum. Terracotta was the hallmark of the 'South Kensington' style, and it established the basis for the use of architectural ceramics in the late Victorian period into the twentieth century. *There were* also some interesting works in a new cement, in timber and in iron as well as in services, though these were less influential.[42]

The style adopted by the Department was based on northern Italian buildings of the fifteenth century. It was characterized by the use of red brick with fawn coloured and red terracotta.[43] As Olsen has pointed out, history played at least as important a role as technology in shaping the consciousness and determining the conduct of the ordinary European during the nineteenth century. Architects used history in buildings deliberately to convey ideas, and the public understood them.[44] Officers of the Science and Art Department, including Fowke, made visits to Italy for inspiration and technical knowledge on historical stylistic and constructional matters.[45] Stratton has suggested that for Cole, Fowke and Scott, the early northern Italian Renaissance style symbolized the reuniting of arts and sciences, and allowed the practical exploitation of modern building technology and materials.[46]

The Survey of London contends that the

appearance of the South Kensington buildings of Fowke and Scott owed most in origin to the ideas of three English architects who had worked under Cole on the fitting out of Paxton's Crystal Palace in 1851: Sir Matthew Digby Wyatt, secretary of the executive, Owen Jones, superintendent of works, and J.W. Wild, decorative architect.[47] Physick has credited Cole with initiating the adoption of the early Italian Renaissance style at South Kensington about 1860. Cole had been impressed by the style during a recent trip to Italy. Physick also maintains that, whereas Fowke and Cole debated the merits of the style, the two of them needed architectural advice, and it was Matthew Digby Wyatt who provided it.[48]

All the same, Fowke was a conscientious student of the chosen architectural idiom. He is said to have studied examples of the "Italian" style for the interior brick and terracotta arcade of his conservatory for the Royal Horticultural Society, completed in April 1861.[49] As explained earlier, he was adept at self education, and his training at the Royal Engineer Establishment in copying architectural drawings would have prepared him for making a record of his observations. More importantly, Fowke had early demonstrated a great talent for drawing and a flair for design, so it is not surprising that he quickly mastered the chosen style. It is more difficult, however, to explain how Scott developed the skills to design in this highly decorative style. As discussed already, he was not so much his own man as Fowke. While Scott acted as the official architect on his projects, it is likely that J.W. Wild provided many of the concepts and possibly many of the details as well. After all, though he had received the same formal education as Fowke and was capable of executing drawings for buildings, Scott had not demonstrated particular talent in architectural design compared to his brother officer. Perhaps most importantly, however, as will be explained below, Scott did not think of himself as an architect.

The appraisal of Fowke and Scott as architects by their contemporaries provides a useful starting point for the present assessment of their contributions to building technology in monumental public architecture. Fowke's greatest supporter and defender was Cole. He referred on a number of occasions to Fowke's skill at constructing sound and useful structures at low cost, to his ingenious use of both new and old materials, and to his attempts to deal with the problem of iron as a structural and decorative material. The clearest articulation of this assessment was in Cole's eulogy of Fowke at a meeting of the Society of Arts, 8 December 1865:

> "Captain Fowke had an almost unrivalled facility of economising the use of materials in his buildings... At this period when Art is so transitional, and Science is making many discoveries, and men's minds are seething with inventions; when the use of new materials is being constantly manifested, and the adaptation of old materials is constantly entered upon, England has lost a man who felt the spirit of his age, and was daring enough to venture beyond the beaten path of conventionalism. Captain Fowke, to my mind, was solving the problem of the decorative use of iron, and by appreciating the spirit of both the Gothic and Renaissance architects, was on the threshold of introducing a novel style of architecture..."[50]

The technical press also provided an assessment of Fowke's architectural talents. In 1861 Building News praised Fowke's arcades and conservatory for the Royal Horticultural Society, saying the key requirement in such buildings was functional suitability and that Fowke's design was a notable success in this respect:

> "It was not merely a successful effort to design and to group together Italian column-supported arches, that the Council of the Royal Horticultural Society sought from their engineer architect, but they also required certain ranges of buildings which should accomplish certain specific duties. And the real merit of the buildings that have actually been produced, consists as well in their applicability to their appropriate uses as in their architectural character."[51]

The Builder's appraisal of Fowke is particularly revealing. In the journal's obituary of the deceased engineer officer, Cole's statements about Fowke's willingness to experiment in search of improvement were reiterated and expanded:

> "Much of Fowke's work was tentative; he was not afraid of trying; not afraid of new materials or new modes. He was gradually, too, improving his taste; acquiring a better perception of beauty; and the last thing he did was the best."[52]

The last thing which Fowke did was his winning competition design for the Natural History Museum in 1864. The Builder had published a plan and perspective view of the proposal and described it as "deserving of reward."[53]

Custodians and users of Fowke's buildings sometimes expressed their appreciation for his design. Thomas C. Archer, Superintendent of the Industrial Museum of Scotland, said in 1863 of Fowke's almost completed new building for the museum in Edinburgh: "... the construction of the building is most admirably adapted, and presents a fitness for its intended objects which has been rarely, if ever, equalled in such structures."[54] Indeed, Fowke's ability to design functional structures was never seriously disputed by his contemporaries, even when they were critical of the artistic merits of his buildings.

Fowke's singular disaster, from an aesthetic point of view, was the 1862 Exhibition building, the story of which has been well told by Bradford.[55] The Builder said that "... the exterior, so far as it can be judged of, is monotonous and ugly."[56] Even more scathing was the Art Journal which commented: "In every detail, and in the combination of the several details into a single whole, there are ever present a poverty of conception and a palpable ignorance of all architecture humiliating indeed."[57] The Art Journal did not see technological virtuosity in a building as creating good architecture. While it was prepared to allow that the Exhibition's picture galleries may be "commodious, of suitable proportions and agreeably lighted", this did not, in the journal's opinion, affect the architectural success or failure of Fowke's design.[58] Indeed, the Art Journal saw Fowke's appointment to design the Exhibition building as a deliberate challenge to the architectural profession: "It amounted to a practical assertion, that an architectural achievement, altogether beyond the powers of the profession, this military amateur was qualified to accomplish."[59] For the Art Journal, the challenge had failed: "Captain Fowke's architectural failure we must call a failure."[60] For all that, most other critics acknowledged that the building had been erected with a rigid regard for economy, and that it was sound and suitable for its functional requirements.[61] Cole in particular defended it on these grounds.[62] The main building had been designed as a basic structure for permanent use as an exhibition centre with the intention of decorating as funds became available.[63] Interestingly, The Civil Engineer and Architect's Journal thought that there was a certain nobility in a bare, functional building:

> "Should either colouring or mosaic be introduced, the result will not be to add beauty or richness; it will only be to destroy the simplicity which we admit to exist, and which in so great a structure becomes in itself, through frequent repetition, something akin to nobleness."[64]

Accordingly, even Fowke's most criticised work was not without praise, and in one case at least it was lauded on aesthetic as well as functional grounds.

The 1862 Exhibition building experience also focussed growing apprehensions on the part of the architectural profession over the role of the Corps at South Kensington, particularly in the failure of the Exhibition Commission to hold a design competition for the project. In May of 1861 The Builder reported that at a meeting of the Institute of British Architects there had been comments "on the interference of the civil and military engineer in the domain really belonging to the architect."[65] This gave rise to some questioning of Fowke's qualifications as an architect which Cole was quick to defend by challenging the definition of an architect as one who had served a certain amount of apprenticeship in an architect's office. Cole pointed out the achievements of the great sculptors, painters, engineers or constructors who had designed revered buildings of Renaissance Italy or of seventeenth and eighteenth century England. He also defended Fowke's ability on the basis of his past record in designing buildings at South Kensington as well as the Industrial Museum of Scotland in Edinburgh and the interior of the National Gallery in Dublin.[66] This same theme was taken up by George Edmund Street in defending Fowke's architectural credentials against the attacks of Robert Kerr, the runner up in the Natural History Museum competition of 1864. Kerr, a founder and first president of the Architectural Association (1847-1848), had apparently blocked Fowke's entry to the *Institute of* British Architects and had written a scathing letter to The Times, claiming that Fowke lacked professional standing as an architect.[67] Street's defence is worth quoting as perhaps the most balanced of contemporaries' views of Fowke's abilities as an architect:

> "Captain Fowke... had adopted a profession which at least involved a great deal of scientific education, and trained him in many ways most admirably for the practice of a constructive art. Then after many year's successful pursuit of his profession, accident or his own choice induced him to devote some eight or ten years of his life almost entirely to the preparation of designs for buildings of various kinds and various degrees of importance... In common fairness one must admit that he was at least likely to do his work well as any man "specially educated" in the usual way would be. The real test of his claim to be an architect in the best sense of the word is the examination of the works which he carried into execution... The simple truth is that he is the best architect who can erect the best building, and

> whatever doubts many of us may have
> as to Captain Fowke's exact rank in
> the profession, there are but few,
> I hope, who would pretend to charge
> him with being a mere amateur..."[68]

The architectural politics which coloured Victorians' assessment of Fowke was symptomatic of the crisis of identity and organization which faced the profession of architecture in the last half of the nineteenth century. It was marked by controversy over the role of the architect versus the engineer, and tended to direct architects toward a definition of their profession as constructor and businessman in addition to, if not before, the artist. The architectural profession's search for order and security was characterized in part by the fear that engineers would intrude on its territory with the growing public recognition of the civil engineering monuments of the Victorian age.[69]

Scott's contemporaries' opinion of him were much less charged with controversy. For one thing, Scott himself made no claim to architectural genius. He said to a meeting of the Royal Institute of British Architects in January 1872, at which he gave a paper on the construction of the Albert Hall, that he had hesitated to comply with their request for his remarks partly because of "the reluctance I felt to appear before your distinguished body in the character of an architect, a title to which I make no pretension".[70] Moreover, later in his address, when comparing himself to Fowke, he said: "... that whilst I have always considered that my late brother officer and friend was naturally gifted with unusual architectural and constructive ability, I have not had equal confidence in my own."[71] Cole thought Scott was defective on the matter of architectural decoration.[72] It has also been suggested above that J.W. Wild was largely responsible for the aesthetic judgements regarding the interpretation of the 'South Kensington' style as well as for decisions on the interior arrangements of buildings. The Albert Hall, on which many building professionals and others collaborated, was clearly Scott's most important achievement at South

Kensington. T. Roger Smith, an architect who had been consulted on the building, paid him tribute:

> "... I am sure we must congratulate Major-General Scott upon the success which has attended an undertaking on so large a scale, when so many new materials and new modes of decoration have been employed on a structure of a character never attempted in this country."[73]

Accordingly, it would probably be fair to describe Scott not as an architect in the same sense as Fowke having command of artistic as well as technical matters in his own right, but rather as a design and construction director. Scott's contribution is no less important in this light.

The Museum of Construction and Building Materials

One of the fundamental purposes of the Science and Art Department was to form and maintain collections illustrative of the application of science and art to manufacture.[74] When the South Kensington Museum opened in the 'Brompton Boilers' in June of 1857, a 'Museum of Construction and Building Materials' was established on the ground floor, under the eastern gallery.[75] In his capacity as an inspector for the Science and Art Department, Francis Fowke assumed responsibility for the direction of this part of the South Kensington Museum from its opening until his death in 1865. For the first eight years he managed the museum's curatorial affairs almost single handedly. In 1864 Henry Sandham, a civilian, was appointed Division Keeper and assigned to the Museum of Construction. Fowke developed this facility into a building research station for the South Kensington Museum as well as a centre for construction technology education and building product marketing. Within the museum he established programmes of collection and exhibit as well as of experimentation, in pursuit of the facility's purposes.[76]

The roots of much of Fowke's work in the Museum of Construction, and to some degree also of the materials and techniques employed in his buildings at South Kensington, lay in his experience at the Paris Exhibition of 1855, already referred to above. Key aspects of his experience at the Exhibition were his Report on Civil Construction and his experiments on the strength of colonial woods. A brief review of these undertakings reveals some important connections and contributions.

In his Report on Civil Construction, Fowke was most impressed with roofing tiles, floor tiles, hollow or perforated bricks and especially terracotta. He described several varieties of new French roofing tiles. These were an improvement on the ordinary flat tile which had to be laid in three thicknesses and which consequently were very heavy. This had led to the virtual abandonment of flat tile roofs for large construction projects in England. The new French tiles were interlocking and could be laid, therefore, in a single layer. They were fastened to battens by a small projection at the back of their upper part. Because they were light, these tiles could be used on shallow pitch roofs. They came in square, rectangular and lozenge shape. The square variety was called 'tuile Courtois', and Fowke later used this form of tile, manufactured in England by J.M. Blashfield, to cover the roof of Sheepshanks Gallery (1856-1857).[77]

Fowke explained in his report that the use of tiles for flooring was rarely seen in England in modern construction but prevailed to a very great degree in France. He said that English manufacture of tiles for flooring or paving was "almost extinct", the notable exception being Minton whose encaustic tiles were well displayed at the exhibition.[78] Fowke pointed out that French tiles were cheap and therefore were used in ordinary houses, whereas Minton's, though more beautiful, were expensive and consequently employed only in high quality construction.[79] Fowke was to experiment at the museum with a variety of cheap floor and paving tiles based on his experience at the Paris Exhibition.

Another building material described by Fowke was a variety of hollow or perforated bricks of French manufacture. These were used for walls, lintels, partitions, ceilings, and flues for light, fireproof construction and for ventilation. The largest exhibit was by M. Paul Borie of Paris. Fowke used perforated bricks in the roof structure of Sheepshanks Gallery.[80]

It was terracotta, however, that most impressed Fowke at the Paris Exhibition of 1855. In his Report on Civil Construction, he described some terracotta facing for brick or stone which had been manufactured in England by a Mr. Taylor, but he was more interested in French decorative terracotta used particularly for cornices and string courses. His description of the building product is of especial significance:

> "This material has been used with success in France for external decorations and would seem to offer peculiar advantages for the same purpose in this country, more especially in localities such as London, where stone dressings are so expensive that their use is almost abandoned in ordinary cases, and recourse is had to cements and compos of various kinds, which are far inferior, both in effect and in lasting qualities to the terra-cotta... Altogether there is enough to convince any one who may look into the subject that terra-cotta and earthenware may be brought with advantage to play an important part, both in the construction and decoration of our edifices of all classes and for all purposes."[81]

This statement demonstrates that Fowke was convinced of the value of terracotta before his appointment to the Science and Art Department and that his experience at the Paris Exhibition of 1855 was vital in forming his opinion of the material. Accordingly, Fowke was well disposed to the introduction of terracotta at South Kensington, and he probably deserves much of the credit for initiating its use there.

Nevertheless, it was with wood that Fowke was to make a personal contribution to the activities of the Paris Exhibition of 1855. He made important experiments on woods from Australia, British Guiana and Jamaica which were unknown in England, unlike those from some other British colonies, especially Canada. According to Fowke, even the colonists were ignorant of the woods' merits compared to the known timber of commerce. The Exhibition, therefore, provided a unique opportunity to test the quality of these new woods which were "for the first time brought into competition with each other, and with ordinary woods already employed by the shipbuilder and carpenter."[82] Fowke was provided with a testing machine by a Mr. Dunn of Manchester, and his experiments were carried out with the help of Corporal James Mack in the machinery area of the Exhibition, from July to September 1855. The testing machine was a hydraulic press by which the exact amount of applied pressure could be ascertained. Fowke used a standard dimension sample of material, and tested both tensile and crushing strength. In his published results, he not only gave data from these tests but also provided information on each timber's availability in the colony of origin, its use there and cost and descriptions of estimated strength, durability or any other valuable quality. In all, Fowke tested 79 different woods; 42 had superior crushing resistance to English oak and 47 were superior in bearing transverse strain, some at the same time being of less specific gravity. Apparently, Fowke's report helped greatly to raise the exports of Jamaican lancewood spars and mahogany.[83] Fowke continued these experiments on colonial woods at the Museum of Construction in 1862. The samples were from woods displayed at the International Exhibition in London of that year. Some 805 different woods from 13 countries were tested using an apparatus loaned to the Science and Art Department by Messrs. Hayward Tyler and Company of Upper Whitecross Street, London.[84] It is not known whether Fowke used any of these colonial woods at South Kensington.

The collections and exhibits of the Museum of Construction were an important means of educating the public and the building industry on the availability and use of new materials and techniques, and the museum provided a unique opportunity for manufacturers to advertise their products. As director of the museum, Fowke deserves a large measure of credit for the collections and exhibits policy. Items for the collection were accepted as donations from manufacturers and others, or were purchased by the Science and Art Department, particularly in the case of foreign products.

Ceramic ware for both architectural decoration and construction was a major item. In 1858 Italian decorative tiles were procured and donated by Cole.[85] An early constructional exhibit was French roofing tiles manufactured by Messrs. E. Muller and Co. of Paris, which Fowke had seen at the Paris Exhibition of 1855 and described in his Report On Civil Construction. These were purchased by the museum in 1861. The tiles featured "an ingenious method of inserting into roofs iron skylights, ventilating tiles, and glazed lights without the necessity of cutting and preparing the rafters and purlins for such purposes."[86] (See Figure 50) Another product was mosaic tiles. Following the 1862 Exhibition, a collection shown there was donated by Russia "which illustrates most fully the successful development of the production of materials applied to the art of rendering pictures in mosaic at the Imperial manufactory at St. Petersburg."[87] Fowke claimed in 1863 that the question of mosaic work had been much taken up during that year by Britain's leading ceramic manufacturers and by glass manufacturers as well. He credited this to the Russian collection displayed at the 1862 Exhibition and later at the Museum of Construction: "This has probably arisen from the collection exhibited of similar productions in Russia... and Messrs. Powell and Son, Whitefriars, and Rust Co., Lambeth, are engaged in this branch of industrial manufacture."[88] By 1864 interest was growing on the part of architects, builders and manufacturers in the museum's display of decorative mosaics either in ceramic or vitreous material, and in order to promote British industry in mosaic productions

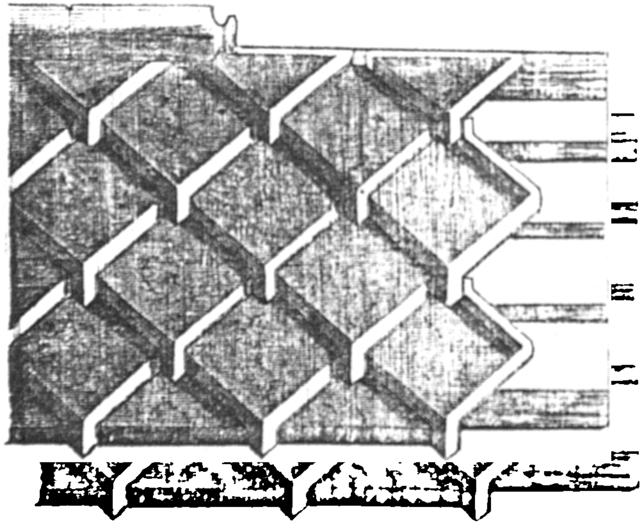
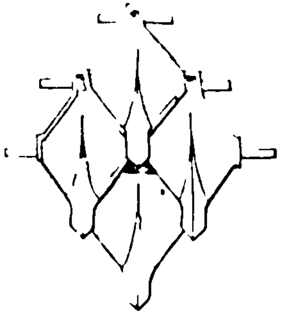
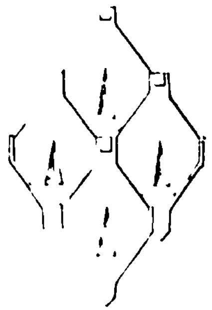


Fig. 1



FRONT VIEW.

Fig. 2



BACK VIEW.

Fig. 3

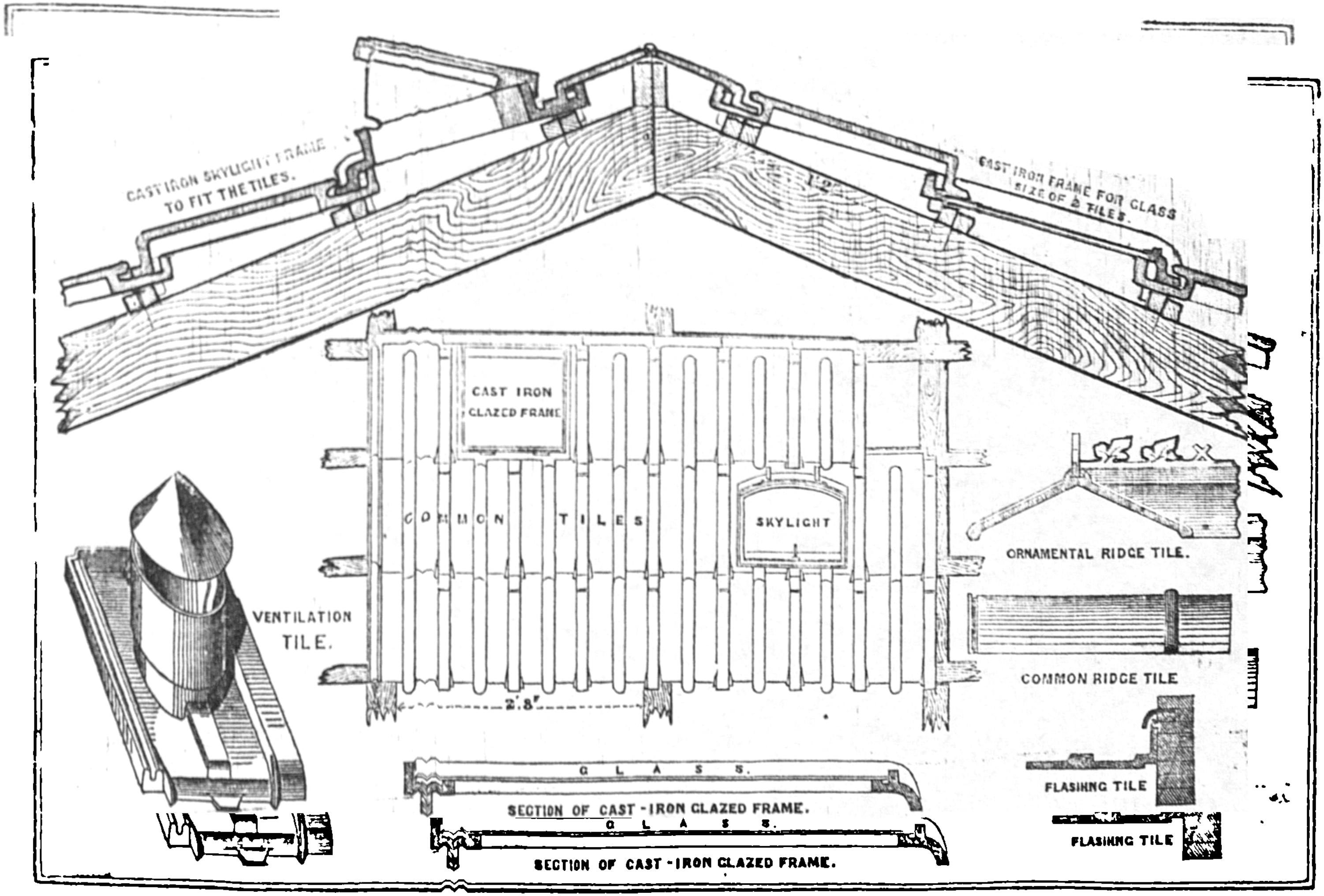


Fig. 4.

Figure 50 Messrs. Muller's Roofing Tiles to compete with Italy and Russia, the museum purchased for exhibit from Messrs. Harland and Fisher of Southampton Street, Strand, a full length figure of 'St. Peter' executed in vitreous or glass mosaic. In the same year, this firm, together with Messrs. J. Rust and Co. of Lambeth, received orders to execute in glass mosaic, from an original design, a picture proposed for panels to decorate the South Courts of the Art Museum.[89] Also displayed at the museum were pictures of tesserae of ceramic, including works by Messrs. Minton and Co., Stoke-on-Trent, and by Maw and Co., Benthall Works, Brosely.[90]

Of all the ceramic collections, terracotta was by far the most important and most related to the construction programme at the South Kensington Museum. In his report of 1860, Fowke said: "Illustrations of the application of terra-cotta as a substitute for stone or cement work in the external decoration of buildings, forms a considerable portion of the Museum."[91] He named the chief manufacturers which exhibited: M.H. Blanchard and Co., Blackfriars; Messrs. J.M. Blashfield, Stamford; J. Pulham, Broxbourne; and Gibbs and Canning, Tamworth. All of these companies did work at South Kensington. Terracotta columns used in the arcading of the interior of Fowke's conservatory for the Royal Horticultural Society, which were manufactured by M.H. Blanchard and Co., were exhibited as part of the collection.[92] In 1862 the museum acquired more space and much of it was devoted to the use of terracotta as a building material. Fowke explained: "... in this branch of material for construction especially, important information will be attainable."[93] In 1864 the museum purchased from Signor A. Boni of Milan a series of works in decorative architectural terracotta to act as models for English manufacturers.[94] The year before, Fowke had visited Boni's works on a trip to Italy.[95] The museum boldly promoted the cost advantage of terracotta over stone for external decoration. It displayed side by side with terracotta a copy in Portland stone of one of the ornamental blocks of terracotta manufactured by Messrs. Blanchard and Co. for the facades of the new buildings at the South Kensington Museum. The stone copy cost nearly three times the price of the terracotta.[96]

Many other new materials were also exhibited. Amongst these were Fowke's colonial wood samples from his experiments, and some specimens of wood from the Gold Coast in Africa contributed by Sir John Burgoyne, Inspector General of Fortifications, which were used in government buildings in that colony.[97]. Also displayed from 1858, as part of a collection of sanitary arrangements, was Scott's selenitic cement which Fowke said gave "a material almost equal to Portland cement at little more than half the price."[98] Scott's new cement was to have a number of important applications in the monumental public architecture at South Kensington. Another interesting example was the ornamental ironwork donated by M.L. Oudry of Arteuil, near Paris, which illustrated his process of bronzing cast iron by a galvanic process. Oudry was also the inventor of a bronze paint which was used in the South Kensington Museum for bronzing the wrought and cast iron work in the construction and decoration of the South Courts (1861-1862).[99]

Models comprised another important aspect of the collections. As early as 1858, Fowke described the model collection as containing several examples of fireproof floors and systems of ventilation, German methods of timber framing for roofs of large span and models of the large scale laminated timber arch roofs of King's Cross Station, contributed by Lewis Cubitt.[100] In 1860 a model of a patent system for trussing wooden girders with cast iron was contributed by J. Coombes, a civil engineer.[101] Fireproofing, ventilation and timber trusses were all important aspects of Fowke's building work at South Kensington.

Manufacturers were the largest contributors to the museum collection. In 1860, for example, 800 new specimens of building materials were donated by 52 contributors, 46 of whom were, as Fowke explained, "... manufacturers of the articles contributed who have sent specimens of their manufacture for exhibition, with the view of bringing them more directly to the public notice."[102] From 1858 the museum published a catalogue which had bound into it circulars and price lists of the exhibitors.[103] The catalogue had sold 462 copies by 1860 and was into its second edition.[104] In the last year Fowke said that demand from manufacturers to exhibit building materials had outstripped available space and called for expansion.[105] Enquiries by builders, architects and others in the building industry were "... upon novel as well as the usual introductions and applications in building contrivances."[106] In 1862 Fowke summed up well the relationship of the museum to the public and the building industry:

> "The collection continues to be practically utilized by the public, *as well as by* persons more closely connected with the particular branch of science and industry which the Museum illustrates, and it is believed that the collection possesses specimens of the most desirable and useful applications to building and construction in general."[107]

By 1865, the year of Fowke's death, Henry Sandham, Keeper of the Museum of Construction, claimed that the museum had the largest collection of building materials and contrivances in Britain.[108] In 1881 a committee was appointed to examine the museum's collection and to determine if it should be maintained, and if so, in what way it should be developed and what specimens should be removed. The committee thought that the establishment of the museum's collection had been of great value in many respects, and gave as an example the terracotta exhibits:

> "As a notable instance of its results we may refer to improvements of terra-cotta for structural purposes; so far back as the year 1867, at the International Exhibition, Paris, the result of this development

> was such as to place English terra-cotta in the highest rank..."[109]

The Museum of Construction's collections and the Science and Art Department's building construction programme for the South Kensington Museum worked in concert. The important link between them was the programme of experimentation at the Museum of Construction on new materials and techniques undertaken by Fowke and his assistants. As well as Fowke's experiments with colonial woods already mentioned, several other tests were carried out in the period 1858 to 1865 on both decorative and constructional materials. In 1861 strength tests were made on Scott's cement and on terracotta. The trial of the cement was upon the crushing weight of an archway of 10 foot span, 2 feet thick, and at the crown 9 inches deep.[110] Photographs of the experiment indicate that the method was to load this full scale model to destruction.[111] Tests on Scott's cement had been made by the Royal Engineers as early as 1857. Fowke's method was not as scientific as the one applied by Kirkaldy in 1872 on his highly acclaimed testing machine (see Chapter 2). Nevertheless, Fowke pronounced his test of Scott's cement satisfactory, and this established confidence for the use of the new material at South Kensington. The trial of terracotta involved testing it "... as a material for building purposes, where great strength and solidity might be required."[112] Fowke investigated the structural strength of terracotta by an experiment using a specially constructed press to determine the crushing weight of one of the columns which he used in 1861 for the ornamental arcades inside and surrounding the conservatory of the Royal Horticultural Society. The tests proved satisfactory.[113]

A great variety of other experiments were also tried. In 1859 Fowke undertook some experiments on a waterproofing product called 'water glass' (silicates of soda or potash). He tried the product on Plaster of Paris and on distempter colouring on external brickwork. The results proved not very satisfactory. Fowke concluded from a paper read in July 1859 by Frederick Ransome at the Society of Arts that he would need to use a fixing agent such as calcium chloride in order to ensure that the 'water glass' coating would resist water and humidity.[114] Experiments were also made on the manufacture and durability of ceramic decoration in walls and pavements. In 1859 a piece of Messrs. Minton and Co.'s Della Robbia ware was exposed to the elements in the museum grounds for several months without harm.[115] During the period 1864 to 1865, Fowke experimented with making ornamental floors and pavements using the Italian method of bedding broken pieces of coloured marbles in white cement in decorative patterns. This material was used in the entrance to the orange houses of the Royal Horticultural Society's gardens and in Prince Albert and Exhibition Roads at South Kensington.[116] He also tried, under sun exposure, a tar pavement in imitation of marble made by Messrs. *Wright and Co. of Bucklersbury.*[117] Fowke performed as well several successful experiments in colouring asphalt for flooring, using Minton encaustic clays, Derbyshire spar, gravel and other hard substances to produce the coloured patterns in the asphalt. He used this material for floors in the north arcades of the Royal Horticultural Society's gardens.[118] Beginning in May and June of 1861, Fowke undertook some experiments on colouring cements for internal ornamentation both in floors and in walls. Coloured floors in Roman cement and Scott's cement proved unsatisfactory, but some success was obtained with Portland cement. Colouring tests in Keene's and Martin's cements for wall surfaces worked well.[119] Finally, in 1863 Fowke tried some experiments with imitation wood inlay decoration by staining deal floorings and cabinet work.[120] All of Fowke's experimental ventures at the museum were aimed at finding cost effective, strong and durable yet beautiful materials for decorative and constructional use - a true marriage of technology and taste.

Fowke was especially interested in timber as a cheap and easily used constructional material. His major achievement in exploiting its advantages was in the development and application of a new semicircular laminated timber arch roof truss. Fowke's novelty was an adaptation of a design introduced by Philibert de l'Orme (1518-1577) in 1561. De l'Orme had developed a method of assembling arched ribs from straight overlapping planks set on edge with laminations in the vertical plane and cut to the arch profile without being bent.[121]

Nevertheless, in the early nineteenth century de l'Orme's system was surpassed by the design of fellow Frenchman, Armand Rose Emy (1771-1851), a military engineer, which used horizontally laminated timber arches. Emy's design (1819) took advantage of the cost effectiveness of using several long lengths of thin timber which were bent and fastened by iron links. *The de l'Orme* system had been most useful when only short lengths of timber were available. Emy's method was widely used for military buildings and it also became an accepted form of construction for factory buildings throughout France.[122] His system was used in England by Lewis Cubitt for the roofs of King's Cross Station (1851-1852), a model of which Fowke had in the Museum of Construction.

It is curious that Fowke adapted the older de l'Orme system over the seemingly more economical and up to date Emy method. Interestingly, Fowke also eschewed the well publicised horizontally laminated timber arch design of Englishmen John and Benjamin Green which had been used in the 1840's for the roofs of a railway station, a church and a house.[123] Fowke's design differed from de l'Orme's timber arch in the number and thickness of the laminations, in the depth and length of the boarding, and especially in the finishing details and bracing employed. The characteristics and advantages of Fowke's system are best revealed in a description of its applications. (See Figure 51)

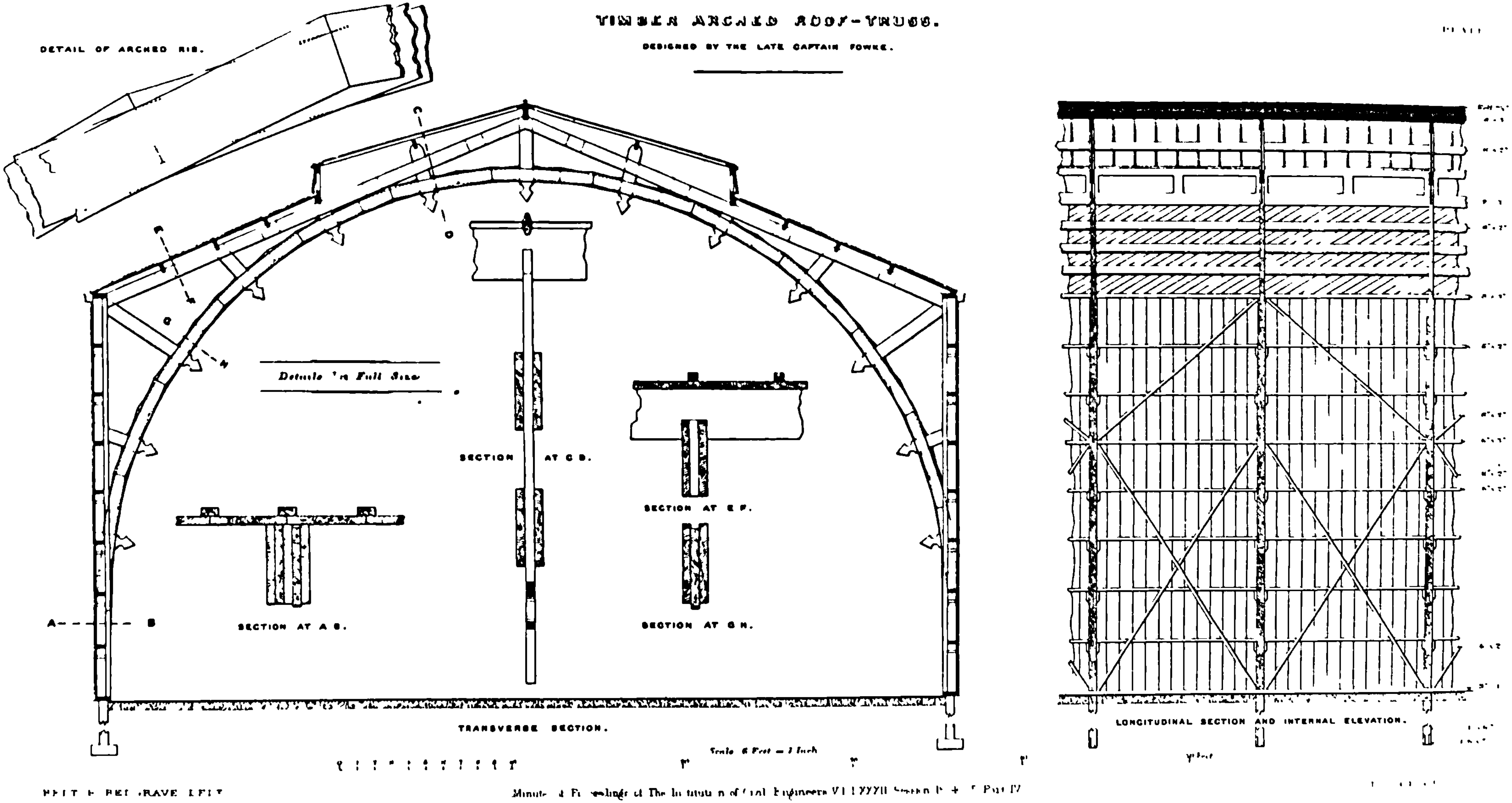


Figure 51 Fowke's Laminated Timber Arch Roof Truss

Fowke first employed the new roof truss in 1858 for the construction of a drill shed at South Kensington for the 1st Middlesex Engineer Volunteers. It was seen as a marvel of cheap yet serviceable construction. A space of 90 feet by 40 feet was enclosed for about £100. De l'Orme's system had two thicknesses of inch boarding sawn to the sweep and put together in lengths of 4 feet, the lengths being so arranged as to break joint. Fowke modified de l'Orme's method for the drill shed roof by using three thicknesses of 3/4 inch boarding, 9 inches deep, in 6 foot lengths, nailed together so as to break joint but not sawn to the sweep. He also improved on de l'Orme's design by the insertion of radiating plank braces, combined with double planks for the vertical framing of the sides of the shed and for the principal rafters. The laminated timber semicircular ribs of 40 foot span were arranged 10 feet apart, and the 3 inch by 2 inch rafters were placed at 2 foot intervals centre to centre. This timber superstructure rested on brick foundations. The exterior was covered with felt and skylights were formed of oiled calico. Fowke's design was used for several other drill sheds for volunteer corps throughout the country.[124]

The next application of Fowke's timber truss was early in 1861 for the entrances to the board room and the conservatory of the Royal Horticultural Society. The spans were 50 feet and sprung from 10 feet above ground level. Timber laminations were heavier than those used in the 1858 drill shed. The arches consisted of three planks, 9 inches deep; the centre plank was 1 1/4 inches and had nailed to it on either side a 3/4 inch plank, the ends breaking joint all through.[124]

At all events, it was in the buildings for the London International Exhibition of 1862 that Fowke made the most extensive use of his novelty. This remarkable group of structures comprised a main building of brick, iron, glass, timber and stone which was intended as a permanent feature and two temporary annexes of wood construction. The Exhibition covered an area of 24 1/2 acres.[125] Fowke's timber trusses were used in the nave and transepts of the main building and for the annexes. The main building had two iron and glass domes, and the roofs of interior courts were of ridge and valley type, wholly of iron and glass. Even so, Fowke had not thought it appropriate to express iron elements on the exterior and clad the building in a massive brick skin articulated with pilasters and arched recesses containing windows. After the lightness of its celebrated predecessor, the building for the Great Exhibition of 1851, it appeared heavy and clumsy.[126] (See Figure 52) Notwithstanding the 1862 Exhibition building's artistic shortcomings much discussed in the press following the project's completion, Fowke's employment of the novel timber roof truss was applauded. The Civil Engineer and Architect's Journal said, for example: "Nothing can be more successful than the design of the light wooden roof covering the annexes, or that of the more solid roofing of the nave."[127]

The nave of the Exhibition's main building was 800 feet long, 85 feet wide and 100 feet high to the ridge of the roof. Cast iron columns carried thirty 85 foot span ribs which consisted of 3 thicknesses of plank from 18 inches to 2 feet 6 inches deep nailed and bolted together and so arranged that their ends broke joint. In this situation Fowke increased the thickness of the laminations. The centre plank was 4 inches and each of the outer ones 3 inches. He also used a heavier bracing system of wooden trusses in place of radiating planks.[128] The original design was lighter; but when the ribs proved not to be strong enough in June 1861, Fowke had to re-design them and it was not until the following October that the first one was set in place.[129] Ribs were prefabricated in the Pimlico yard of the contractor, John Kelk, and carted to the building site in four pieces where they were joined to make two and raised by an ingenious steam powered hoist and the final junction made at the roof ridge.[130] Kelk was contractor for the Exhibition of 1862 in conjunction with Messrs.

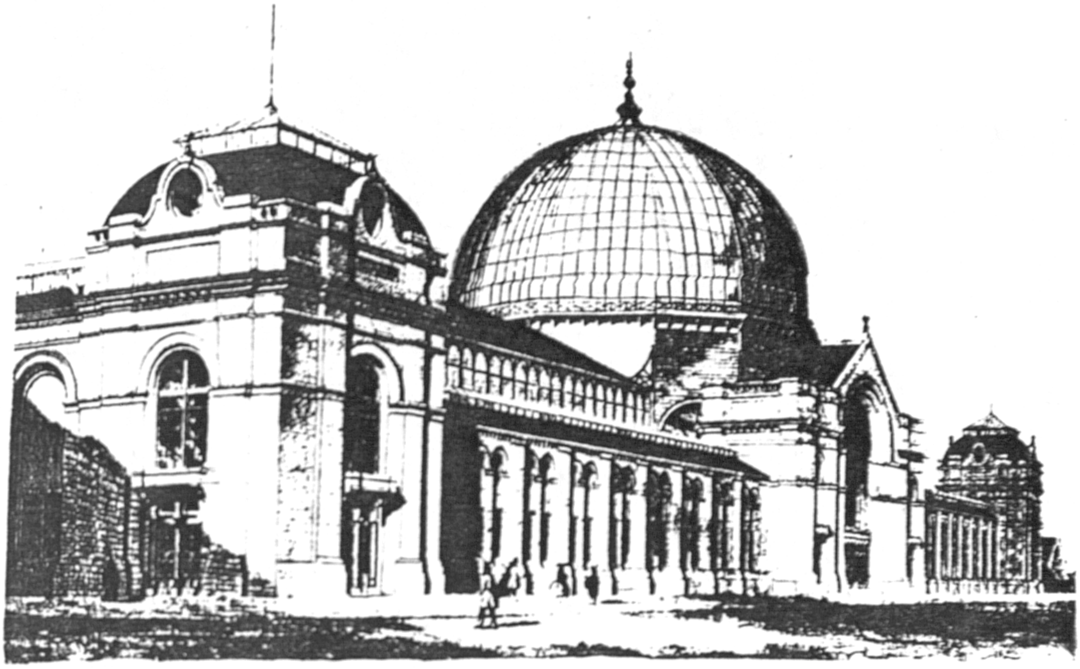


Figure 52   International Exhibition Building, 1862

Lucas. Both were amongst the largest building contractors of the day. Sir John Kelk (1816-1886) had been apprenticed to Thomas Cubitt and early in his career had been in partnership as a builder in Westminster with a Mr. Newton. His work included large contracts for railways and public works and he was perhaps best known for Victoria Station (1860) in association with the engineer John Fowler.[131] Kelk deserves some credit for helping to realize the industrialized, mass produced fabrication of Fowke's timber roof truss design in the 1862 Exhibition buildings. The roof was covered with felt on 1 1/3 inch planks, and the nave was lighted entirely by clerestorey windows. Transepts at each end of the nave were of exactly the same width and height as the nave and their roof ribs were of precisely the same construction. (See Figure 53)

Roofs for the annexes or temporary buildings adjoining the Exhibition were lighter. The annexes had widths of 200 feet and 150 feet respectively, and were covered by ridge and valley roofs supported on Fowke's laminated timber ribs of 50 foot span. These ribs were identical to those used in the entrance structures for the Royal Horticultural Society except that they were stilted up six feet higher and were 15 feet apart instead of 10 feet. The radiating braces of 1 1/4 inch planks, which connected the principal rafter and upright with the curved rib, were brought below the intrados of the curve, and were finished off, for the sake of decoration, by a spear head. Half the roof was covered by boards and felt, the other with a glazed skylight with louvres for ventilation throughout the whole length. Each rib was assembled on the ground over a full sized drawing marked on a platform, and when completed was hoisted into position using scaffold poles tied across the angles to stiffen it in erection.[132] (See Figure 54)

The use of timber was an ingenious solution by Fowke to the demands of building where economy was paramount. His roofing of the nave and transepts and the annexes was in marked contrast in this respect to his

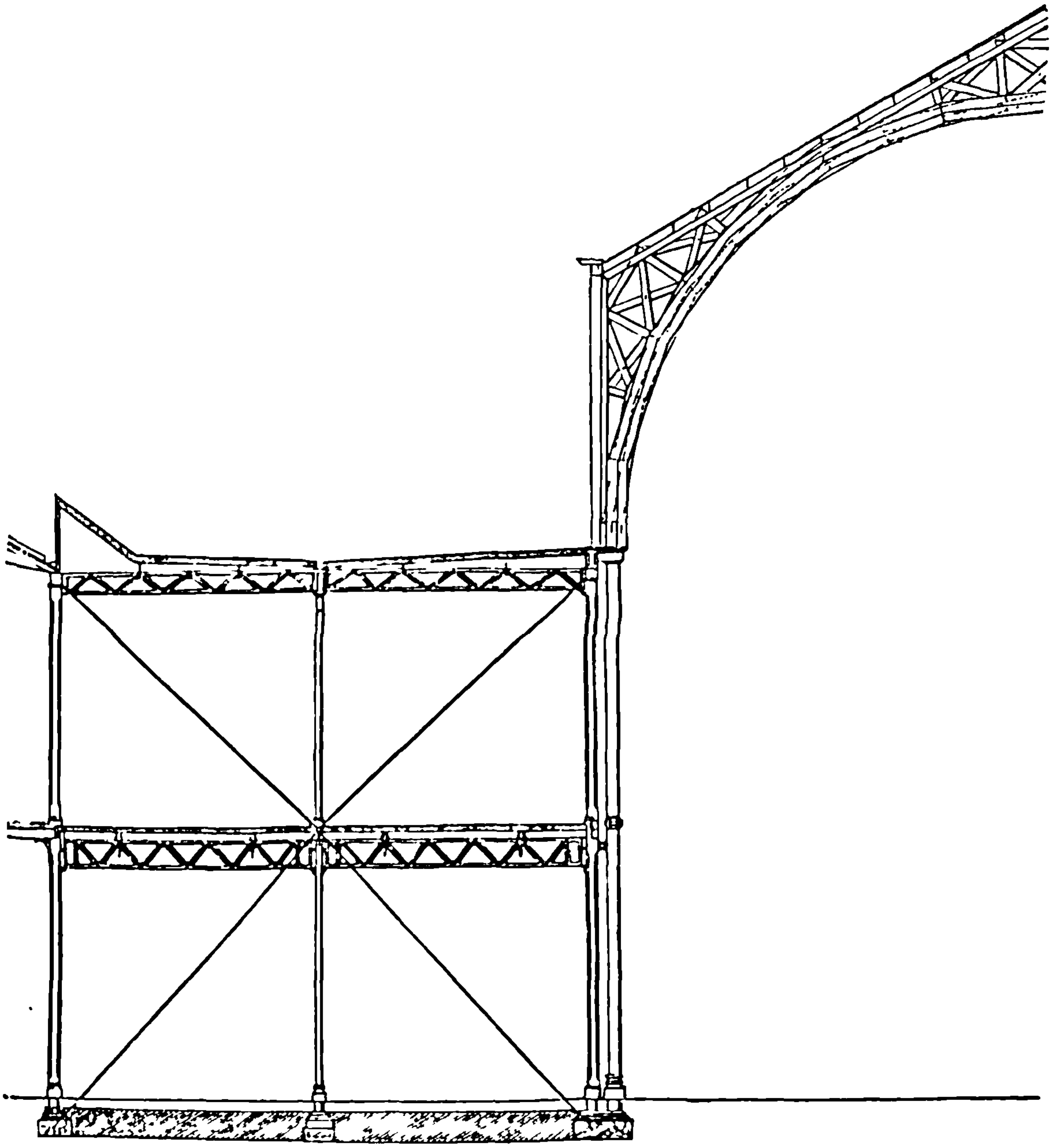


Figure 53 International Exhibition Building, 1862 : Section of Timber Nave Rib Showing Cross Bracing in the Gallery

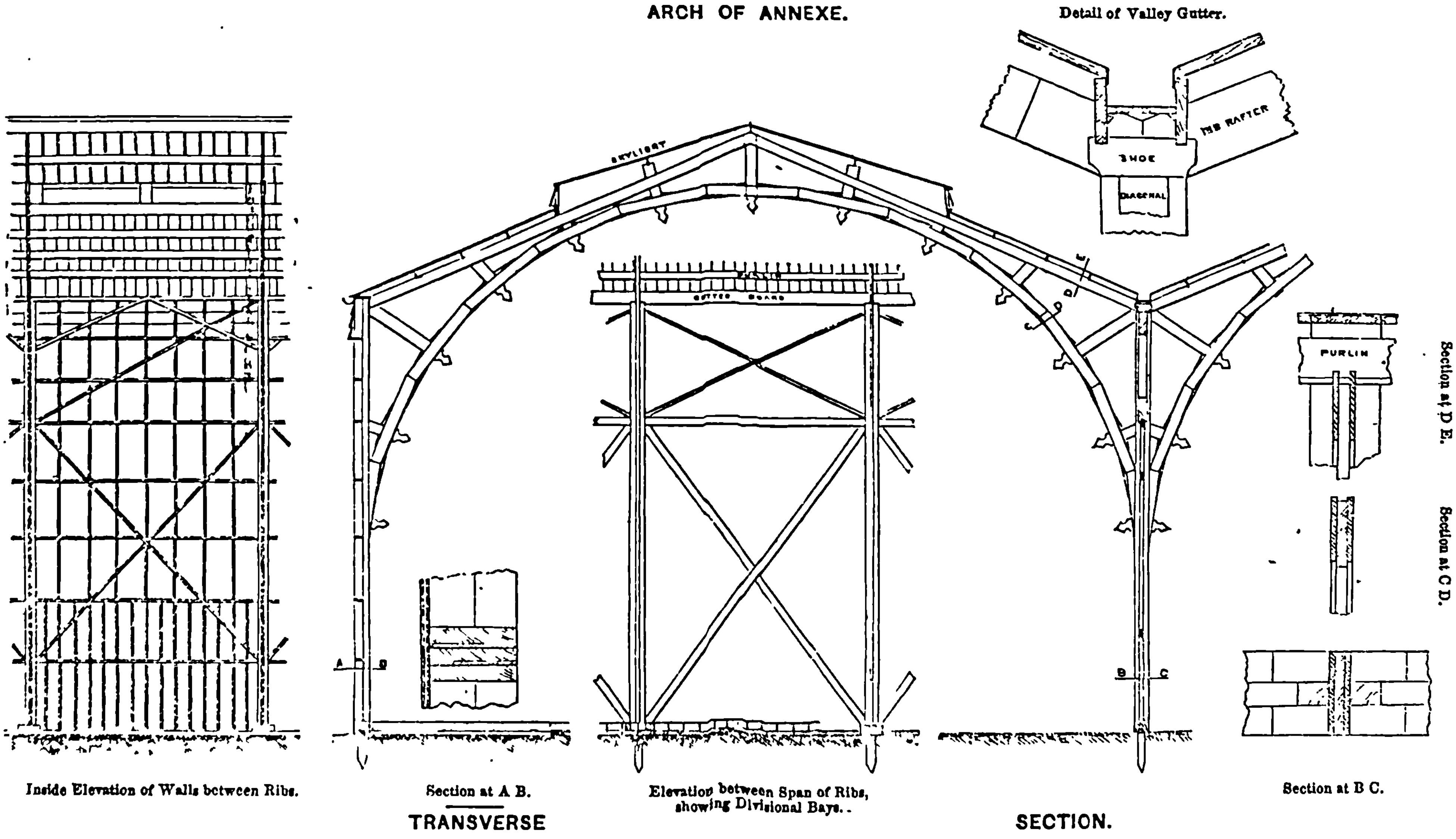


Figure 54 International Exhibition Building, 1862; Timber Arch of the Annexes

much criticised iron and glass domes for the 1862 Exhibition building. He also used timber in the roofs of the Exhibition's picture galleries but the truss was to a completely different design. It consisted of principals made up of two trussed double timber rafters connected together by an iron tie bar four feet above the level of the wall plate, making a coved ceiling correspondingly higher than could be achieved with an ordinary tie beam roof. This was a decided advantage in top lighting for picture galleries. The span was 50 feet. Fowke apparently used this design in one of the South Kensington galleries and also in the Irish National Gallery in Dublin.[133]

At the same time as the 1862 Exhibition buildings were under construction, Fowke used his semicircular laminated timber arch truss to roof the great hall of the Industrial Museum of Scotland (1861-1863) in Edinburgh. This grey sandstone structure in the Venetian Renaissance style was designed by Captain Fowke and executed under the superintendence of Mr. R. Matheson, surveyor to the Office of Works in Edinburgh. It consisted of a western wing for offices and library, and an eastern wing for a large lecture theatre; while the space between and in the rear of these projecting wings was occupied by the museum proper which consisted of a series of glass lighted courts, opening upon a great museum hall 265 feet long by 70 feet wide and 70 feet high with galleried aisles. The timber arches spring from slender cast iron columns and are similar in design to those for the nave and transepts of the 1862 Exhibition building. Skylights cover the greater part of the roof.[134] (See Figure 55)

Scott used Fowke's novel timber roof design on an extensive scale for the buildings of the International Fisheries Exhibition which opened in May 1883 on the site of the Royal Horticultural Society's gardens in South Kensington, covering an area of 300,000 square feet. Some of the roof trusses originally used in Fowke's annexes for the 1862 Exhibition apparently had been stored for twenty years for they were re-used by Scott

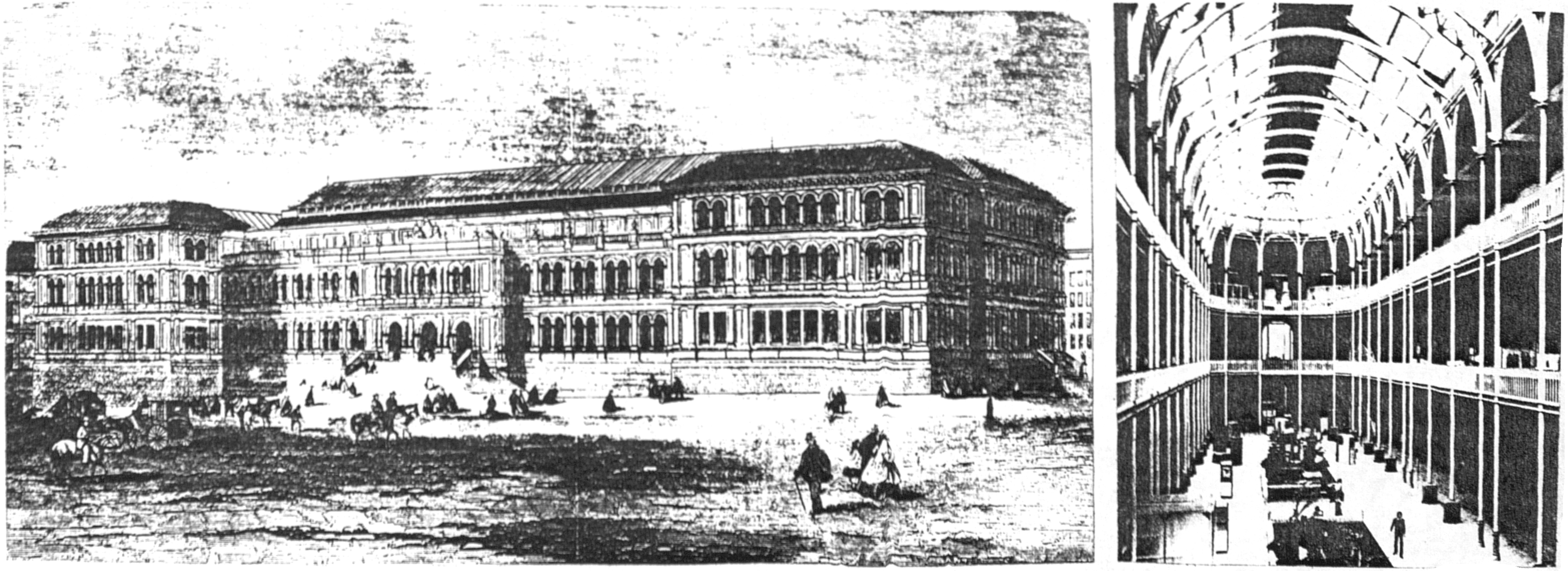


Figure 55 Industrial Museum of Scotland, Edinburgh, 1861-63 : Perspective View and Great Hall

along with new roofs to exactly the same design throughout, except for a few buildings. Engineering praised the cost effectiveness of Scott's work:

> "The executive committee have, indeed, wisely repressed all tendency towards extravagance in construction and it must be admitted they have succeeded admirably in covering a very large area successfully at a low cost."[135]

The cheapness of Fowke's timber roof truss design could be credited with much of this economy in construction.

One of Fowke's assistants for the 1862 Exhibition project, Captain William C. Phillpotts, described the advantage of his brother officer's novel roof truss design in a paper to the Society of Arts. He said of the annexes:

> "The building itself will be worthy of its contents, for in ingenuity, *economy, and simplicity, it is* allowed to be a triumph of construction. It *requires no* framing; any person of ordinary intelligence, able to drive a nail, could construct the ribs, which have nothing in them but nails and sawn planks."[136]

Herein perhaps lies part of the explanation as to why Fowke adapted de l'Orme's system rather than Emy's method which, while arguably potentially more economical, was technologically more sophisticated and more difficult to construct, especially in the apparatus needed for bending the horizontally laminated ribs and fixing them together. Fowke originally designed his roof truss for army volunteers who may not have the skills or equipment to employ more complicated designs in timber roof trusses for their drill sheds. He was also a military man, and one had always to favour the simplest solution in consideration of the potential difficulties of executing works in the field.

Fowke's design was not, however, without its problems. Gilbert Redgrave's experience in using it, as Scott's assistant in the 1883 International Fisheries Exhibition, indicated that it had a tendency to spread at the springing. To counteract this, Redgrave recommended securing the feet of the rib to a firmly fixed plate or sill, and making the total width of the eaves, for a span of 50 feet, 6 or 7 inches less than at the springing which would allow the haunches to give sufficiently to bring the sides upright. He also suggested that great caution be used in rearing the truss into position owing to the extremely small lateral rigidity of this form of construction. Notwithstanding these observations, Redgrave was convinced of the utility and artistic merits of Fowke's design:

> "A notable advantage of this system of construction is that the building internally assumes a decorative appearance, and readily lends itself to decoration; it is also very much cheaper than a wood, or wood-and-iron, truss of the ordinary kind."[137]

Recognizing Redgrave's art training and practical experience in architectural design and building science, his verdict on Fowke's novel timber truss roof must be considered significant.

Scott's Cement in Construction at South Kensington

Scott's cement was exhibited in the Museum of Construction almost from the museum's founding. Francis Fowke experimented with the new material to prove its strength in construction and quickly applied it in the South Kensington Museum building programme. Both Fowke and Scott were to make important and extensive use of the material in mortar, plaster and in sgraffito decorative panels.

Besides terracotta, another hallmark of the South Kensington style was bright red brick with a very homogeneous texture owing to the extreme thinness of its mortar joints. This jointing precision was achieved partly by the use of Scott's patent selenitic cement which was far superior in strength to ordinary lime mortar.[138] Fowke may have used Scott's cement in the Vernon and Turner Galleries (1858-1859), a bare brick range constructed northward of the Sheepshanks Gallery and intended originally as temporary accommodation only. The brickwork was built with cement mortar, and Fowke boasted that, although conceived as temporary, the structures would stand for a century.[139] He was right; this range survives, though unrecognizably, as part of the north-east section of the Victoria and Albert Museum.[140] All the same, Fowke did not say what kind of cement he used, but it is possible that it was Scott's since the product was in the Museum of Construction at the time construction began. On the other hand, Fowke did not test the strength of Scott's cement by experiment until 1861, and this may suggest that he used another cement in the Vernon and Turner Galleries. The first clearly documented use of Scott's cement for mortar at the South Kensington Museum was in the exterior brickwork of the South Courts (1861-1862).[141] This building consisted of two galleries east and west of an open ground floor arcade surmounted by a narrow gallery, and it featured exposed iron construction in the interior.

Scott's cement was used most extensively as a plaster for the interiors of museums, exhibition buildings and in the Albert Hall. Once again, the earliest clear documentation of its use was by Fowke in the South Courts of the South Kensington Museum. Scott made considerable use of his patent product, and described the process of preparation and application in addresses to civil engineers' and architects' professional associations. His new material was used in plastering the interior walls of the buildings for the London International Exhibition of 1871 which comprised a series of top lighted galleries and side lighted rooms erected adjoining the covered arcades of the Royal Horticultural Society's gardens.[142] Scott explained to a gathering of the Institution of Civil Engineers the formula for the selenitic cement used in this project:

> "... in using this new method of mortar making (which he termed the selenitic method) for plastering the walls in the galleries of the Exhibition Building at South Kensington, he employed 6 parts of

> sand to 1 part of lime, and for the finishing coat 1 part of lime with 4 parts of sand."[143]

Perhaps the single most extensive use of Scott's cement in plastering building interiors was in the Albert Hall (1867-1871). In 1872, Scott described in considerable detail to a meeting of the Royal Institute of British Architects the process for manufacturing the product on site as well as for its application in the walls and ceilings of this familiar landmark at South Kensington:

> "One quarter of a cubic foot of plaster of Paris was stirred into a bucket of water and thrown into the pan of an ordinary mortar mill, so as to make a milky fluid of the plaster of Paris; another bucket of water or so was then added, and 5 cubic feet of the ground grey lime gradually added ... with more water ... until the pan contained a thin slip of the lime and plaster. To this mixture 30 cubic feet of sand were added and thoroughly incorporated with it, and the mortar was then ready for use. Thus treated the lime sets without slaking, and makes what I have termed "selenitic mortar". For the finishing coat in rough stucco, the quantity of sand was reduced to 20 cubic feet, and after the first coat was put on the wall, the plasterers could in a few hours' time follow on with the finishing coat. For the first coating on lathwork the usual quantity of hair, but unbeaten, was added whilst the mortar was being incorporated, and the ceilings were finished with a mixture of slip prepared as before, with 1 part of chalk and 2 parts of sand for every part of lime used in the slip."[144]

Scott's selenitic cement was also used to make sgraffito decorative panels for the recessed portions of the back exterior walls of the Science Schools (1867-1871), now known as the Huxley Building. This four storey building with an upper arcaded gallery on the main facade featured a rich combination of brickwork, stone and terracotta. Scott was the architect but was greatly assisted by others, principally J.W. Wild and James Gamble. The sgraffito decoration was to designs by F.W. Moody (1824-1886) of the National Art Training School and was executed by his students in 1871-1873 . Various techniques were used in undertaking the work which was confined to the back of the building by reason of its avowedly experimental character.[145] The process of applying Scott's cement was described by The Builder in September 1871. Walls were first rendered with a coat of selenitic mortar of ordinary fineness. On this, when dry, was spread a second thinner coat of a finer description of the same mortar, blackened with manganese. A third and yet thinner coat of fine selenitic mortar tinted with light grey was spread on the black background. Designs were traced on the upper coat when dry, and the parts of the design to be left as ground work were then scraped out leaving a white pattern relieved on a black ground. The Builder thought that Scott's selenitic cement would be durable but questioned its ability to stay clean in the polluted London atmosphere, a concern which it had too about terracotta at South Kensington.[146] It was with terracotta that Fowke and Scott collaborated with their artist colleagues most closely in combining strength with beauty in a structural and decorative material at South Kensington.

Pioneering Works in Terracotta

Architectural terracotta was not an innovation of the nineteenth century. It had been used in late Gothic and Renaissance buildings of Italy and Germany as a constructional material arranged to form complete facings or dressings for brickwork. The revival of architectural terracotta dates to the early eighteenth century but most especially to Coade's manufactory in 1769. It was used initially in decorative architectural details as a cheap alternative to carved stone. In 1822 William and Henry Inwood used terracotta extensively in the decoration of St. Pancras Church, including the encasing of structural iron columns. By the 1840's experiments were being tried in the structural use of the material. In 1842 and 1844 Edmund Sharpe designed two churches at Lever Bridge and Rusholme in Greater Manchester, built of solid terracotta blocks bonded into brickwork walls in the same manner as traditional stone facing. By the 1850's it was used on a small scale by provincial architects and builders, and in the next decade by commercial architects to a limited extent for polychromatic effect in conjunction with stone, brick and tile. Charles Barry Jr. used terracotta in both decoration and construction in his New Alleyn's College (1866-1870), Dulwich.[147]

At South Kensington, terracotta was used as a decorative material from 1856, as a structural material in columns from 1861, and as a constructional material in ashlar facing from 1867. *Stratton has argued that the* South Kensington movement was a vital formative influence on the adoption of terracotta as a significant decorative and constructional material in the late nineteenth century.[148] Fowke's and Scott's experience influenced the choice of terracotta for the interior and exterior in Alfred Waterhouse's Natural History Museum (1873-1881) which was the first building in England and possibly the first in the world where the main facade was entirely faced in the material.[149] This well known building represented the climax of the advances in terracotta manufacture and use achieved by the 1870's.[150] The work of the Royal Engineers at South Kensington was pioneering in the sense that it helped to establish the credibility of terracotta as a durable, cost effective and tasteful material, a product born of the linking of art and industry, craftsmanship with factory production.

Fowke established his personal confidence in the structural capabilities of terracotta by his strength tests on full size columns in 1861. However, David Kirkaldy's experiments for Charles Barry Jr. seven years later were much more sophisticated and consequently more supportive of the utility and safety of the new material.[151]

Even so, Fowke was more concerned, it seems, to promote the durability of terracotta than its strength or for that matter any other quality save perhaps economy. In his report on the completion of the National Art Training Schools (1863), which had terracotta dressings in substitution for stone, Fowke explained:

> "The experience of several years' exposure to the weather both here and in the arcades of the Horticultural Gardens has proved that the power of resistance of terra-cotta to the deteriorating influences of the London atmosphere is very much greater than that of Portland stone. The contrast between the degraded and sooty tints of the latter and the bright fresh colour of the non-absorbent terra-cotta being so remarkable as to provoke a doubt of their being exposed for equal periods; and it is this remarkable quality, even more than its beautiful original colour, which has induced the change above alluded to, and which marks it so emphatically as the best material for architectural decoration in large and smoky towns."[152]

Scott too was to emphasize the durability of terracotta. In the Albert Hall, for example, he used it extensively on the exterior ground floor facing. For this application he specified that the material be used with a superficial roughness to the surface, the way it came from manufacturers' Gibbs and Canning. Alfred Waterhouse praised the use of the material in this way without any attempt to chisel it down to a true surface. He said that if "successful use is to be made of terracotta, this treatment must be insisted on."[153] Scott concurred and added:

> "As surely as you scrape off the surface from terra-cotta it undergoes degradation, and readily takes up soot and dirt. We tried it in one part of the Hall, in one or two of the door-ways, and even there, though protected somewhat from the weather, we were obliged to give it up."[154]

Fowke and Scott, therefore, knew well the durability of terracotta in the environmental conditions in which they were working, and they appreciated the qualities of the material which made it so. Moreover, while they were not moved personally to extol the cheapness of terracotta, they no doubt shared the confidence of the Science and Art Department in this advantage of the material. The Department's 15th Report (1867) claimed that building costs in terracotta and red brick had been kept under 1 s per cubic foot. This was about 1/3 cheaper than George Gilbert Scott's Foreign Office and almost 3 times cheaper than Charles Barry's Houses of Parliament, both of which were built in stone.[155]

Nevertheless, terracotta was not foolproof. Charles Barry Jr. pointed out that the use of the material made more work for the architect in producing detailed drawings and undertaking other tasks to allow for manufacture and timely delivery on site. He also indicated that failure in manufacture could cause delays in the progress of the building works.[156] Waterhouse's Natural History Museum required terracotta in such unaccustomed quantities that the sub-contractors were unable to deliver on schedule and this and other problems connected with it were said to have helped cause the bankruptcy of the main contractors.[157] Fowke and Scott complained of these problems but not excessively. In his report of 1864 on new buildings at South Kensington, Fowke explained that the rate of progress was slow on the north side of the principal quadrangle because of "... the delay consequent on the careful modelling and manufacture of the terra-cotta, which material is exclusively employed in all the dressings and ornamental details of the exterior."[158] While discussing the construction of the Albert Hall, Scott complained of the hold up in progress on the outer walls which were faced with terracotta: "The outer wall was, of course, delayed for the terra-cotta. Delay in the supply of this material appears to be an ever irritating difficulty in its use."[159] Notwithstanding these irritations, Fowke and Scott made creative and extensive use of terracotta and it is revealing to review their various uses of it in some detail.

Fowke's first use of terracotta at South Kensington was in the interior of the Sheepshanks Gallery (1856-1857). This was a somewhat plain, two storey brick building. Fowke designed it with coupled round-headed blind windows on the upper floor. External brickwork was polychromatic as was the tile roof covering. This stylistic treatment was later to give way at South Kensington to the characteristic red brick and terracotta exterior. The interior space was divided by a brick cross wall and on the upper floor by a longitudinal brick wall of hollow construction. The latter wall was carried on cast iron girders which extended between brick piers up the centre of the building. Picture galleries were located on the top floor. It was in the lower rooms, however, where Fowke experimented with terracotta both for decorative and functional purposes. For fireproofing, a terracotta shield was used to encase the bottom flange of the cast iron girders which rested on the brick piers in the centre of the building. This shield was in the form of a simple cavetto which ran round the lower rooms. Below this shield was a terracotta frieze which was perforated in an ornamental pattern. It was connected to ventilating shafts in the upper hollow walls. This important component of the building's ventilation system will be discussed further in another section of the present chapter. The terracotta cornice acted as a principal decorative feature of the lower rooms, in addition to its fireproofing and ventilation functions.[160]

After 1860 Fowke, in collaboration with Godfrey Sykes, was to use terracotta for all manner of architectural dressings and ornaments. In the Quadrangle (begun 1862) of the South Kensington Museum, for example, terracotta was early substituted for brickwork in pilaster capitals, and the material was also used for a frieze over the first floor windows and in highly ornate columns in the central recess.[161] By 1863, with the construction of the western wing of the National Art Training Schools, a court of rather plain ranges behind the Quadrangle, terracotta had replaced stone for simple decorative elements. Fowke explained:

> "... the use of stone, which in the last-named building was confined to projecting cornices and horizontal mouldings, has here been entirely done away with, experience having shown that these mouldings, equally with ornamental work, can be readily produced in terra cotta."[162]

Fowke was applying techniques which he had seen at the Paris Exhibition of 1855, and which now had become part of the standard architectural vocabulary of South Kensington.

Henry Scott also used terracotta freely and extensively for decorative purposes. Perhaps the crowning achievement in this use of the material at South Kensington under his direction was in the distinctive mosaic frieze of the Albert Hall which encircles the building exterior below the main cornice. Originally it had been intended that this feature be sculptured, but the idea was abandoned for want of time, money and competent modellers. It was executed instead in terracotta tesserae, with buff figures outlined in black on a chocolate ground. A number of leading artists designed the figures; the terracotta was manufactured by Minton, Hollins and Company; and the tesserae were assembled in the frieze design by ladies of the South Kensington Museum's mosaic class.[163]

The role of the Royal Engineers in this process is interesting. It involved the 'new' science of photography. Sergeant Spackman took the artists designs and enlarged them by preparing small photographic negatives from the originals, and by means of a camera, illuminated with a lime light, threw an image of the required size on to a screen covered with paper and upon these made the necessary outlines in black lines, the thickness of which he determined. These large pictures were made into the terracotta mural decoration by the fitting together on them of tesserae of five gradations of thickness from 7/8 to 1/4 of an inch.[164] Scott gave particular attention to Spackman's role in the development of the mosaic frieze in his paper to the Royal Institute of British Architects on the Albert Hall in 1872. He also promoted the use of this form of flat decoration over modelling in relief because, as he said "... in London soot deposits and birds' nests have somewhat marred the effect of the sculptured figures in the pediments of our public buildings."[165] The mind of the engineer was ever on functional utility, even in artistic appreciation.

The use of constructional terracotta at South Kensington, however, is of greater interest from the perspective of the present study of building technology development. Fowke's first venture in this use of the material was in 1861 for the surrounding and interior arcades of his conservatory for the gardens of the Royal Horticultural Society. The massive internal flight of stairs and arcade in brick, tile and terracotta contrasted with the light iron and glass envelope of the conservatory (see Figure 56). Building News described the arcades as "Italian" in style.[166] Terracotta columns 8 feet 6 inches high were employed to support brick ornamental arches in the arcades.

Artistic design and modelling of the terracotta columns were by Sykes, but Fowke furnished the structural design and subjected the columns to strength tests.[167] The terracotta was manufactured by M.H. Blanchard of Blackfriars Road, London.[168] Blanchard had worked at Coade's works and bought some of the moulds when it closed. He exhibited at the 1851 Exhibition and won medals. His most publicized early work was in the Brighton Aquarium, the South Kensington Museum, and the arcades of the Royal Horticultural Society's gardens. He was one of the first terracotta manufacturers to develop an extensive export trade. Blanchard may have supplied as much as 95% of the terracotta for the South Kensington Museum; he bid lowest and produced the finest material.[169] The Builder said of Fowke's and Syke's terracotta work in the Royal Horticultural Society's gardens that it "is one

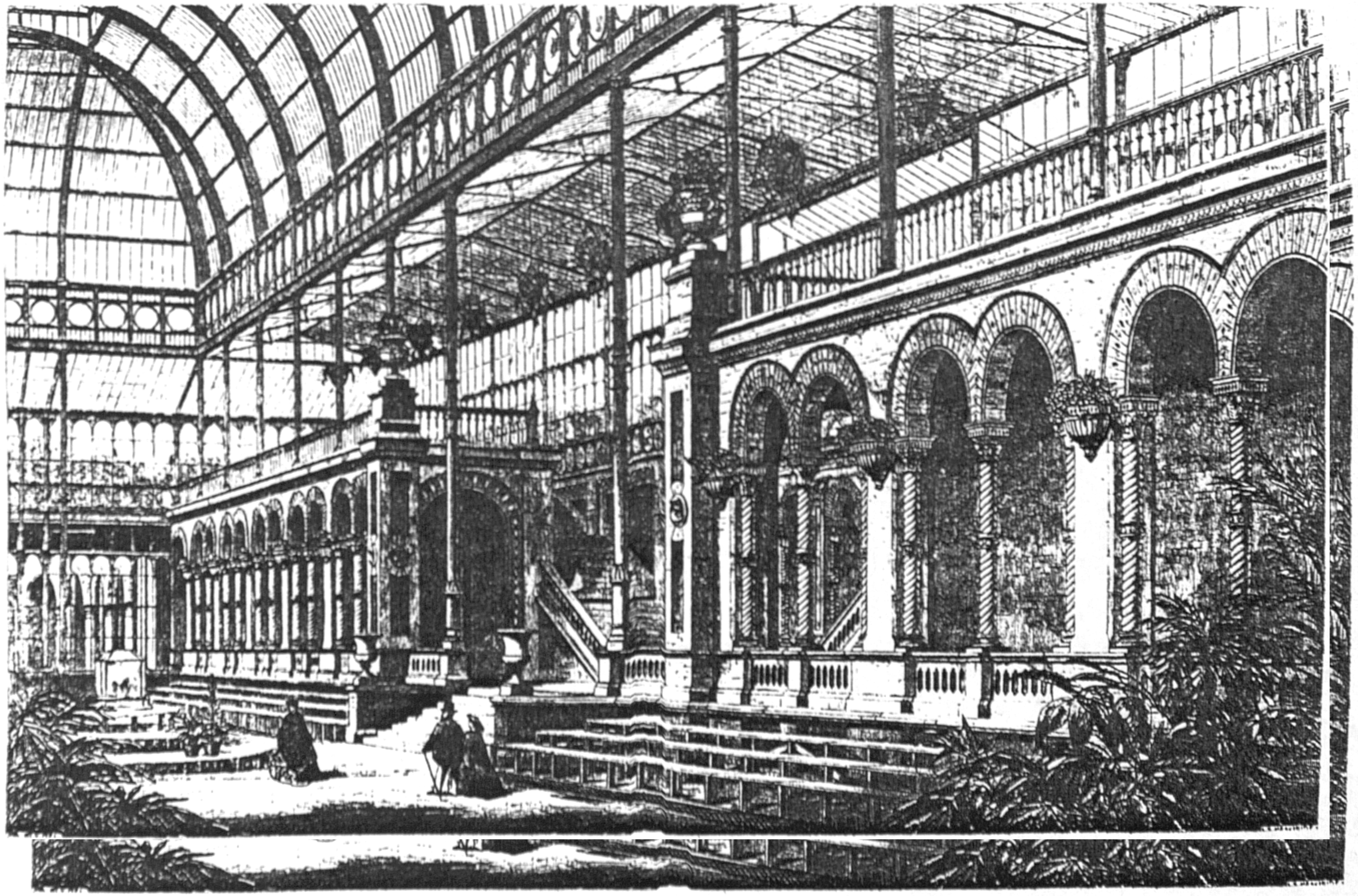


Figure 56 Interior of the Royal Horticultural Society Conservatory, South Kensington, 1861

of the best things of the kind that we know of."[170] Building News said: "The terra-cotta works ... are admirable examples of this most effective and valuable material."[171]

Scott first experimented with terracotta as a constructional material in facing for the upper balcony of the Science Schools (1867-1871). This terracotta arcaded balcony was carried on richly moulded terracotta cantilevers secured and tied back by iron members. It projected 5 feet 5 inches from the face of the wall, each cantilever being composed of five pieces of terracotta joggled together. The centre piece had a key joint, and in the core ran a 5 inch flanged iron bar which passed through the wall and was tied down by a bolt running down in the thickness of the floor.[172] The Builder criticised this sham terracotta cantilever saying it was "an inappropriate application of this material, as the pieces of which it is composed seem to have but partial support, though of course they are fully secured, and produce a feeling of danger."[173] (See Figures 57 and 58)

Scott used terracotta more extensively as a constructional material in the exterior ground floor walls of the Albert Hall (1867-1871). Terracotta was regarded simply as a superior description of brick. Small blocks with rough lines and edges were used to effect the desired impact of adding to the massive appearance of the building, one which would depend more for its appeal on the sweep of its lines than on exquisite finish. This artistic judgement owed most to Reuben Townroe who undertook the modelling.[174] Even so, as indicated previously, Scott preferred the rough surface treatment mainly because it preserved the material's properties of resistance to decay from environmental pollution. Moreover, he selected terracotta from Messrs. Gibbs and Canning because their formula for manufacture "promises to render it very durable" and because their blocks were chambered from behind so that brickwork of the wall could be built into them, unlike the blocks made by competitors Blasfield and Blanchard which had cells which had to be

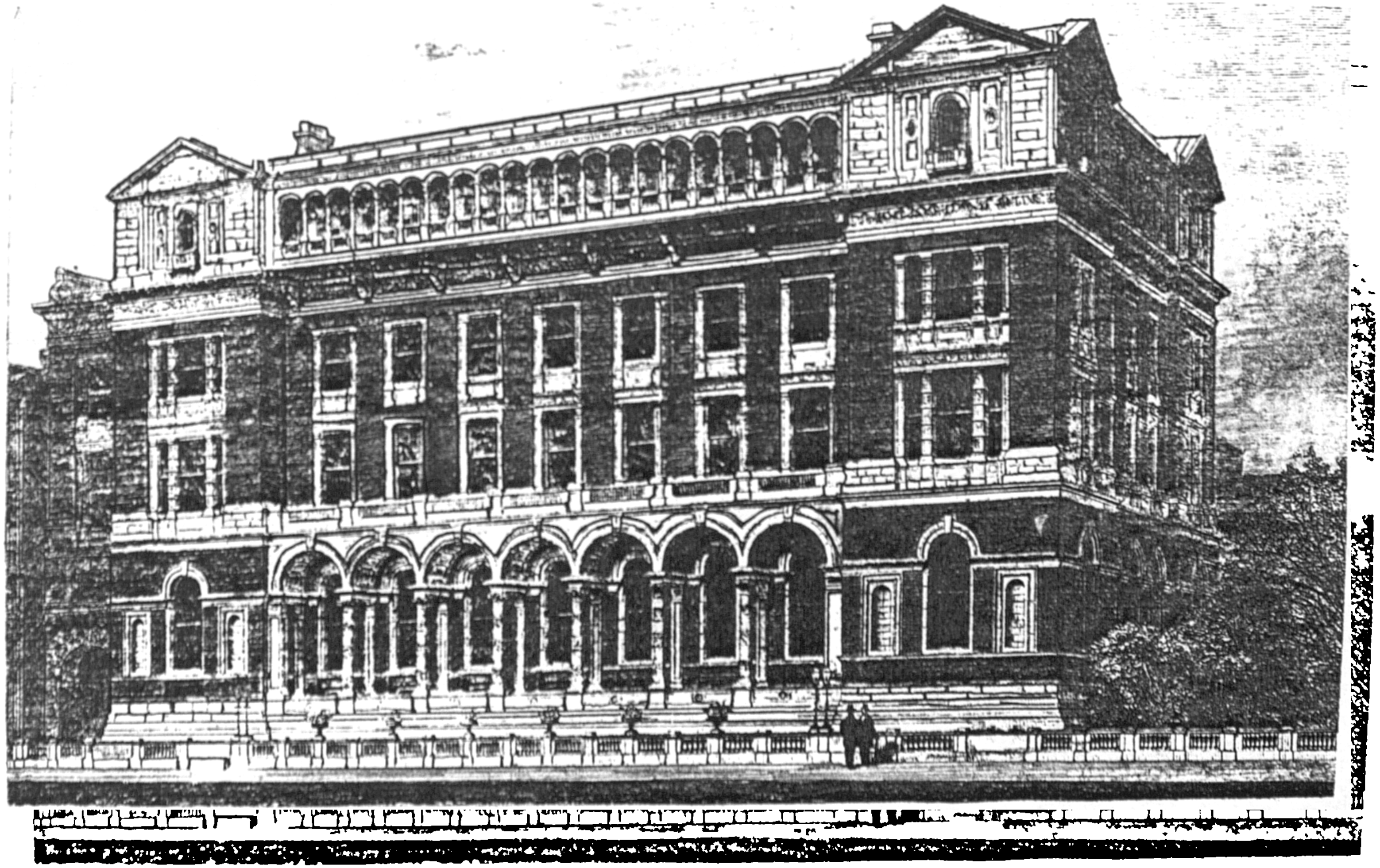


Figure 57 The Science Schools, South Kensington, 1867-71

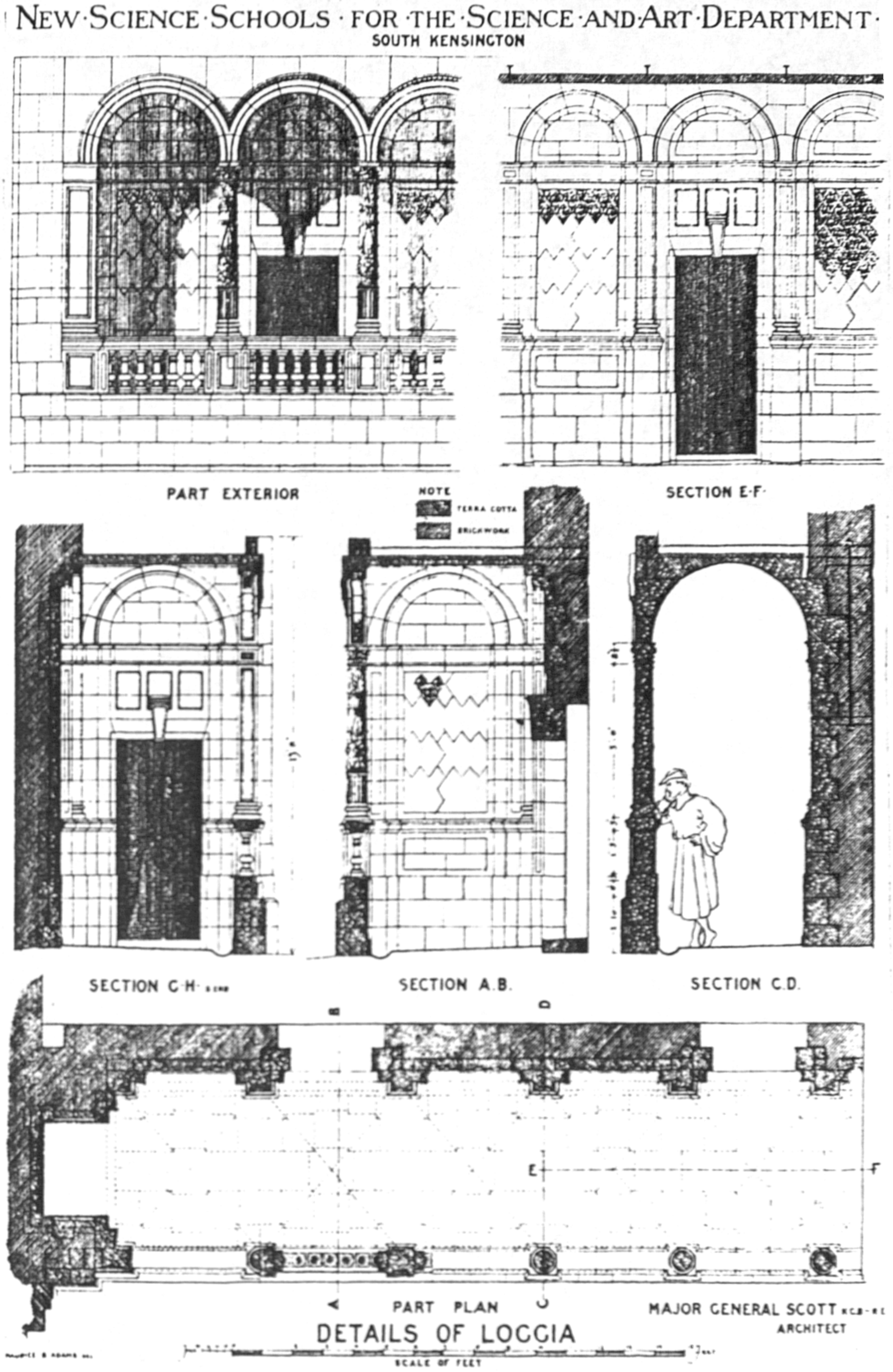


Figure 58 The Science Schools : Details of Terracotta in the Loggia of the Upper Balcony

filled with concrete or grouting.[175] Scott admitted that Gibbs and Canning's terracotta blocks necessitated extra cost for brickwork, but said this was offset by saving in grouting and in concrete. He added: "This system appears to me to make a better job than blocks with cells closed at the back."[176] Scott credited Gilbert Redgrave "for the whole of the work connected with the preparation of the terra-cotta, as well as his advice and assistance in every part of the work."[177]

The form of terracotta block used by Scott is interesting. Charles Barry Jr. used Blashfield's hollow blocks bonded into the walls for his New Alleyn's College which was under construction at the same time as Scott's Albert Hall. Earlier use of solid terracotta blocks, as in Sharpe's churches in the 1840's, had experienced reliability problems due to the difficulty of achieving a consistent thorough burning of solid blocks in the kiln. Solid blocks were also more expensive. Barry filled in Blashfield's hollow blocks with Roman cement and brick, not Portland, Lias or other cements which contained lime in the free state. He indicated also that hollow blocks may be solidly bound together by pieces of hoop iron being turned into the hollow of adjoining blocks before the cement was run in. Kirkaldy's tests for Barry showed that filling in doubled the strength of hollow blocks.[178] Chambered terracotta blocks with built in brickwork achieved a more satisfactory bond as well as a strong wall. It is interesting that Waterhouse chose Gibbs and Canning's terracotta block design for the Natural History Museum, thus siding with the engineer Scott over the architect Barry.[179] Gibbs and Canning started their business in Glascote, near Tamworth, Staffordshire in 1867. They pioneered the transformation of terracotta from ornamental to large architectural contracts.[180] Scott demonstrated his faith in the scientific development of new materials in selecting Gibbs and Canning's novel system of hollow block terracotta soon after its development, and therefore helped lead the way to the success of this advance in building technology.

Iron Roofs and Domes: Structure Versus Decoration

Innovation in iron was not exclusively a concern of engineers in the nineteenth century, and the issue transcended strictly structural considerations. As Muthesius has shown, architects and architectural writers were deeply involved in the question by the 1850's. Some thought the use of iron inevitable but argued that it should be concealed in structure; others advocated exposed iron structural members but decorated with motifs taken from stone architecture.[181] This debate was still going in the 1870's.[182] The climate of conflicting views on the iron problem necessarily affected both Fowke and Scott. They turned to iron for the medium and wide span roofs needed to satisfy the programmatic requirements of many of their buildings, especially in providing unobstructed space, abundant natural lighting and fireproof construction. An examination of their various works in iron reveals an interesting interaction between the engineer's search for structural efficiency and safety, and the architect's quest for beauty with soundness and commodity. It also manifests some important relationships between each of these engineer officers and private sector engineers, architects and manufacturers in trying to solve the iron problem.

Fowke's first major essay in iron was the conservatory for the Royal Horticultural Society which was erected in April 1861. Iron and glass conservatories were no novelty. As early as 1818 Thomas Clark of Birmingham produced cast iron components for the conservatories of the nobility.[183] Richard Turner produced several wrought iron curvilinear conservatories in Ireland in the 1830's, and became one of the pioneers in the structural development of the wrought iron I beam for wide span roofs in the Palm House at Kew (1844-1848).[184] Nevertheless, it was the 1860's which saw foundries producing large conservatories and winter gardens on an extensive scale. A major producer was Andrew Handyside and Company, a specialist in iron buildings for export.[185]

The Royal Horticultural Society conservatory was a splendid example of a decorated cast iron and wrought iron, glass enclosed building of the mid-Victorian period (see Figures 59 and 60). It was 210 feet long with a central aisle of 45 feet covered by an arched roof. Cast iron columns having decorative capitals and bases were made in two lengths, with an average diameter of 8 inches, and were 49 feet high to the springing of the roof. The crown of the arch was 71 feet from the ground. Roof ribs were 14 inches deep, and were each composed of a web plate 1/2 inch thick, pierced in an ornamental pattern, and four L irons, 2 1/2 inches by 2 1/2 inches. A large cast iron gutter girder ran round the building on the outside at the foot of the arched ribs to which it formed a curb. At the top of the arched ribs was a lantern for ventilation. The purlins were of T iron 6 inches by 4 inches and upon them rested glazing bars of cast iron arranged for panes of glass 14 inches wide. A space between the columns below the springing of the arched ribs was filled in with a framework of cast iron and wood, and fitted with circular opening casements. On the north side of the building was an entrance corridor with a trussed roof of T rafters and cast iron struts, covered by glass in cast iron sash bars carried on light T purlins. On the south side of the central span was a small lean-to roof with principals of T rafters and light T purlins glazed in the same way as the north side roof. A verandah, 11 feet 6 inches wide and covered with corrugated galvanized iron, extended around three sides of the conservatory. Its roof had principals of curved T bars placed back to back with wrought iron rings in between, giving the verandah a decorative appearance. The sides of the conservatory between the columns were filled in with wooden frames with arched panels, the whole being glazed with clear glass.[186]

Ironwork for the conservatory was manufactured by the Britannia Works at Derby owned by Bray and Waddington, but it seems that this firm was in association with Messrs. Handyside and Co. who advertised the

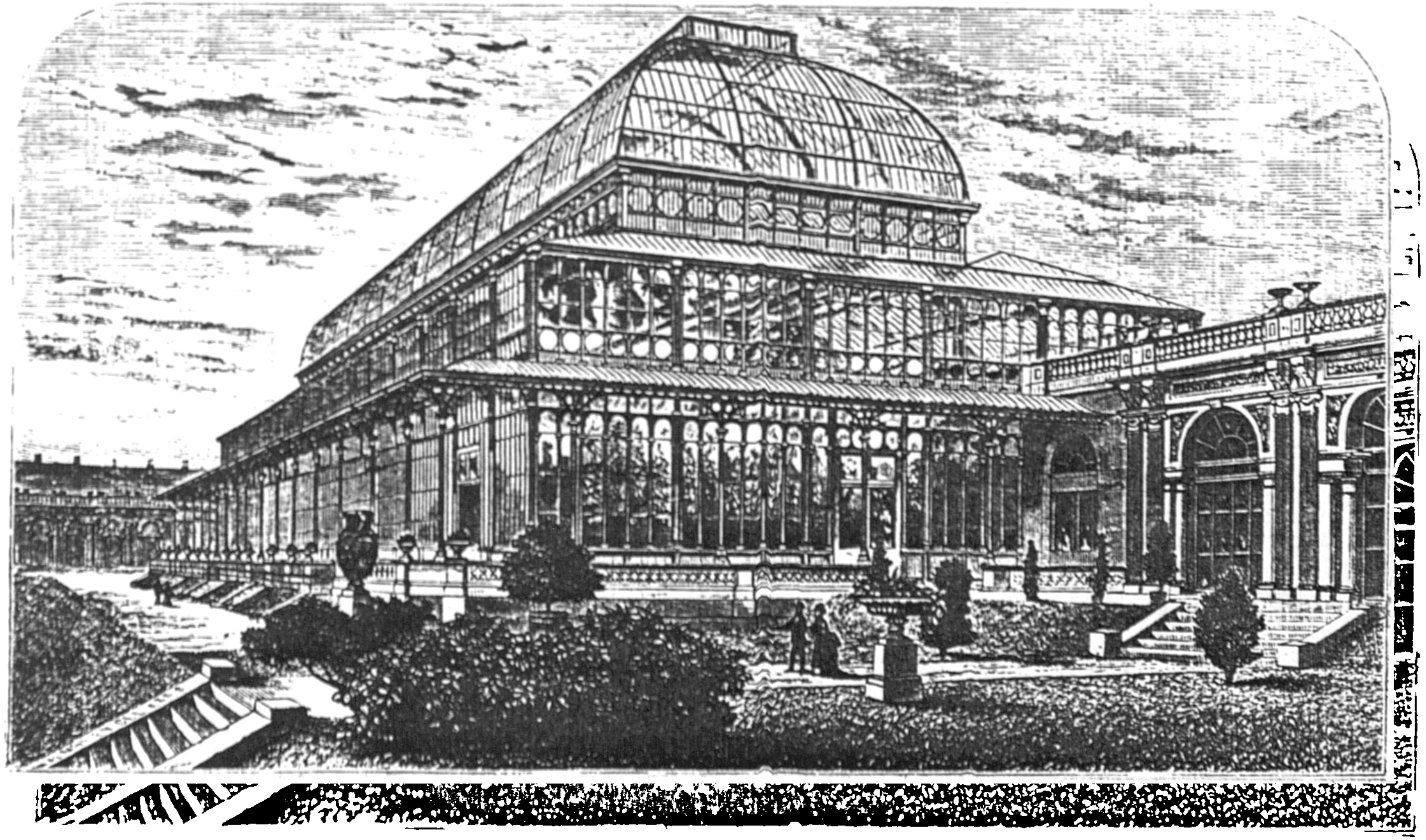


Figure 59   Royal Horticultural Society Conservatory, South Kensington, 1861

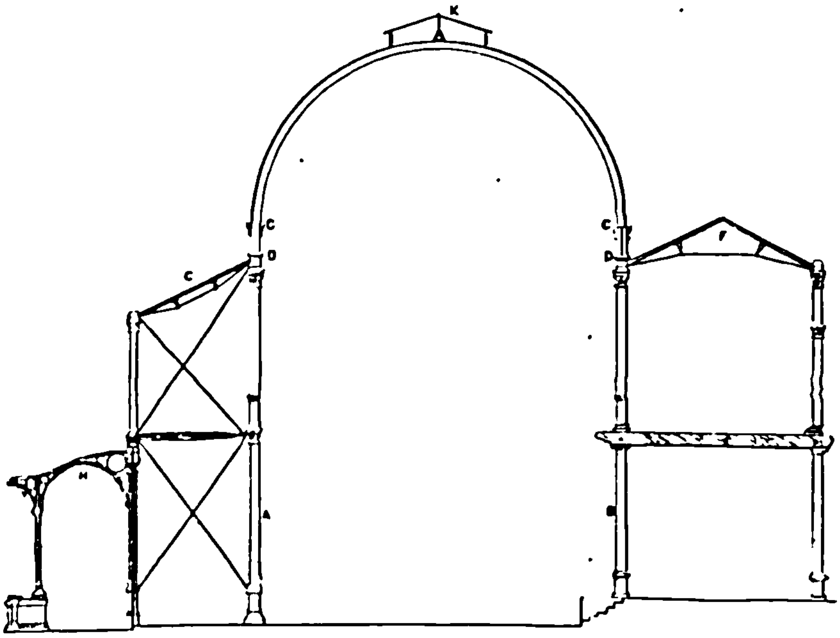


Figure 60   Royal Horticultural Society Conservatory,
South Kensington: Section

conservatory as theirs in an 1868 booklet.[187] The iron and glass structure was erected by contractor John Kelk, and work was supervised by Fowke's engineer assistant J.W. Grover.[188] In July of 1859 Fowke had inspected E.M. Barry's Floral Hall (1858) in Covent Garden and was no doubt influenced to some degree by this iron and glass dome constructed by C.T. Lucas with iron work by Henry Grissell.[189] Fowke probably relied to some extent on Grover for the details of his design. Even so, this does not diminish his responsibility for a work of virtuosity in a building type that was fast becoming ubiquitous by 1860 with large scale factory production. Henry Cole thought it was one of Fowke's most successful works.[190] The conservatory was said at the time to be "the lightest piece of ironwork extant."[191] Indeed, Ewing Matheson, an expert on structural iron who had worked for Andrew Handyside and Company, remarked in 1873 that the chief characteristic of the conservatory was the extreme lightness of its parts and praised the design for its elegance and symmetry. His only criticism was that he thought the lightness of the castings was carried to a point which was perhaps excessive.[192] Accordingly, in the eyes of his contemporaries, Fowke's conservatory was a testimony to his flair for architectural design and his careful attention to economy in construction.[193]

Nevertheless, iron and glass conservatories for horticultural activities had become entirely acceptable to Victorian architectural taste. It was quite another matter, however, when exposed iron was employed for works of public architecture traditionally built of masonry. In this respect, Fowke's projects for the North and South Courts (1861-62) of the South Kensington Museum are most revealing. These two separate structures demonstrated contrasting approaches to the iron problem.

In the North Court, galleries for British pictures and an extension of the art museum had been carried around three sides of an open court and it was decided to roof this space which would make the ground floor rooms of surrounding buildings dependent on it for light. Consequently, it had to be an open glass covered roof. Fowke first had the idea of erecting a small glass dome in the centre, standing on columns and connected with side walls by glass roofs at the lower level. He abandoned this concept after visiting with Cole and Redgrave the University Museum (1855-1860), Oxford, where the decorative iron interior in High Victorian Gothic created obstructions with its numerous supporting columns. As Fowke explained, he adopted instead a concept that would have the advantage of greater simplicity of construction and of making a larger space available for the exhibition of large objects and of leaving the space unencumbered by columns or other obstructions.[194]

Fowke set himself a design brief for an iron and glass roof that would allow for the greatest amount of light *under perfect control, give access to all* parts of the roof and provide for good ventilation to control interior temperature and evacuate vitiated air and gas light fumes. His solution for roofing the 110 by 110 foot court was to span it with a series of intersecting girders anchored into new brick walls built on those of surrounding buildings. This divided the space into a centre square of 50, four corner squares of 30 feet, and finally four rectangles of 50 by 30 feet. The five squares were roofed by square pyramids at the level of the top flange of the intersecting girders. The remaining four rectangles were roofed at the bottom level of the girder forming a clerestorey for ventilation. Fowke's design was very functional without applied decoration to the ironwork. It provided well lighted, unobstructed space. Also, careful attention was paid to making the roof leakproof. Gutters were positioned well, elastic putty was used in glazing to obviate the effect of the expansion of iron sash bars, and condensation was prevented from falling into the court by casing the glazed frames with an absorbent material which retained the moisture allowing it to slowly evaporate. Light was regulated by blinds operated by a manually controlled hoist located on the roof top.[195] Notwithstanding its suitability to the working requirements of the museum, The Builder pronounced on the completion of the North Court in 1862 that the interior effect of the roof was "ugly beyond permission."[196]

A completely different approach was taken in the South Courts. This space was divided by a gallery into two equal courts of 85 by 50 feet. These were spanned transversely by semicircular wrought iron ribs on cast iron columns supporting an A frame glazed wrought iron roof which consisted of a pair of principal rafters and a pair of upright wall posts and a small ventilating lantern on top. (See Figure 61) There was much less glass in this roof than in the North Court. It was blinded by a common spring roller blind in each bay of the roof. Decorative cast iron columns were used and the spandrels of the semicircular wrought iron ribs were filled with decorated cast and wrought iron work, all designed by Sykes in the Italianate mode and manufactured by the firms of Thomas Potter and Son, and George Smith and Company. The wrought iron ribs, rafters and wall posts were undecorated. Ironwork in the South Court as well as the North Court was supervised by Fowke's engineer assistant J.W. Grover.[197] The technical press was much kinder to Fowke in its assessment of this work in iron. Building News said of the roofs:

> "The way in which the cast and wrought iron are employed in them is particularly worthy of study. It shows considerable skill, and what is even more important, a love of honest and common sense construction. This last quality is so rare in Italian designs that there is an unexpected pleasure in meeting it there."[198]

It seems that contemporary architectural taste was more willing to accept the decorated iron approach of the South Court than the strictly functional design in iron and glass of the North Court.

In the opinion of his contemporaries, Fowke's least successful work in iron and glass was the twin domes of the 1862 Exhibition building. Despite this

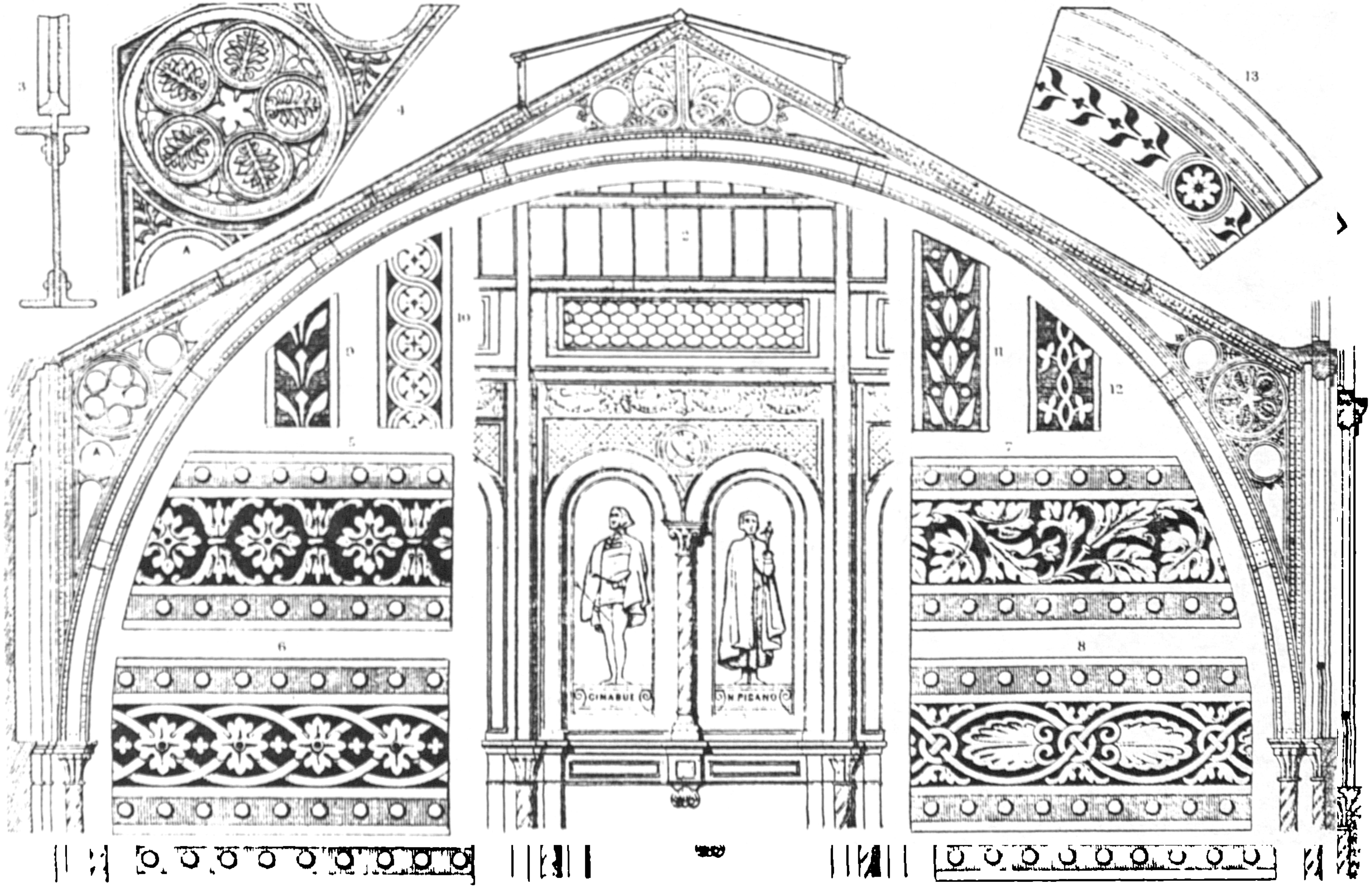


Figure 61 South Court, South Kensington Museum, 1861-62 : Details of Iron Roof

negative appraisal, the story of the domes and other roofing approaches in iron for this much maligned project reveals some interesting features of Fowke's achievements in building technology. It also reflects clearly mid-Victorian attitudes towards iron in architecture.

The domes were a substitute for Fowke's original plan for a huge central hall that had to be abandoned because of cost. His dome design was a dodecagon, 160 feet in diameter and 250 feet high, resting on 16 points, with groined diagonal ribs supporting the ribs of the dome. Each of these ribs was in the form of a semi-ellipse and spanned 79 feet 2 inches. They were made of wrought iron plates and angles rivetted together. The principal rafter and uprights were also of wrought iron and so were the radial supports that connected them to the ribs. At the intersections, ribs were strengthened by plates of wrought iron which for a short distance were in the form of a box girder. The intersections of the principal rafters and semi-ellipse ribs were connected together by a cast iron standard. Hollow cast iron columns supported the ribs and a double wrought iron tie plate acted as the dome's hoop. The dome had 8 wrought iron purlins bolted to the ribs. Wrought iron sash bars were rivetted to the purlins every 15 inches, every fifth one being made heavy enough to assist in cross bracing and to prevent the purlins from twisting. The crown of the dome for about 32 feet down had an ornamental zinc covering and the remainder was glazed.[198] (See Figure 62)

Fowke claimed that his domes were "the largest of ancient and modern times."[199] In this achievement he had probably benefitted from the assistance of J.W. Grover who was the chief draughtsman on the domes project. Fowke was also helped to some extent by John Fowler, the distinguished civil engineer, who was consulted on the project, and by the fabricators of the wrought iron, Thames Iron Works Company.[200]

In spite of Fowke's technical achievement, the domes were seen as folly by architectural critics. The Builder's remarks focussed the issue on the conflict

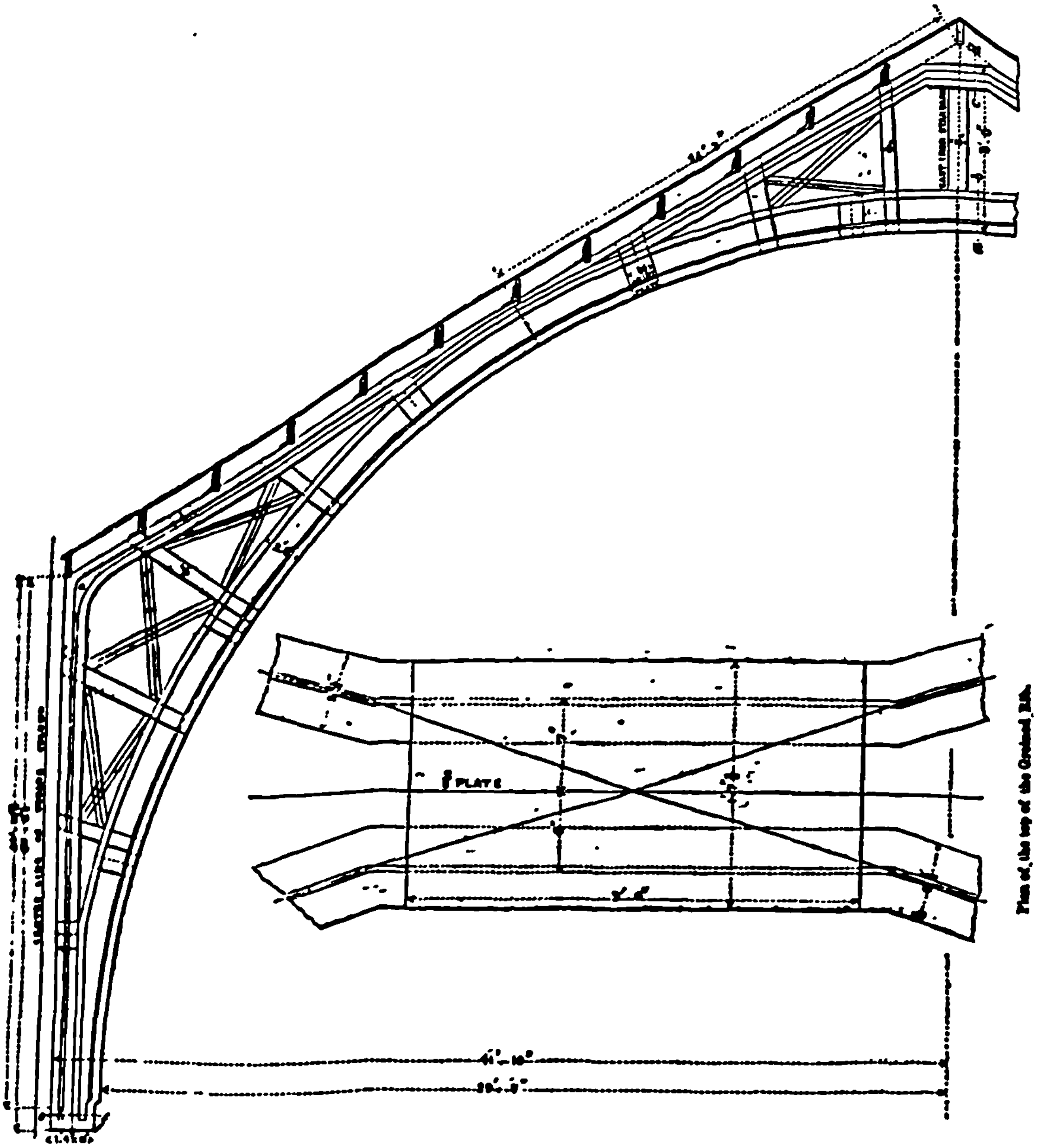


Figure 62 International Exhibition Building, 1862 : Elevation of the Diagonal Ribs, Supporting the Ribs of Dome

between structural virtuosity and artistic excellence:

> "As to the external design enough has been said. We cannot however leave the question of it, without registering protest against the idea that what is big, and a great feat of engineering, is necessarily a beautiful thing... It is not the possession of the biggest dome, so to speak of it, that makes merit of a design, or goes to realize the effect of beauty, which was the object; size may be an element of grandeur; but mere dimensions are relative to others which can be contrasted with them."[201]

The Builder thought that the twin domes had the effect of reducing the grandeur of each and that they could not be seen distinctly above the mass of the building with the result that "a more lame result than that produced by either of the Exhibition domes externally ... was certainly never realized in attempted architecture."[202] The Art Journal was even more scathing:

> "No condemnation can be strong enough for want of judgement which tolerated the erection of those absurdities, and sanctioned the slovenly manner in which they are being completed. Sash bars have been carried up in parallel lines, cutting principal ribs at sharp angles. The glazing is of the most paltry description, the glass in narrow strips, as being the cheapest applicable form, and the consequence is that it is subject to leakage which will cause very serious inconvenience."[203]

It is interesting that in none of this vitriolic criticism were examples given of 'good' design in iron and glass domes by way of comparison.

Fowke employed another iron roof type at the 1862 Exhibition which deserves brief mention. The Exhibition had open or glass covered courts roofed, as in the Crystal Palace of 1851, on the ridge and valley system, except that unlike its predecessor they contained no wood. Spans were 50 feet and were carried on hollow, square cast iron columns at the top of which, 50 feet above ground, wrought iron trellis girders were fixed which supported the trussed rafters of iron. The Civil Engineer and Architect's Journal said the court roofs were "very good and the diminished number of points of support is very much in favour of this part of the new building..."[204] Galleries which enclosed the six courts played an important part in the stability of the adjacent nave and transept roofs. The galleries acted as abutments to counteract the roof thrust tending to throw the columns out of perpendicular. An ingenious diagonal bracing system was devised by Rowland Mason Ordish for securing the columns in the vertical plane and the roof flats in the horizontal plane. The bracing was all adjusted by connecting screw links similar to the method for joining railway carriages.[205] Ordish was to play a major role in roofing the Albert Hall, an achievement that surpassed all of Fowke's works of structural iron in technological virtuosity.

Scott's wrought iron dome for the Albert Hall (1867-1871) was a triumph of collaboration with the private sector and was based on state of the art technology and design for wide span structures. The elliptical roof spanned 219 feet 4 inches. Its principals were wrought iron trussed ribs which sprang from cast iron shoes resting on a continuous wrought iron curb built on top of the brick wall. These distinctive ribs met at the roof top in a wrought iron ring curb. The curb on the brickwork was like a plate girder laid on its side and the cast iron shoes were fitted with adjustable wedges at the back to give the right proportion of strain to the 30 curved principals which acted as both a truss and an arch. Bracing was by way of diagonal rods fitted with screws. Purlins consisted of braced angle iron flanges with channel iron struts. Glazing was on rolled iron sash bars but the lower part of the roof was boarded and slated to 12 feet above the springing. The massive principals were influenced, according to Scott, by those in Hawkshaw's Cannon Street Station (1866) but, as Hawkshaw himself explained, the prototype was really Fox, Henderson's New Street Station (1854), Birmingham. These trussed principals had the same bowed wrought iron strut with cast iron spacers as the New Street Station, a structural element that had its origin in the mid-1840's in a Fox, Henderson slip roof at Woolwich naval dockyard. (See Chapter 4) The Albert Hall roof, therefore, can be said to mark the end of a chain of development in wide span structures in wrought iron which started with the slip roofs in the naval dockyards and matured in the railway trainshed roof.[206] (See Figures 63 and 64)

Scott acknowledged the initial help of John Fowler (1817-1898) and John Hawkshaw (1811-1891) who were arguably the ablest railway engineers of the second Victorian generation and both well experienced in wide span bridges and trainshed roofs. Both were members of the advisory committee on the Albert Hall construction. Scott also credited Messrs. Grover and Ordish for the preparation of all drawings and calculations. Grover had been in private practice since 1862 after working under Fowke in the Science and Art Department.[207]

It was Ordish who was most responsible for the calculations and arguably for the design of the roof. R.M. Ordish (1827-1886), after a few months in an architect's office in 1847, trained under a London engineer and draughtsman, R.E. Brounger, and in Brounger's employ designed his first important work, the Victoria Bridge over the Thames. Ordish was lent by Brounger to Fox, Henderson to work on the 1851 Great Exhibition building for which Ordish and Fox did the detailed drawing of the ironwork. Ordish also did working drawings for Fox, Henderson's New Street Station, Birmingham upon which the Albert Hall roof principals were modelled. He became a friend and colleague of Fox and collaborated with him in numerous works. For a short time he was a draughtsman at the Admiralty Works Department in London during Greene's term of office as Director, but it is not known what he did there specifically. Ordish later set up practice on his own concentrating on iron structures and foundations. He collaborated with Owen Jones in designing a cast iron prefabricated kiosk for India

ROOF OF THE ROYAL ALBERT HALL, SOUTH KENSINGTON.

COLONEL SCOTT, R.E., ARCHITECT

(For Description, see Page 117)

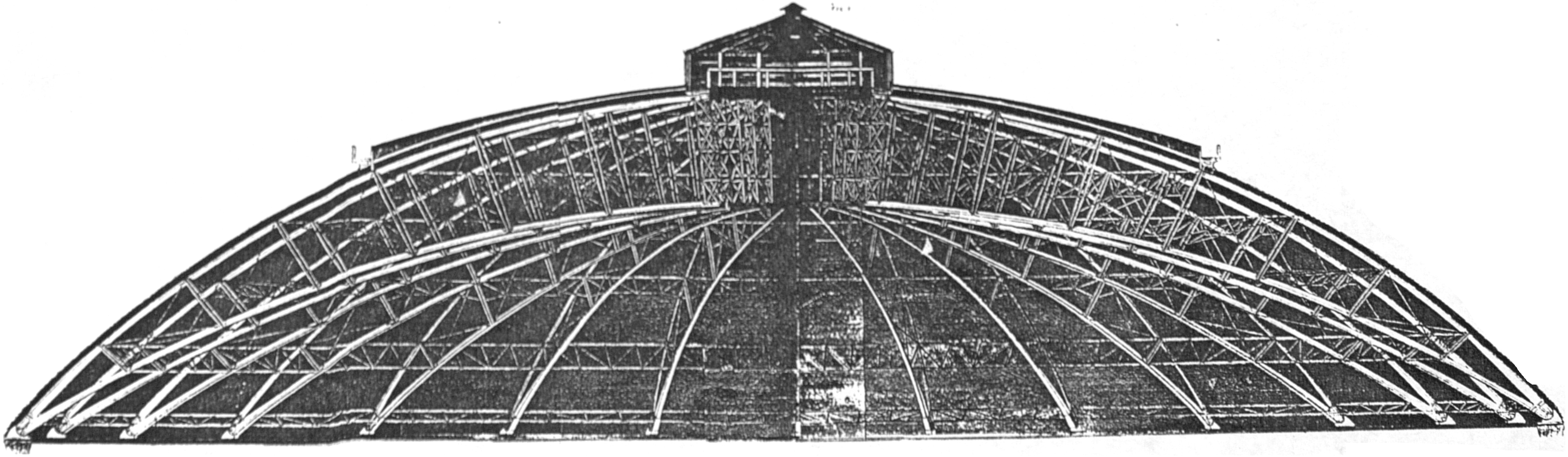


Figure 63 Roof of the Albert Hall, South Kensington, 1867-71

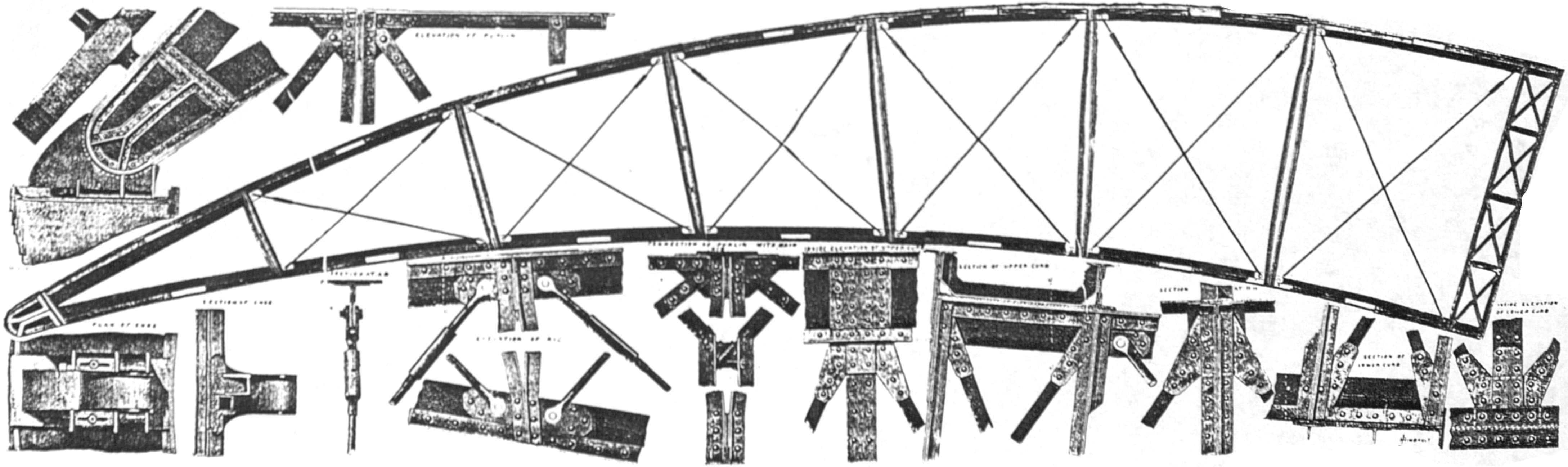


Figure 64 Roof Details of Albert Hall

manufactured by Andrew Handyside where he developed a technique of giving stability to columns against the outward thrust of an arched roof where no abutments were available by attaching them to foundation plates running inwards from the columns. Ordish also worked with G. G. Scott on the rectangular iron and glass Winter Garden roof of Leeds Infirmary (1868), and probably also had been consulted on Scott's iron dome for Brill's Baths, Brighton (1866) since he was known for his close association with Scott from the 1860's. He designed with W.H. Barlow the roof of St. Pancras Station (1868), the climax of the railway roof in Britain. Ordish's work on the Albert Hall roof was in co-operation with his chief assistant Max am Ende.[208] The Engineer said of Ordish on his death: "In no spirit of exaggeration we venture to say that during the last twenty years R.M. Ordish has been the ablest and most original engineer in this country for all matters of structure."[209]

The ironwork was prepared and the roof assembled by way of a trial by Fairbairn Engineering Company of Ardwick, Manchester. Scott credited William Fairbairn with "much valuable assistance in modifying certain details of our original plans..."[210] Fairbairn was one of Victorian Britain's foremost experts on structural iron manufacture, and it is not surprising that his firm was selected for the Albert Hall roof fabrication.

The Albert Hall dome was a triumph in span, being within 21 feet of the record width St. Pancras Station roof. It represented engineering virtuosity in light wrought iron construction with exact proportioning of the metal, well calculated for resistance to strains, and little affected by temperature variation.[211] For all that, it was not conceived purely as an engineering structure. Scott related that his first idea was that the roof should have a form which was the best from the engineering point of view, that is "that the ribs should be alike and that they should spring from the wall-plate in a perpendicular instead of skew direction..."[212] But as he explained:

> "The plan adopted is, however, on whole, a benefit to the architectural appearance of the interior, for that which was best from the engineering point of view would have given an ugly shuttle-shaped figure in the centre of the ceiling instead of the present ellipse."[213]

Even so, The Builder was concerned over the architectural effect of the interior:

> "Ironwork has no architectural beauty. Its merits are intellectual, not aesthetic; structural not decorative. If then, we make the details of our glass wait upon our ironwork, we shall have something poor and inartistic - a station roof or a factory skylight - not a great crystal velarium."[214]

Evidently, the plan adopted in the Albert Hall of concentric zones of hanging glass was influenced by the suggestion of The Builder, and an earlier plan of lighting by elliptical openings in the roof was abandoned.[215] The architectural treatment of the ceiling was greatly influenced by the adoption of a hanging cloth velarium, the main function of which was to improve acoustics. Scott credited J.W. Wild with "urging upon me that it was the only appropriate way of covering the building..."[216] (See Figure 65)

Considering all the assistance Scott enjoyed, it might be suggested that he had little responsibility for the Albert Hall dome. Cole said that Scott was "as modest about it as a Maiden, giving everyone credit but himself."[217] Indeed, some had even suggested that the achievement in the design of this landmark building, apart from the roof, owed much to the concept developed by Fowke shortly before his death in 1865 from suggestions by Cole. Yet the argument for Scott's primacy in the final design solution is fairly compelling.[218] Nevertheless, it is probably fair to say that Scott, realizing his virtually negligible experience in structural engineering for wide span roofs, had the skill to call in the top men in the field and to co-ordinate their individual contributions into a coherent, successful design - the true mark of the architect in the modern sense.

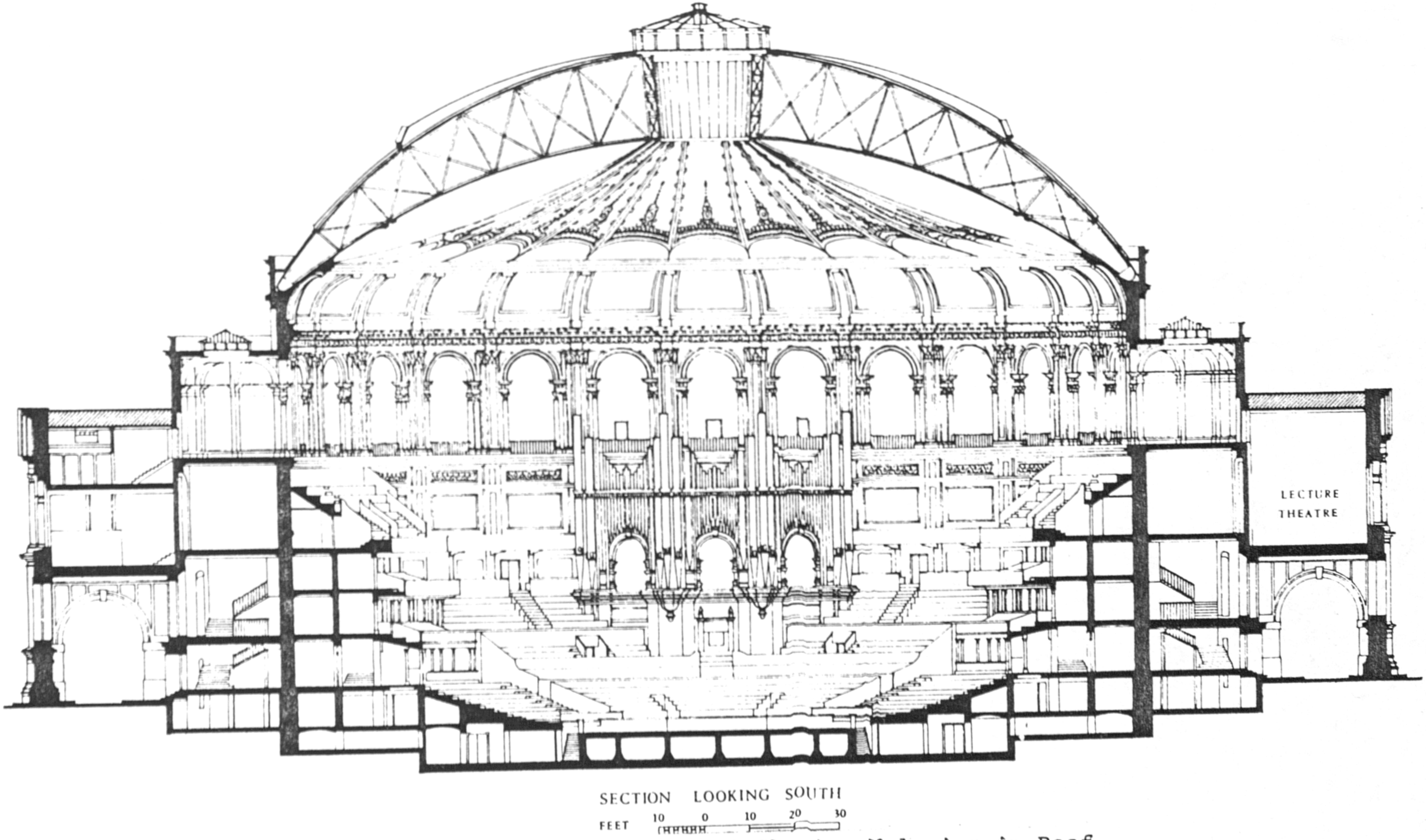


Figure 65   Section of Albert Hall Showing Velarium in Roof

Lighting of Picture Galleries

In the construction of Sheepshanks Gallery (1856-1857), Fowke pioneered techniques for natural and gas lighting of picture galleries that were subsequently adopted in many of his other works at South Kensington in galleries and public rooms. This contribution is a testimony to Fowke's constructive and mechanical genius and to a tradition in the Corps of concern for functional architecture. (See Figure 66)

A major problem in lighting picture galleries was to prevent the viewer from seeing 'glitter' on the pictures caused by the reflection of light from the varnished surfaces. Top natural lighting was usual in picture galleries because it greatly increased wall space for hanging. Some galleries used flat skylights but with these the problem was to get the roof at the right height and the skylight the right size. Another method was a lantern ceiling. In cases where only the perpendicular sides of the lantern were glazed light was often deficient, and where part or the whole of the top was glazed also the proportion of light was uncertain and it created an awkward architectural treatment.[219]

In the development of the Sheepshanks Gallery, the conditions for the display and care of pictures were specified by Richard Redgrave R.A., and Fowke prepared the design and supervised construction. The contractor was John Kelk.[220] Richard Redgrave, the father of Gilbert Redgrave, was an officer of the Science and Art Department and Surveyor of the King's Pictures (1857-1880).

The gallery building measured 87 feet by 50 feet and 34 feet high from the ground to the eaves or 50 feet to the roof ridge.[221] Fowke chose a low pitched skylight approach for the natural illumination of the galleries which he located on the top floor of the two storey structure. He studied in meticulous detail and graphically analysed various incident angles of light on the proposed level of pictures and the sightlines of viewers looking at the pictures so hung.[222]

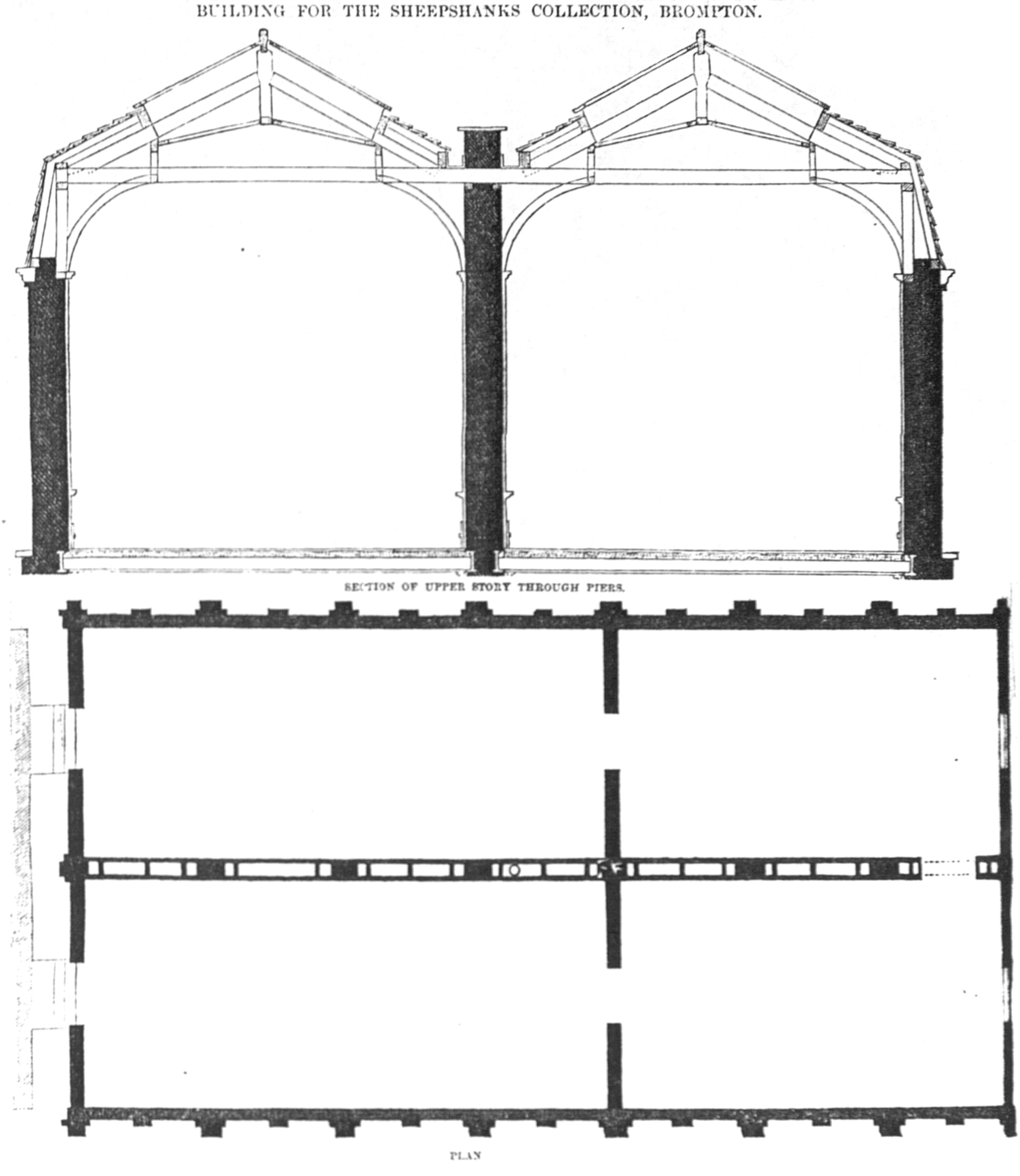


Figure 66 Sheepshanks Gallery, South Kensington, 1856-57

Informed by this careful study of the science of optics, Fowke designed a structure with features and proportions adopted to afford as much light to the gallery as possible while at the same time avoiding 'glitter'. The skylight opening was exactly half the floor area of the gallery and precisely equal to the entire surface of either interior wall for hanging pictures, and the height of the skylight from the floor was carefully calculated to prevent light reflection on pictures.[223] The coving of the ceiling from the sides to the centre, which butted up against the cross wall at either end, admitted far greater volume of light, especially for pictures in the corners of the room.[224] Deep transverse roof trusses helped diffuse brightness and the mansard type roof allowed low pitched double glazed skylights to be inserted. Blinds were fitted to control light and heat from the sun. Richard Redgrave described the advantages of the Sheepshanks skylight design:

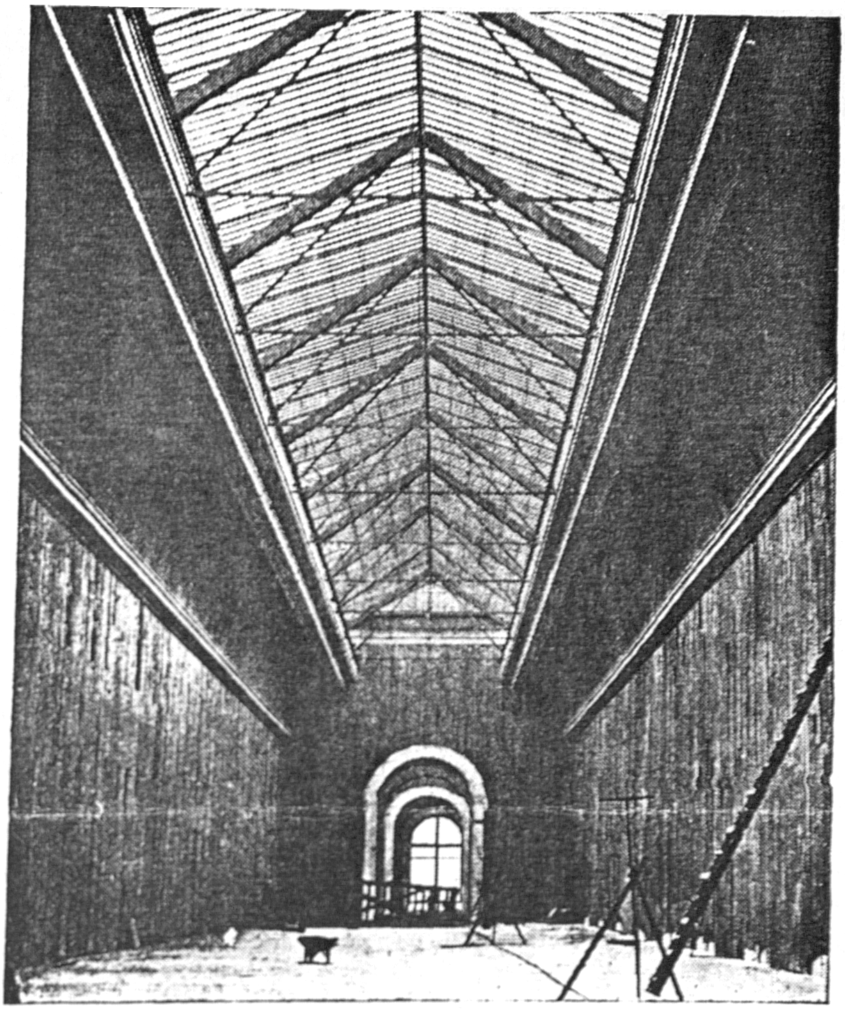
> "The Sheepshanks Gallery is provided with an outer skylight on the roof, and an inner light of glass below it. This obviates all danger from leakages, affords ample opportunity for abundant ventilation, and screens the pictures from the direct rays of the sun, so that it is only in the extreme brightness and heat of summer that the blinds need to be used."[225]

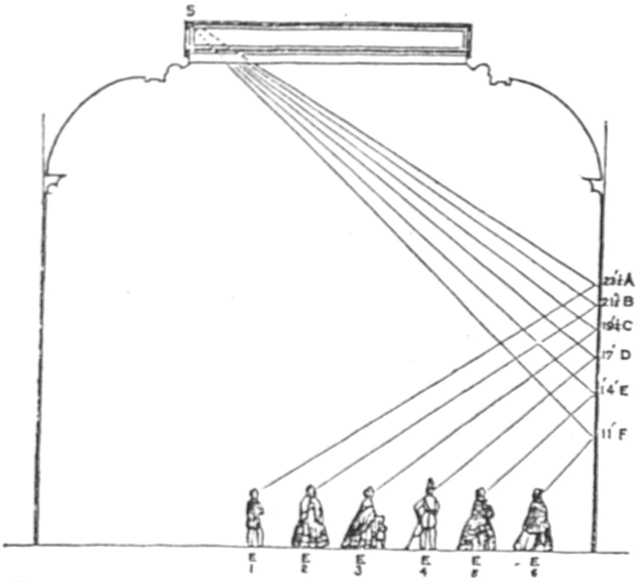
The Science and Art Department considered the Sheepshanks Gallery as a model for the construction of small picture galleries, and evidently the Department received requests for the plans and details of the building. Department officials were particularly impressed with the rapid erection and remarkably moderate expense of Fowkes's structure. It was built in seven months and cost £4,948.[226]

Fowke's design for the natural lighting of picture galleries was also adopted for the 1862 Exhibition building. Picture galleries were located in the main building of the Exhibition. The principal gallery, which extended the entire length of the South Front, was 1150 feet long, 50 feet wide and 50 feet high above the ground floor. Auxiliary galleries were located on the top floor of the East and West Fronts of the main brick building, and comprised four distinct rooms, 247 feet long, 25 feet wide and 17 feet high. The galleries had the characteristic coved ceiling, and the skylight was of the appropriate size and height (see Figure 67).[227] Fowke's natural lighting system for picture galleries was also used by the French for the International Exhibition of 1867 in Paris and by Scott for the picture galleries of the building which housed the International Exhibitions in London from 1871 to 1874.[228]

Fowke also designed a gas lighting system for Sheepshanks Gallery which allowed the gallery to be open at night. This was an innovation for museums and public galleries in Britain. It was nearly a quarter century later before this was adopted as a general practice.[229] Fowke's gas lighting system was also used in other galleries and public rooms at South Kensington.

In the Sheepshanks Gallery, Fowke developed an ingenious system of gas lighting that dealt with the problems of avoiding 'glitter' on pictures, evacuating gas combustion fumes and of quick lighting. A horizontal pipe was carried the entire length of the gallery at a height of 18 feet from the floor, directly under the centre of the skylight. From the pipe a number of fish tail burners projected on small brass elbows at each side of the pipe at about 2 inches from it.[230] Fowke arranged his gas lights to coincide with the intersection of the two rays from the extremities of the skylight which struck the opposite walls respectively at the highest glitter point, to avoid reflections on the pictures. Gas lights in the top floor picture gallery were ventilated by perforated panels located in the ceiling, the foul air being drawn out from the roof space by the extracting shaft of the heating apparatus or by a gas burner in the summer. The ventilation and heating system of the Sheepshanks Gallery is interesting in itself and will be discussed more fully below. To facilitate the operation of the lighting, Fowke designed a device whereby a small





Transverse Section of Picture Gallery, showing the way of admitting the light to avoid glitter.

Figure 67 Picture Gallery, International Exhibition Building, 1862 lamp, borne by a carriage travelling on a rod running underneath and parallel to the line of burners was so arranged that the lamp could be lighted, hoisted into place, attached to the carriage and pulled along its rod by an attendant standing on the floor. Fowke claimed that the burners could be lighted at the rate of 50 in a second.[231]

Fowke's gas lighting system for Sheepshanks Gallery was employed as well in the North and South Courts of the South Kensington Museum. The system was also adapted for night lighting the Royal Horticultural Society conservatory. Cole claimed that it allowed the conservatory to be "brilliantly lighted with perfect ventilation, and without damage to the plants."[232]

Gas lighting for picture galleries presented a particularly difficult challenge for ventilation arrangements since gas combustion products could damage the pigments and fixatives in oil paintings. In 1859 a special commission investigated the effects of Fowke's gas lighting system and ventilation arrangements in Sheepshanks Gallery. Its conclusions were positive:

> "The Commission have examined the Sheepshanks Gallery as an experimental attempt to light pictures with gas, and are of the opinion that the process there carried out fulfills the conditions of effectively illuminating the pictures, and at the same time removing the products of combustion."[233]

The Commissioners added that gas lighting aided ventilation and did not increase heat in the locations where pictures were hung by more than 1° F.[234] Ten years later another commission, on which Scott served, was appointed to investigate the heating, lighting and ventilation of the South Kensington Museum and it confirmed the earlier commission's findings: "... pictures are not exposed to the products of combustion, and cannot suffer any appreciable injury from the effects of the lighting of these rooms."[235] Accordingly, in the opinion of the experts of the time, Fowke's gas lighting system was a great success.

Fowke was openly proud of his innovation in the lighting and ventilation of picture galleries. He explained with reference to the galleries for the 1862 Exhibition building:

> "Given therefore these conditions of lighting and ventilation and economy of space, as principles which must not be impaired by any considerations of architectural design, it would be interesting to see produced a better structural design for realising them than the present."[236]

All the same, as Fowke had conceded, the inflexibility of these principles precluded windows in the upper walls of picture gallery buildings, thus limiting their architectural treatment. Captain William C. Phillpotts who had assisted Fowke on the 1862 Exhibition building project also pointed out this limiting feature of Fowke's design but strongly supported it in the interest of the preservation and appreciation of pictures.

> "This system of lighting increases the difficulty of successfully treating the exterior of the building, for it prevents windows being placed in the upper part of the side walls, but after the successful application of these principles of lighting to picture galleries which have been constructed within the last few years at South Kensington, it was wisely determined to forego all other considerations, and apply the same principles to rooms destined to receive the choicest works of art of the present age."[237]

Fowke's lighting solutions for galleries and public rooms clearly reflected his emphasis on functional design and effective services, a characteristic shared by many of his brother officers in the Corps, especially those who made contributions to building technology in the nineteenth century and who are the subject of this study. Richard Redgrave, the distinguished artist who collaborated with Fowke in the design of the Sheepshanks Gallery, appreciated Fowke's approach. Redgrave said in a lecture about the Sheepshanks Gallery at the South Kensington Museum in November 1857 that the "architect is too often more intent on displaying himself, and what he improperly considers his art, than the works for which the structure is intended."[238] He went on to say that the design details of a picture gallery ought to be determined in consultation with or preferably by a painter before the architect proceeded with his task. Redgrave thought that in this way "a nobler, because more characteristic structure should arise, than by the usual method of neglecting utilities and considering the elevation and decoration before the purpose."[239] Redgrave's collaboration with Fowke had been a testimony to the success of this design approach and a mark of Fowke's ability to work with other professions to ensure that a building's fitness for purpose was the first priority.

Heating and Ventilation for Public Buildings

The relationship between architects and heating and ventilation experts, be they engineers, doctors or others, was rather strained throughout the greater part of the nineteenth century. According to one experienced Victorian heating engineer, problems were mainly attitudinal not technical. Heating and ventilation were almost always an afterthought. It therefore became difficult for the building services expert to develop the best arrangements for warming and the ingress and egress of air, since modifications could not be made to completed plans without interfering with accommodation and the architectural design. Even if he were involved from the outset of the design process, the heating and ventilation expert often had to struggle with the architect to subordinate beauty to utility. Moreover, it was difficult if not impossible to satisfy everyone. If a building had no pretensions to ventilation, its occupants seldom complained because they knew it was futile; but in buildings which designers claimed were 'scientifically' ventilated, virtually everyone complained because the conditions were not exactly what each person desired.[240]

Fowke and Scott combined the role of architect and engineer in their work at South Kensington and consequently they were not as much confronted with this conflict of attitudes. They regarded heating and ventilation as a major aspect of design to be included at the outset of the design process, and their buildings reflected this approach. While their solutions for this component of building services involved no major technological advances, their choices of ventilation and heating arrangements and their collaboration with other professionals are revealing and merit brief examination by way of a postscript to the more substantive issues of this chapter.

Fowke's first major building at South Kensington, the Sheepshanks Gallery, was designed with ventilation as a major priority both for the preservation of the pictures and the health and comfort of the occupants. A complex ventilation system was employed. Outlets for vitiated air were located in the upper part of each room. Those in the top floor picture gallery were in 224 upright perforated panels between the tops of the ceiling coves and the eaves of the interior ground glass skylight. Through the ornamental perforations in these panels vitiated air passed into the space between the ceiling and the roof from which it was carried off by an extracting shaft heated by the iron flue of the heating apparatus or by a gas burner in the summer. Louvre board ventilators also provided an opening into the roof space as an additional escape for air in hot weather or when the building was crowded. In the evening when the gas was lighted and when most visitors were customarily in the gallery, a part of the skylight was made to slide back for additional foul air escape. The upper floor picture gallery was divided by a longitudinal wall of hollow construction in which were located ventilating shafts with access to these from the lower rooms by way of a perforated ornamental frieze of terracotta. The heating system was a modification of the arrangement patented by Mr. Gurney whereby the air was dampened as well as heated. Gurney's apparatus was a form of ventilating stove which drew fresh air via a shaft from the outside. The stoves had an air chamber with a large heating surface of metal standing in a pan of water. Fresh air passed through the chamber and was heated and humidified at the same time and was then distributed to rooms via shafts. The stove combustion flue provided updraft for ventilating.[241]

Fowke was satisfied that the ventilation system at Sheepshanks Gallery was "perfectly successful" but he thought in retrospect: "... in an atmosphere like London where a great deal of impurity is present, I think a better way of ventilating a picture gallery would be to supply it with air by mechanical means in such quantity that it would always be as it were in a state of repletion or compression, and the advantage of such a method would be that at any opening the air would have a tendancy to escape from the building."[242] Fowke thought that mechanical ventilation could be achieved by a small noiseless fan, driven by even so low a power as a four or six horse engine, and that it would be quite simple and inexpensive. He also favoured humidity control and screening for mechanical and some chemical impurities but he did not specify means of achieving this.[243] Despite this expression of interest in mechanical ventilation, Fowke used only 'natural' or 'heat-aided' ventilation in his South Kensington Museum buildings.

In the North and South Courts, Fowke developed the prototype of what was to become the predominant heating and ventilation system in the South Kensington Museum - hot water pipes for warm air heating and heat-aided ventilation. A sunk passage or tunnel was constructed across the centre of each court communicating through the walls of the surrounding buildings with the outside air where the intake was covered with an open iron grating fitted with an air cleansing device. Large pipes carrying hot water at a moderate temperature were placed in the tunnel. The boiler and furnaces were located outside the building. This apparatus was in effect a heat-aided ventilating device. It forced warm air into the room at the floor level which exited through every opening, but especially via the clerestorey in the square pyramid roofs of the North Court and the ventilating lantern on the top of the A form roof in the South Court.[244]

Fowke next used this heating and ventilation system in the National Art Training Schools, a three storey brick and terracotta structure. In this case, the hot water pipes were laid in trenches which were made in the thickness of the Fox and Barrett fireproof floors by leaving out a portion of the concrete between the wrought iron joists. These trenches in the hollowed out concrete were carried through the external walls and terminated in iron grated boxes from which a constant supply of fresh air was obtained. Foul air exited via a lantern which ran along the length of the roof and via the swing sash in the upper part of windows in the top floor. Since the ground level of the building was cut off from large ventilating courts adjacent, special measures were taken to provide for the extraction of gas light fumes there. Chimneys were supplied to each of the clusters of sunlight burners and the fumes exhausted through a small earthen pipe in the concrete floor above which communicated with flues in the exterior walls and thereby to the outside atmosphere.[245]

Fowke tested the effectiveness of his ventilation and heating system for controlling temperature in the North Court soon after it opened in 1862. He found that the courts ranged from 79° to 84° F in summer and 50° to 66° F in winter.[246] Six years later a commission was appointed to report on the heating, ventilation and lighting of the South Kensington Museum, and its findings are interesting. Some witnesses testifying before the commission argued that open fireplaces were better than hot water pipes for galleries because they gave a more equable temperature and were more effective in promoting air circulation. Some also complained of the dryness of the atmosphere in the South Kensington Museum galleries. These complaints, however, were dismissed by the commissioners on the basis of data from experiments by Captain Festing, Scott's Assistant Director of Buildings.

In their report of 1868 the commissioners unequivocally endorsed Fowke's system. They said that the ventilation was "highly satisfactory and efficient", and the heating "the best that has been devised up to the present time."[247]

Accordingly, on the basis of the expert opinion of his contemporaries, Fowke's ventilation and heating arrangements for the South Kensington Museum worked well. It appears that Fowke may have developed this system mindful of the ventilating beams commonly used in barracks and military hospitals before 1863, which Jebb had improved in the late 1840's. Hot water heating in large pipes was old technology in the 1860's, but Fowke had adapted it in a clever way. It is interesting that, like Jebb and Galton, he preferred a low technology option notwithstanding his endorsement of forced air mechanical ventilation. It was left to his brother officer Scott to adopt mechanical ventilation combined with central heating; but even he used it only once - in the Albert Hall.

As Gilbert Redgrave explained, Scott was confronted with a heating and ventilation challenge in the Albert Hall "almost without precedents."[248] Scott's response to this challenge was the same as his approach to solving the problem of roofing this distinctive building. He called in an expert. As he explained: "In the warming and ventilating arrangements I had the assistance of Mr. W.W. Phipson, who has had great and varied experience in the heating of large buildings."[249]

Wilson Weatherley Phipson (1838-1891) was educated in Brussels and Paris, and in 1857 attended the École des Ponts et Chaussées. On completion of his studies he assisted Dr. Van Hecke in applying a new method of heating and ventilating to hospitals in Paris and Bordeaux and in some government buildings in Holland. In 1859 Phipson moved to London where he attempted to introduce Van Hecke's system but without success. Nevertheless, through his father's influence, he got the contract to warm and ventilate Baron Rothschild's residence in Piccadily and a bank in St. Swithin's Lane. The success of those projects drew him to the attention of many leading architects and he soon won commissions for many large projects, especially banks, offices and public buildings. Besides the Albert Hall, he also won the contract for Waterhouse's Natural History Museum at South Kensington. At the same time as he was working on the Albert Hall, he had the commission for heating and ventilating G.G. Scott's Glasgow University. He employed the same system, with modifications, in both buildings.[250]

In the Albert Hall, Phipson, under Scott's direction, installed a mechanical forced air central heating and ventilating system. Hot water coils of 4 inch diameter cast iron pipe were placed in three separate hot air chambers under the arena, the amphitheatre stalls and the main corridors of the building respectively. A moisturising tank was connected to the coils to ensure requisite humidity in the air. Steam was brought into the Hall from an outside boiler and condensed in metal tubes contained in a chest through which water was conveyed and heated. Hot water then passed to the coils in the separate hot air chambers. External air was forced by two fans 5 feet 9 inches in diameter, each worked by a 5 h.p. steam engine, into the hot air chambers via two down cast shafts and then through a long underground passage where it was filtered by fine wire gauze screens and washed with water sprays. The heated air in the three chambers, moving under the force of the fans, was conveyed from under the arena through the intricacies of the floor, from beneath the amphitheatre through the risers of the steps on which the seats were placed, and from under the main corridor through passages in the wall and thence into the boxes, the picture gallery, the corridors, the refreshment and private rooms and the small lecture theatres.[251]

The Albert Hall had a supplementary ventilation system to the fans. This comprised an elliptical ring shaft in the centre of the ceiling with moveable louvres above roof level. The shaft's drawing power could be increased by a heat-aided system of three rings containing 960 gas burners situated at the lower end of the shaft. Phipson's heating and ventilating arrangement was flexible. By way of valves, connecting flues and distribution channels it was possible to introduce heated air over the whole floor area from two of the chambers while forcing cold air in at every level by means of the main chamber, or vice versa.[252]

Evidently, the chief difficulty with the management of the warming and ventilation system was in the control of the inward draught when the doors were open for the ingress and egress of the audience.[253] The heating expectations were not particularly high compared to today's standards of comfort. Phipson contracted to give a mean temperature of only 55° to 58° F. Even so, the Albert Hall's heating apparatus was apparently cheaper to operate than Phipson's system in Glasgow University.[255] It appears that Scott, in his collaboration with Phipson, had achieved economy if not complete effectiveness in heating and ventilating the Albert Hall.

8. COLONIAL CONNECTIONS AND GLOBAL BUILDING EXPERIENCE

In addition to their many achievements at home, the Royal Engineers played an important role in the global diffusion of building technology through British imperial expansion in the nineteenth century. Technology transfer in building materials, structural forms and methods of construction was a two way process. It involved the interaction of European experience with indigenous environments, traditions and techniques. The Royal Engineers provided both military and building technology expertise for British imperial expansion and were therefore in the front line of European interaction with native conditions and cultures. Still, this important global phenomenon has been little explored by scholars except in general terms or with respect to individual British colonies.[1] Considering the great number of territories in which the Corps served during the century, it has been necessary in the present chapter to limit discussion, for the most part, to four major seats of the British Empire - India, Australia, Canada and the West Indies. It is felt, however, that this provides a representative sample both geographically and in terms of physical and cultural environment types. Moreover, a number of case studies have been selected to illustrate how the Royal Engineers acted as agents in the transfer of advanced building technology to the colonies, and particularly how they modified construction practices based on British conditions and training in response to different colonial conditions. The case studies include: experiments with limes, cements and concrete; testing colonial woods; the use of asphalt in cold climates; influences in bridge design; pioneering work in prefabrication; and designing barracks, hospitals and prisons for tropical lands.

Imperialism and Technology Transfer

Headrick has shown that technological changes were indispensable to the expansion of Europe in the nineteenth century and profoundly affected its timing and location.[2] Technological innovations lowered the cost in both financial and human terms of penetrating, conquering and exploiting new territories.[3] Unfortunately, Headrick's case studies do not include the role of building technology but clearly it had a place in establishing order and maintaining imperial control through the development of military, political and economic infrastructure.[4]

As Buchanan has discussed recently, from the late 1830's British engineers played a vital part in the diffusion of technology through European imperial expansion. He has further explained that the great movement of British engineers overseas in the second half of the century was not the result of a conscious strategy of government or other central authority but rather the result of individual decisions and aspirations. Buchanan contends that their impact varied greatly depending on the receptivity of each country and territory concerned and on its ability to assimilate Western technology. European nations and the United States dispensed fairly quickly with British assistance. Canada, Australia and Japan built steadily on British experience and liberated themselves from reliance on it. At the extreme pole of reliance, India became heavily dependent on British engineers, receiving little encouragement to develop its own resources of talent until the last days of the Raj.[5]

British military engineers were well ahead of their civil engineer countrymen in establishing a significant presence in foreign territories. They had been active in India as a separate branch of the British army in the service of the East India Company from the mid-eighteenth century and had produced major works of building by the early nineteenth. The British were in the Caribbean from the 1650's and military engineers probably served there as part of the armed forces from the early eighteenth century at which time imperial control was secured through the construction of naval dockyards at Bridgetown, Barbados, English Harbour, Antigua and Port Royal, Jamaica. Royal Engineers served in the West Indies from the Corps' inception. With the British conquest of Quebec in 1759, the Engineer Corps of the Ordnance Board arrived in Canada. The Royal Engineers took over in 1787 and by the beginning of the nineteenth century were established in St. John's, Halifax, Quebec, Montreal, Kingston and a few other locations. Their work increased markedly with the building of the Rideau Canal and the Quebec and Halifax citadels in the 1820's. By comparison with these major colonies, the Royal Engineers' arrival in Australia was late. The Corps was sent in 1835 to New South Wales and Van Dieman's Land to build military garrisons, convict establishments and public works, and in 1839 to South Australia for duty in surveying and building roads and bridges. Royal Engineers did not arrive in Western Australia until 1850. Their duties in the colony included convict establishments and public works.[6]

In contrast with British civil engineers, the country's military engineers were a deliberate instrument of imperial authority directed principally by the War Office, the Admiralty, the Colonial Office and the East India Company (until 1862). Engineer officers usually had little or no choice in their posting and regularly played a number of roles - military commanders, colonial governors and officials, builders of miliary works, and staff of colonial public works departments. As engineers and architects, their work was affected by the purpose, timing and duration of their colonial assignments, by official policy respecting the procurement of materials, building standards and other aspects of construction, by central authority directions on plans and specifications for certain building types, and by the policy and procedure for project execution, including source of labour and contractual arrangements. They shared with the private sector the problems of working on the frontiers of European overseas expansion - remoteness from an established scientific community, lack of testing and experimental facilities, absence of manufacturers, and a chronic shortage of skilled labour. In addition to this, some engineer officers were acutely aware of their ignorance of materials and conditions in foreign lands and urged their fellow officers to work continually at improving their knowledge and skills in this regard. Two examples will illustrate this point.

Richard John Nelson (1803-1877), commissioned in 1826, first served in Bermuda (1827-1833). During this time he made a study of estimating building materials and labour concerning works of defence with which he was engaged, chiefly for the protection of entrances to Bermuda at St. George's and of its dockyard at Ireland Island. Nelson would later serve in the Cape of Good Hope, Canada, Nassau, Ireland and England. In 1840 he published his study of Bermuda building conditions in the Royal Engineer Professional Papers and urged his fellow officers to be mindful of the necessity of in-career training to meet their global building responsibilities:

> "... I trust our brother officers will unhesitatingly bring forward useful details of every kind, for the information of their juniors; who, on joining the corps, cannot be too well warned of the variety of fields for execution ever before them; whether in peace or war, or at home or abroad, so as to become indefatigable and systematic observers."[7]

Another example is from Captain John Smyth who spent nearly six years in the West Indies (1828-1833) and became very proficient at designing barracks for tropical climates. In an article published in the Royal Engineer Professional Papers in 1842 concerning constructional timber in Demerara, Smyth counselled his brother officers:

> "The necessity to an Officer of the Engineers of an accurate knowledge of the resources of the country in which he may be serving, need not, I am convinced, to be pointed out here; for it meets us in every change of station; and all officers who have been in our colonies know how much time is lost, and how much difficulty is experienced, in obtaining such information; and I would therefore very strongly urge upon my younger brother officers the importance of preparing, when they have leisure and opportunity, memoranda on the nature, quality, price of materials, with

> tables (on the plan of Tredgold's) and short descriptions of the timber, etc of the places in which they may be stationed."[8]

The Royal Engineers readily communicated their ideas and experiences concerning building technology while posted in foreign lands through the British technical press. This was similar to the practice of other professions. They utilized the technological advances in steamships and railways which permitted faster mails, and later took advantage of transcontinental telegraphic cables, to communicate information home from the far corners of the globe.[9]

Experiments with Limes, Cements and Concrete

Perhaps the most fundamental aspect of the engineer officers' role in the global diffusion of building technology was their experimentation with and application of new materials in the colonies. Experimentation with limes and cements was stimulated in the Corps at many of its foreign stations by the publication of Sir Charles Pasley's Observations Deduced from Experiment Upon Natural Water Cements of England and on the Artificial Cements That may be Used as Substitutes for Them (1830). Nevertheless, Pasley was not the only influence on engineer officers' experiments with limes and cements. In India and Canada especially, there was to be a good deal of local initiative.

One of the earliest British military engineers to experiment with limes and cements in India was John Thomas Smith (1805-1882). Commissioned in the Madras Engineers in 1824, Smith arrived in India the following year and remained there until 1834 when ill health forced his return to England. In 1837 Smith published a translation of Vicat's A Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural which included certain additions based on Smith's own experiments. This proved to be especially influential with engineer officers in India and rivalled Pasley's work amongst British engineers generally. The Civil Engineer and Architect's Journal said in a review of this publication in 1838.

> "... the original text is well known to many of the profession as being a most valuable work, but there has been difficulty in understanding many parts, in consequence of the local and technical terms made use of by the author. The translator appears to have combated with these difficulties, and made himself completely master of them; he has very ably done his duty, not only in the translation, but also for his valuable additions."[10]

Smith returned to India in 1838 where he was principally engaged in the development of mint machinery and the minting process as well as lighthouse construction. After 1856 he became consulting engineer to the Madras Irrigation Company and a director of the Madras Railway Company and later its chairman. In 1845 Smith founded the Professional Papers of the Madras Engineers and edited its first three volumes.[11]

Smith credited his friend Dr. Malcolmson of the Madras medical service and Colonel Sim of the Madras Engineers for assistance in his experiments with Indian limes, mortars and stuccos. From Vicat, Smith developed a preference for hydraulic limes, the French practice, over the English choice of natural cements or the artificial cements advocated by Pasley and others. Smith pointed out the advantages of hydraulic limes over natural cements. Cement stones had to be pulverized by manufacturers whereas hydraulic limes could be used unground by the mason himself or by an ordinary workman without machinery and at about the same cost as common lime. In England, especially in London, it did not matter if the builder was dependent on the manufacturer but elsewhere, despite their slower setting and other defects, hydraulic limes had the advantage of easy production; they simply had to be burnt. On the frontiers of the empire in India, the use of hydraulic limes over cements was therefore largely governed by the simplicity of the preparation process, especially the fact that special skills or machinery were not required.

Smith used Vicat's methods for recognizing and estimating the quality of hydraulic limes while superintending the works of the Northern Division of the Madras Presidency at Masulipatan. There he discovered an excellent hydraulic lime previously unknown and superior to English Aberthaw lime in setting power. He urged experimentation on these Indian 'cancars' as holding great potential since his preliminary investigations showed they combined qualities of the best cements and hydraulic limes. Smith was also interested in artificial pozzolanas and undertook experiments on making these using Vicat's method of heating the preparation on a plate of iron. The material employed was broken pieces of a fireclay water vessel which had lain in a rubbish heap for several months, and later a stiff brown clay and a white pipe clay.[12]

A new material with which Smith and others experimented in India was 'Magnesia cement', more accurately described as a natural hydraulic cement made from magnesian limestone. Pasley experimented with specimens of magnesian limestones from northern England in the 1830's and found they had hydraulic properties.[13] It appears, however, that he was anticipated in discovering the hydraulic properties of magnesia by Dr. Macleod of India who first brought this to the attention of the Madras government in 1825. The material was used in that year in the repair of Fort St. George at Madras.[14] Macleod received a donation of 3000 rupees from the East India Company for his contribution after an investigation in England proved that he had first discovered the material and not Pasley who had claimed the honour.[15] Tests were undertaken in 1826 by the Madras Engineers comparing sand and magnesia cement with lime and iron stone as well as with common chunam plaster. After a heavy monsoon the magnesia cement proved strongest and hardest, and "was thought to be fully equal to Parker's cement."[16] In 1825 the cost of this new material was about equal to Parker's Roman cement but only 1/6th by the 1840's. This was due to the discovery in the 1830's of deposits at Salem and especially

Trichinopoly (1837) which made magnesia more accessible and therefore economic in use.[17]

A number of engineer officers in India experimented with magnesia cement in the 1830's. Arthur Thomas Cotton (1803-1899), commissioned in the Madras Engineers in 1821, first tested the material in 1834 by making cubes of brickwork. He found that "it set very rapidly, and in a few months it became so hard, that it was impossible to separate it from the bricks; however small the cube was broken up, the bricks were always broken, without the cement being separated from them."[18] In 1837 Cotton tried a great variety of experiments using magnesian limestone from various quarries and with different proportions of sand and other materials. He explained in a letter to the Secretary to the Board of Revenue, Department of Public Works, Fort St. George, Madras the results of his experiments: "Almost every one of them has formed an excellent cement, setting generally in one or two hours, sufficiently to be secure from the effects of water passing over it."[19] Cotton had problems getting one batch of his magnesia cement to set if immediately covered with water, but could not find any explanation for this other than the nature of the particular stone used. Notwithstanding this problem he was confident in recommending the use of magnesia cement:

> "... it is undoubtedly a most important addition to the means we have hitherto had for managing the irrigation of the Delta, both by enabling us to form a masonry of much greater strength than could be formed with lime, and also on account of its being quite secure from injury by water, within an hour or two after it is used. As the rivers never continue full for many days together, slight repairs can always be performed during the season of the freshes, which before could not be effected from the want of such a material as this. Its extreme hardness also will enable us in many cases to use it as a plaister (sic), where otherwise granite must have been employed, which is so very expensive a material in the Delta."[20]

In 1837 Cotton used magnesia cement for plastering an irrigation channel dam (annicut) and claimed that it "became in a fortnight harder than any stone, except granite, marble and stones of the first degree of hardness."[21] He had earlier designed two dams across the Coleroon River, a tributary of the Cavery River, which was used as an irrigation channel. The works were built in 1836 under the superintendence of his brother Captain Hugh Cotton. At the time of his later experiments (1837) A.T. Cotton was in charge of the railway from the Red Hills to Madras for the transport of stone, and in this capacity he gained much experience with building materials, including magnesia cement, which was to influence his future work in dams and canals for irrigation. In 1844 Cotton was put in charge of the Godavery District and submitted plans for irrigation including a great dam across the Godavery River at Dowlaish which was constructed 1847-1852.. The works also included an aqueduct of 49 arches of 40 feet span each.[22] This project was considered daring at the time and by the mid-1850's Cotton had a reputation as "practically the great authority and referee on all matters connected with irrigation..."[23] Effective hydraulic limes and cements were critical to irrigation engineering, and the link between Cotton's experiments with magnesia cement and his dams and aqueducts is significant. Engineer officers made a major contribution to British irrigation engineering in India during the nineteenth century.[24]

Following Pasley's experience with experiments on carbonate of magnesia, Smith found in some small tests of his own that a paste of equal parts of hydrate of lime and magnesia calcined together set with great firmness in a few hours, and inferred from this that some of the magnesian limestones may be found to be useful as good hydraulic limes.[25] Smith's friend Dr. Malcolmson undertook to analyse specimens of the magnesian limestone for him. Smith found that after calcination the magnesia was capable of hardening under water but it was preferable to let it dry for 12 hours or more before immersion. His specimens were from magnesian limestone from the Madras Presidency deposits. Notwithstanding some continuing problems of accessibility, storage and preparation, he thought it was a rival for the traditional chunam, a sea shell lime plaster:

> "As a stucco it is considered the most beautiful of all the cements, and that even in Madras, where the chunam, so long celebrated, is made of the greatest perfection. In fact, the only impediments to its exclusive adoption seem to be the cost of transporting it from the situation in which it is found, and the difficulty of preserving its properties after calcination, unimpaired, it being subject to deterioration by absorption of moisture from the atmosphere; together with the cost of pulverising it previous to use."[26]

Magnesia cement did not supersede traditional chunam and seems not to have been adopted widely in architectural work notwithstanding its success in hydraulic engineering projects. No mention was made of it, for example, in T. Roger Smith's 1866 address to the Royal Institute of British Architects on buildings for Europeans in India wherein he discussed materials at some length.[27] Nevertheless, magnesia cement was an important new material in early Victorian India and the Madras Engineers had played a significant role in its development through experimentation and application.

The Royal Engineers in Canada were experimenting with local cementatious materials at the time Pasley published his 1830 pamphlet. As early as 1829, Ruggles Wright, one of the contractors working on the Rideau Canal, sent to Colonel Elias Walker Durnford, Commanding Royal Engineer stationed at Quebec, samples of what he believed to be a hydraulic lime with the request that Durnford test it and suggest the best method for manufacturing hydraulic lime from the rock. Durnford complied with this request and soon after Wright's Hull cement replaced Harwich cement for pointing the stone work of the canal locks. It was a much cheaper solution than importing cement or hydraulic lime from England, although Hull cement took longer to harden than Harwich cement. Harwich cement had been supplied to Nova Scotia as early as 1813, and Parker's Roman cement had been used in hydraulic works in Newfoundland in 1811, but these were isolated cases and the greatest use of these imported materials by the Royal Engineers was in the 1840's.[28]

The need for locally available, cheap supplies of rock in Canada which would produce hydraulic mortar was a continuous one. At Quebec in the 1830's Lieutenant Frederick Henry Baddeley worked on the black rock of Cape Diamond in the hope that from it he could make a hydraulic mortar. Experiments were made at Quebec in 1834 by Lieutenant Alexander Gordon, on orders from Colonel Gustavius Nicolls, to test the relative strength of Baddeley's Quebec cement, Harwich cement and Wright's Hull cement, and the results were published in the Royal Engineer Professional Papers five years later. Gordon reported that in setting time for pointing a wall Harwich was the fastest and most durable after seven months of winter. In setting time and durability in building a wall, Harwich was also the best but others stood well after the winter test period. For plastering in water (a well), Harwich was the only one that stood the winter test. Nevertheless, for general adhesive quality, Quebec cement was superior. The conclusion was that Harwich was the best followed by Hull cement; the chief advantage of Quebec cement was its availability on the spot which made it attractive for any work not requiring a quick setting cement.[29]

Samples of Quebec rock were sent to England for further tests by Pasley. Pasley first found that Baddeley's cement would not set underwater but later found it would be useful for hydraulic purposes if first allowed to set in air. This led Pasley to re-evaluate slower setting cements and to conclude that these were not without value in situations where they would not immediately be exposed to water. Baddeley patented his discovery but the Inspector General of Fortifications refused to recommend payment for his expenses because he might be expected to profit from the new cement. It will be remembered that Pasley did not patent any of his artificial cements but that Scott later patented his.

(see Chapter 2). However, there is no evidence that Baddeley derived any benefit from his discovery. He continued his experiments on local cementatious rocks when transferred to Fort Henry in Kingston, Upper Canada, in 1837, and sent to Pasley specimens of his Kingston cement rock. Pasley calcinated these samples and included them in experiments on comparative strength tests of various sorts of cement, natural and artificial. He found that the Kingston cement had an average adhesiveness to brick of only 565 lbs fracturing weight compared to 1453 lbs for Pasley's best artificial cement. In a letter to the Inspector General of Fortifications of 1837, Pasley said that Kingston cement should not be used for important works underwater and agreed with the decision not to use it for work on the Rideau Canal (1826-1832); Royal Engineers were responsible for building the canal and for its maintenance and operation until 1853.[30]

The Royal Engineers' experiments with cement in Canada during the 1830's were not of lasting significance in the adoption of lime and cement technology in British North America before mid-century. On instructions from the Board of Ordnance, Colonel Holloway reported to the Inspector General of Fortifications in 1843 on the availability of hydraulic cements in the country. Holloway found that the only one actually made in Canada was Hull cement which had been developed by the private sector, albeit with some help from Royal Engineers at Quebec. Also being used for public works in Canada was Rosendale cement, a natural cement produced from 1828 in New York State. Harwich cement continued to be superior to both Hull cement and Rosendale cement in dependability. No mention was made of Baddeley's Quebec or Kingston cements, which apparently were not in use at the time.[31]

By mid-century the Royal Engineers in Nova Scotia were eager to take up Portland cement, somewhat in advance of their brother officers at home. The Commanding Royal Engineer at Halifax requested a supply of Portland cement for works in 1851-52 but encountered some incredulity in England. The Inspector General of Fortifications' office searched for a supplier and wrote back asking to know why he wanted it. This was indeed an early interest in

Portland cement; the material's first major use was at Cherbourg, France, 1848-1853, and in 1851 manufacture was still confined to England and to six firms. Portland cement was first imported to the United States in 1868 and was not manufactured there until 1871. Supplies of Portland cement requested by the Corps at Halifax were eventually sent from Messrs. J.B. White and Sons, one of the largestand most reputable firms then making the material. By the 1860's Portland cement was used extensively by the Royal Engineers in both Canada and the Maritime provinces. In Nova Scotia and New Brunswick it was generally obtained from Halifax importers, although when the price proved high it was sent from England by the War Office. Portland cement was first manufactured in Canada at Marlbank, Ontario, in 1890.[32]

The Royal Engineers' experience with limes and cements in the colonies was related, as at home, to their attitudes and practices concerning the use of concrete. Interestingly, there were at least two examples where the Corps' experience with concrete construction techniques was linked to the adoption of the earlier tradition of pisé construction, a type of building with earth. The technique of laying mass concrete in formwork was adapted from pisé work methods.[33] At all events, as has been discussed in Chapter 5, the Corps' earliest experiment with mass concrete was in a model of a casemate arch constructed of Ranger's patent material in 1835 to test the resistance of the novelty to artillery fire. The first actual use of mass concrete for the superstructure of permanent fortification works in Britain was not until 1865 in the revetments of Newhaven Fort, and Scott's cement was used for the concrete. It is significant that this achievement was preceded by the use of concrete above ground for fortification works in British North America and followed very soon by similar employment of the material at Fort Cunningham, Bermuda.

The 1860's witnessed some use of concrete for fortifications at Halifax, Nova Scotia which proved to be slightly ahead of the mainstream of British military construction. Between 1862 and 1865 the use of cement concrete was tried by the Corps at Halifax and the results closely observed. They used Portland cement imported from England. Because of its expense they also tried American natural hydraulic cement but specimens proved unsatisfactory. Initial concrete work was in the replacement of foundations for gun platforms, but from the mid-1860's it was used also for escarp walls, in place of brick arches in galleries and for expense magazines at Fort Charlotte, Fort Ogilvie and York Redoubt. Concrete's use on a large scale was resorted to because of the lack of skilled labour for masonry construction and it proved quite successful. Different types of mixtures were tried until the best solution was found by experiment which combined strength with economy.[34]

The earliest work in concrete above foundation level was in an escarp wall at Fort Ogilvie in 1864, thus predating by a year the revetments at Newhaven. This escarp wall was built on rock and was drained by 3 inch diameter pipes. The concrete was 4 parts stone broken to pass through a 3 inch ring, 2 parts beach shingle, 2 parts sand and 1 part Portland cement. Another part shingle was later added which was found to make a better, more solid concrete. After removal of the formwork, the greater part of the face was found firm and even. The rough portions of the face were rendered with cement mortar composed of 3 parts of sand to 1 of cement.[35] Lieutenant Colonel F.C. Hassard, Commanding Royal Engineer, reported in 1866 that, while with ample funds and skilled workmen he would prefer masonry in fortifications, he had found with concrete that "for economy, dispatch and military labour the advantage is undoubted."[36] The extensive use of Portland cement concrete for fortifications at Halifax anticipated the large scale use of the material for similar construction by the Corps in Britain which dates from the early 1870's.

The Royal Engineers in Bermuda also seem to have been off the mark faster than their brother officers in Britain for the large scale use of Portland cement concrete in fortification superstructures. From the late 1860's Portland cement mass concrete was used for a casemated battery at Fort Cunningham in the second half of the works as a substitute for stone. The decision to try concrete was made by the Commanding Royal Engineer at Bermuda but Lieutenant H.C. Fox superintended the works.[37]

The concrete was made of hard crystalline limestone, Portland cement and oolitic limestone powder (used as sand). Since concrete had not been used before for building purposes at Bermuda, many combinations were tried before the proportions of these materials were arrived at. Most of the work was built of concrete composed of nine parts broken stone, with its sand in it, to two parts of cement mortar consisting of one Portland cement to one of soft stone sand. Some of the technique for the preparation of the concrete appears to have been taken from Q.A. Gillmore's 'Practical Treatise on Limes, Hydraulic Limes and Mortars', Professional Papers of the Corps of Engineers USA, (1863). The concrete was laid in the formwork at the rate of 9 inches a day, and when finished had a fine smooth surface, as good as if it had been rendered. Moveable boards wedged out from uprights were used as moulds for the walling. For constructing arches, a ring of brick, with a few headers to bond with the concrete above, was turned over centres to form a soffit, and the remaining 2 feet of the arch formed in concrete. In one case, an arch of 10 foot span and 2 foot rise was built entirely of concrete; in some cases no stone or other lintels were used over openings in the walls. The main difficulty was found in forming exterior angles. A variety of expedients were tried to overcome this but the most successful was that of building a quoin at each angle, either of 14 or 9 inch brick, stone or, best of all, in moulded concrete blocks. These quoins were built in strong cement mortar, and when formed of blocks of stone or concrete were pinned together with small wooden dowels. Besides ensuring the accuracy of the concrete work, the quoins improved its appearance, according to Fox. The cost of the concrete work at Bermuda was about 7/16ths that of brickwork.[38]

In describing his work at Fort Cunningham while back in England in 1872, Lieutenant Fox illustrated the lineage of concrete construction as well as his attitude towards Portland cement and the making of mass concrete and artificial stone.

> "I consider that Portland Cement is the only safe material of its kind, which can be used in building "pise" concrete walls, but good blocks may be made of many other materials if sufficient time can be allowed for "setting"; I have made good blocks with pure lime and sand; - puzzuolana (St. Vincent's), pounded brick, or ground cinders being used in certain proportions."[39]

The story of the Royal Engineers and concrete in fortifications at Bermuda is an excellent example of their role in the diffusion of European building technology to the colonies. They were clearly the first to use Portland cement and concrete for building in Bermuda, and one engineer officer appears to have used local material as well in making concrete blocks. Finally, it is interesting that Fox's account of the work at Fort Cunningham appeared as part of his article on Portland cement concrete in the Professional Papers on Indian Engineering published by Thomason College Press, Roorkee, India. This demonstrates well how Royal Engineers kept their brother officers around the world up to date on the latest applications of advanced building materials and methods through the technical press. Communications technology was one of the vital tools of empire.

Testing Colonial Woods

One of the more interesting examples of the Royal Engineers' work in foreign lands is their experiments on the strength and durability of colonial woods. The theoretical basis for the Corps' experiments was in the publications of Peter Barlow and Thomas Tredgold, more particularly in Barlow's An Essay on the Strength and Stress of Timber (1817) which went through six editions, the last in 1867, and Tredgold's The Elementary Principles of Carpentry (1820). Barlow was clearly the major influence. It will be remembered from Chapter 1 that he taught at the Royal Military Academy. Barlow's and

Tredgold's works gave practical rules for the calculation of the strength and deflection of timber using the direct application of a constant (c), the tabulated results of c being derived from tests on small sections of comparable timber loaded in the same way. It is notable that they devoted as much space to deflection as to strength, a clear follow on from the time when sagging was the first - and probably the only - indication of inadequacy.[40] Royal Engineers, working mainly from Barlow's formulae, developed calculations of the strength and deflection of a variety of foreign woods in a host of colonial locations around the world. The Corps was also interested in gathering information by way of personal observation and through reports from inhabitants on the performance of colonial woods in practice in their native environments. In many ways this was a more important contribution than their 'scientific' experiments on strength which added little or nothing to Barlow's and Tredgold's theoretical writings which were not original either.[41] Even so, Royal Engineers did provide by their tests a method of numerical comparison between 'new' colonial woods and the known timbers of commerce in Britain. This was an invaluable tool for adopting native woods for construction projects in foreign territories and in some cases for their importation and use at home.

The best recognized of the Corps' experiments on colonial timber took place in Canada. This was not surprising since Canada became Britain's principal source of imported constructional softwood throughout most of the nineteenth century.[42] A Canadian timber industry was fostered by the cutting off of Britain's Baltic supply in the Napoleonic Wars which reached a crisis point in 1808-1809. The method of securing the Canadian trade was a preferential colonial tariff which established a generation of monopoly for British North America (1814-1846).[43] As late as 1856, nearly half the timber imported to Britain came from Canada.[44] Major timber exports in order of importance were white pine (which the English called yellow pine or Quebec pine), red pine, spruce (red, white and black), oak (white and red) and a variety of others such as tamarac, elm, ash, and birch. British importers demanded square timber partly because of the vested interest of English sawmills to get raw materials for manufacture but more so because of conservatism. As supply qualities and manufacture of deals from Canada improved, the British market accepted them, English saw pits resawing the timber in deal form into lumber. Canadian scantlings and inch boards, the completely manufactured article, were kept off the English market until the 1880's.[45]

The engineer officer responsible for experiments on Canadian woods was William Thomas Denison (1804-1871) whose work as founder and editor of the Royal Engineer Professional Papers and for the Admiralty at the naval dockyards has been discussed earlier. Denison was born in London, the son of John Wilkinson, a merchant who later took the surname of his cousin William Denison of Kirkgate, Leeds whose property and business he had inherited. W.T. Denison was educated at private school in Sunbury, at Eton and under a private tutor. He entered the Royal Military Academy in 1819 and passed out in 1823 but did not receive his commission until 1826, having spent a portion of the interval working with the Ordnance Survey where he was first posted after commissioning. Denison was stationed from 1827 to 1831 with a company of Royal Sappers and Miners and other engineer officers under the command of Colonel John By in the construction of the Rideau Canal in Canada. His work was concerned mainly with the junction of the canal with the Ottawa River at Bytown (Ottawa).[46] It was significant that Denison was assigned to canal works at Ottawa. The Ottawa Valley was one of the greatest centres of the Canadian timber trade from its earliest beginnings.[47]

Denison undertook his experiments in Canada in 1830 and 1831. The woods were Canadian though he called them American. His experiments had a twofold objective: "to establish some proportion between the strength of different kinds of American timber, and then by reference to Mr. Barlow's experiments, between these and European timbers", in order to establish the constant factors which were part of the formulae for calculating the correct dimensions of timber for different strength requirements; and "to ascertain the difference, both in dimension and strength, made by seasoning, or by difference of age, or position in the tree."[48] Denison claimed that his experiments in part "corroborate in a remarkable degree the experiments made by Mr. Barlow upon wood of the same nature, but of very different scantling and in different circumstances."[49]

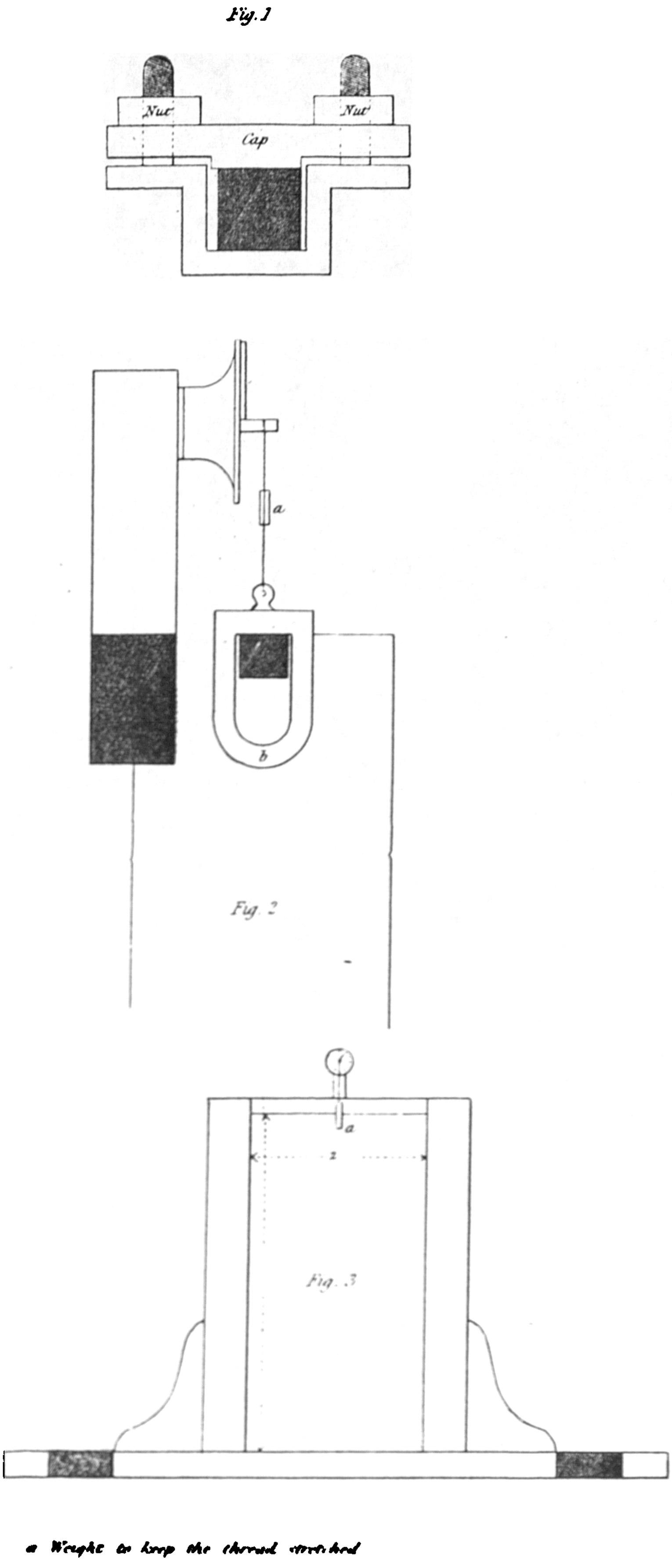
Barlow was not the first to experiment with Canadian timber. Some of Barlow's data leading to his Essay on the Strength and Stress of Timber (1817) came from experiments by Mr. Couch, timber master at Plymouth naval dockyard who tested Canadian white pine, red pine and oak for the Admiralty, 1810-1812.[50] Barlow's own experiments were also directed to providing information for the Admiralty on woods for shipbuilding. His purpose in experiment was to take an independent look at the subject upon which others had written with conflicting results so as to "ultimately furnish such *practical* rules as might be had recourse to by practical men."[51] Barlow's experiments were undertaken at the Royal Military Academy, Woolwich and at Woolwich naval dockyard and arsenal. His report was made to "the Honourable the Principal Officers and Commissioners of His Majesty's Navy."[52] Barlow's work was clearly attempting to establish on a sound basis the strength of Canadian timber as a constructional material for both ships and buildings given Britain's recent adoption of it as a substitute for its usual supply of softwood from the Baltic which had been cut off during the Napoleonic Wars.

Denison, for his experiments, had trees felled in the vicinity of his station at Ottawa. The trees were of the same size, and from them he had a plank sawn through the heartwood which he divided into pieces one inch square and three or four feet in length, numbered according to their position in the tree from the heart inwards. His testing apparatus consisted of two blocks of oak about 6 inches square by 4 feet high morticed into a 3 inch plank and supported by struts. The blocks were tied together at the top by a cross bar which served to support at its mid-point a circular gauge for indicating the amount of deflection. Also from the cross bar a scale was suspended for holding weights applied as load on the specimens. A groove was cut into the top of the uprights to receive the specimens. It was lined with iron in order to fix the ends of the specimens by screws and caps.[53] (See Figure 68).

The experimental process involved placing the specimen on the supports of the apparatus and adding 20 lb weights one at a time and measuring the deflection after each addition. Once it was thought that the limit of elasticity was reached, weights were added more gradually and allowed to remain longer, and the weight *often was* removed to see whether the specimen would return to its original state. When the limit of elasticity was passed, weights were added quickly until the specimen gave way. The specific gravity of the specimen was taken after the process was completed. Denison tested 26 species of Canadian woods. Much of what he tested was green timber since he was called back to England before specimens he had put aside to season were ready for test. In 1833-1834 Denison resumed his experiments on Canadian woods at Chatham on scantlings he obtained from the Admiralty dockyards. He tested 23 species and compared these with timber sent to him by Lieutenant-Colonel Brown from Ceylon (Sri Lanka) as well as specimens from New Zealand, Van Diemen's Land, New South Wales and Rio de Janerio.[54]

Denison was hopeful that his experiments would help to stimulate further research on colonial woods as well as establish practical rules for specifying North American timber, the key building material in the new world:

> "I cannot conclude without expressing my hopes that officers and others employed in the colonies will be induced to turn their attention to this subject. In America especially, for many years, timber from its cheapness will be employed in preference to iron, and should Mr.



a Weight to keep the thread stretched

b Hook for scale

[illegible] R.E. del

Figure 68 Denison's Apparatus for Testing Canadian Woods

> Kyan succeed in his attempt to secure it from the attack of insects, and from decay, we may look forward in that country, at all events, to its employment in a variety of situations where its destructibility is now a complete bar to its use."[55]

John Howard Kyan had patented in 1832 a timber preservation process which consisted of soaking wood in a solution of chloride of mercury. Kyan's process was used extensively and seems to have been effective where properly applied; but after the patent was purchased by the Anti Dry Rot Co. the process was imperfectly carried out and then fell into disrepute and disuse.[56] In 1836 the Anti Dry Rot Co. built a tank for treating timber by Kyan's process at the Royal Arsenal, Woolwich, for use by the Royal Engineers. The Corps *appears to have had* hopes for the process, especially *for extending the life* of wood material in Canadian and West Indian buildings.[57]

On 27 February 1837 Denison presented a paper to a meeting of the Institution of Civil Engineers on his Canadian wood experiments for which he was awarded the next year the Institution's prestigious Telford Medal.[58] The Institution's annual report of 1839 *singled out* Denison's paper as an exemplary contribution:

> "They point out the above communication with especial pleasure, as an example to other Military Engineers, of the very valuable services which their opportunities will enable them to render to the science of the Civil Engineers."[59]

However, Denison's testing work did not escape criticism. Thomas Webster, Secretary of the Institution of Civil Engineers, said in a paper delivered to the Institution entitled 'On experiments on the strength of materials' (1837), that Denison in some cases had imposed first weights too large effectively to find the elastic weight (weight which could be borne without impairment of elasticity) as distinguished from the breaking weight. Webster said it was critical to observe when deflection no longer increased in exact proportion to the weight increase and that therefore only small weights should be applied in succession. As Webster noted:

> "The experiments of Lieut. Denison bore out these remarks; for it would be seen that the point at which he had noted the first permanent set was in many cases, immediately after the change, which was here laid down as the condition for determining Elastic Weight."[60]

Nevertheless, whether or not Denison's experiments on Canadian woods were of scientific significance measured by the state of the art in the 1830's, the Institution of Civil Engineers' recognition of his contribution is important, and the comment quoted above from the Institution's annual report proved prophetic. Denison's interest in the subject stimulated a considerable amount of research and discussion by the Royal Engineers on colonial woods at a number of their global stations. Denison used the Royal Engineer Professional Papers to publish the results of some of these activities.

As Denison explained in an introduction to a series of articles on colonial timbers published in 1842, the Corps was "anxious to establish something like a term of comparison between timber generally employed in our different colonies and that in common use at home."[61] Denison expressed confidence in the engineer officers' findings since the results of their experiments corroborated the strength values given in the second edition of Barlow's work: "... I am disposed to place the greater confidence in the results shown in the before-mentioned columns of mean values, from their near coincidence with those determined by so well known and so accurate an experimentalist."[62]

The most extensive and interesting of the experiments performed by engineer officers on woods in the colonies, besides those of Denison, were by Lieutenant Richard John Nelson at Bermuda. Nelson, who was briefly introduced at the beginning of this chapter, was especially interested in building materials and labour as engineering issues. He wrote an illuminating paper on these matters which was published in the Royal Engineer Professional Papers in 1840. Nelson returned to England in 1833 after six years service in Bermuda. He later served at the Cape of Good Hope (1833-1838) where he proposed unsuccessfully to build a laminated timber arch bridge modelled on a design by the Royal Prussian Engineers, thus reflecting his keen interest in wood as an engineering material. Nelson's career later took him to Plymouth, Devonport and Pembroke in England, and to Ireland, Nova Scotia and Nassau (1849).[63]

Nelson's experiments at Bermuda were undertaken sometime between 1827 and 1833. The precise date is not known. He experimented with timber used by the Admiralty and Ordnance at Bermuda. His work included tests of strength as well as assessments of texture, weight, durability and economy. In the publication of his experiments in the Royal Engineer Professional Papers (1842) he included for comparison information from the late Captain Young who had been stationed at Demerara and Bermuda, and data from Sir Robert Seppings (1767-1840), Surveyor of the Navy, on tests of 22 different woods conducted by Mr. Moore, Timber Measurer, at Chatham naval dockyard. Nelson also included test results on South African sneezewood made at Cape Town by Colonel Lewis. Nelson himself tested some 21 different woods the locations of which were Bermuda, America, Guadaloupe, Canada, Nassau, England and Africa. These included hardwoods and softwoods. His apparatus consisted of a simple lever. Specimens 6/10ths of an inch square were strained between the short end of the lever and a ring bolt screwed into the sleepers of the floor. The weights consisted of the longest arm of the lever (dead weight) plus grape-shot in a canvas bag suspended 10 feet from the pivot. Nelson said he used much the same methods as Barlow to measure strength.[64]

The most interesting aspect of Nelson's work with colonial woods was not so much his development, by way of experiment and the application of Barlow's formulae, of numerical strength values for these timbers but his evaluative remarks on the performance of the various woods and their natural properties. In this he apparently gathered much of his information from local informants and sought the help of Mr. Lindley, the celebrated botanist who was vice-secretary of the Royal Horticultural Society, in compiling data on the origin, nature and other botanical aspects of his test specimens. Nelson's detailed comments on his test woods reveal that his overwhelming concern was the durability of wood in tropical climates. A few examples will illustrate this point. Bermuda cedar he found:

> "... an admirable wood for durability, where attention is paid to ventilation, and where freed from the white outside sap. Repeated instances have occured of its lasting 100, 150 or nearly 200 years; and in one case it was taken from a house where it must have been 150 years, and then worked up as a timber for a boat."[65]

For Nelson, American white cedar was: "Said to be the most durable wood for all out-door purposes, palisades etc, as it is not apt to decay where it meets the ground."[66] On the other hand, American white pine was:

> "A cheap wood, and much used for such purposes as temporary establishments during the progress of works, in shops, stores, sheds, centerings, moulds etc... but in all respects, except price, is objectionable in permanent buildings, and is inferior to all other American pines."[67]

According to Nelson, English oak was: "... a bad wood in hot climates for Royal Engineer Department purposes; it splits too much."[68]

In the 1840's and 1850's the Corps continued experiments on colonial woods, this time across the world in India, Singapore and Australia. The nature of the activity was much the same as the earlier tests and information collecting. In 1840 Captain S. Best of the Madras Engineers undertook four experiments at Guntoor (Guntur) to measure the deflection and strength of three different India woods. He was assisted by a civilian, J. Goldingham. As with some of the engineer officers' earlier experiments, the testing apparatus and process were necessarily imaginative given the problems of conducting scientific enquiries on the frontiers of the empire. As Best explained;

> "Having no other convenient weights, and the public Treasury being close to the spot where we were trying them, we made use of bags containing each 500 Rupees, and weighing their contents each 12 lbs 4 oz the pieces of wood were laid on supports not fixed. The deflections were measured in the middle after each bag was added..."[69]

In 1843 Best joined Lieutenant C.M. Elliot of the Royal Engineers in Singapore in conducting experiments on five different Malay woods. On this occasion they used bricks for weights. In both the Guntur and Singapore experiments, the engineer officers used the formulae "in the edition of Professor Barlow's work, published in 1837."[70] For comparison purposes, they listed with their results the breaking weight and deflection, from Barlow's experiments, for English oak, pine, cast iron and forged iron, and from experiments by Lieutenant Brown of the U.S. Corps of Engineers quoted in Mahan's Elementary Course of Civil Engineering (1837), data for pine and cast iron. The engineer officers relied on local informants for descriptions of the use and performance of native timber in practice to supplement the results of their 'scientific' enquiry. Best explained that he obtained his information for the five Malay woods with which he and Elliot experimented in 1843, "from an intelligent Chinese Carpenter at Singapore, named Ah-See-Ah."[71]

In Western Australia, during the period 1851 to 1856, Royal Engineers Edmund Yeamans Walcott Henderson, Edmund Frederick Du Cane, Henry Wray, and Edward Metcalf Grain undertook an interesting variety of experiments and collected notes on their observations concerning the use of 'jarrah' (eucalyptus), a wood native to the Swan River area. They found this hardwood had properties making it peculiarly applicable for works in the tropics and sea coasts because it was resistant to white ants and sea worms and extremely durable in a hot moist atmosphere. Captain Wray with clerk of the works James Manning made tests on jarrah for strength and elasticity at Freemantle and found it equal to Riga fir.[72] Henderson and Wray, possibly with Manning's assistance, specified jarrah for a laminated timber arch roof in the Freemantle Prison chapel (1857).[73] Wray used over 3,000 loads of the new material in buildings, jetties and bridges.[74] Captain Grain sent samples to Frederick Able, Chemist for the War Department at the Royal Arsenal, Woolwich, to determine why jarrah was so resistant to insect attack. Able determined by experiments on mice that jarrah's resin was toxic and that its chemical properties probably were responsible for its proof against white ant and sea worm attack.[75] Du Cane promoted jarrah's adoption for tropical conditions as a structural timber, claiming in 1864 that its price was better than teak.[76] It appears that the Corps had much to do with establishing the utility of jarrah but they had not discovered it. A specimen was displayed at the International Exhibition of 1862 which had been in a door step at Freemantle for thirty years without decay.[77] This was clear evidence of use of the material before the Royal Engineers arrived in Western Australia. Once again, the Corps demonstrated its ability to adapt to considerable profit local materials which had been used traditionally before their arrival, and to establish the materials' credibility for Europeans through 'scientific' experiment and observation which they brought with them from a more advanced British technological civilization.

Asphalt in Cold Climates

Another material with which the Royal Engineers experimented in the colonies was asphalt. It took place in Canada and the key issue was adaptation to a cold climate. Part of this story has been told in Chapter 5 where the pioneering works of the Corps with asphalt in Canada were discussed briefly in terms of their formative influence on the adoption of this new material for works of fortification. Here the emphasis is on the diffusion of building technology and climatic adaptation in foreign lands, and on the transatlantic experiment and debate concerning the introduction of a new material.

It will be recalled that Colonel John Oldfield had first tried asphalt at Fort Henry in Kingston, Ontario, in 1842 but that it had failed because the material, which he had exposed directly to the air, had cracked in the winter frost. Nevertheless, Oldfield had managed to apply the new material in this way successfully in works at the Plymouth Citadel, beginning in 1846, and his Memorandum on the Use of Asphalte two years later was adopted by the Board of Ordnance as the model for the application of asphalt by the Corps in fortifications.

Although authorities in London seemed to take Oldfield's views as the last word on asphalt, the Royal Engineers in British North America had a different opinion based on their experience with the material in the colonies' cold winters. Following Oldfield's return to England, engineer officers were careful to keep asphalt from being exposed directly to the atmosphere. During the late 1840's, casemates at Fort Henry which had asphalt over the rubble filled arches for waterproofing were covered over with earth to protect the material from the frost, and drainage pipes were run inside rather than outside the walls for the same reason.[78] In several Martello Towers at Kingston in 1847 asphalt was used over arches of rubble masonry core and brick facing. Here the surface of the first course of brick was covered with 1/2 inch of asphalt but was protected from direct contact with the air by top courses.[79] Asphalt was also being used in the late 1840's for staunching casemates at Quebec. The asphalt was covered but the results were not successful. In August 1851 Lieutenant Colonel Whinygates reported that the casemates in the North Redoubt at the Quebec Citadel were still leaking. When the arches were uncovered the asphalt coating was found to be cracked. Whinygates expressed his doubts about the utility of the new material:

> "Asphalte has never been used in Canada, except by the Engineer Department, and its adoption for the dos d'anes of the Redoubt, could only be considered as an experiment to test its efficiency, and the present failure clearly shews (sic), that unless perfectly protected from atmospheric action during winter, by a covering of at least 3'0" thick it is

> quite unfit for general use and for the purpose of staunching Bomb-proof Arches especially."80

Colonel Patrick D. Calder, Commanding Royal Engineer at Halifax, experimented with various methods of keeping casemates dry from the time he took command of the Halifax Citadel in 1842. When he reported to London the techniques he had used he was sent Oldfield's 1848 memorandum on asphalt and evidently referred to the use of the material at Quebec and Kingston. Calder replied that he was dubious about the material in Nova Scotia's climate. He said he found the utility of asphalt:

> "... extremely doubtful though it may serve in the mild climate of Devonshire, nothing appearing to resist the alternate frost and thaw which is of daily occurrance here for four or five successive months excepting solid materials; and it is doubtful whether what would answer in Canada Province where the weather is more steady would in this place."81

It was Calder's successor, Colonel Henry John Savage, who really gave asphalt its most extensive test in British North America. He had served in Canada earlier and on his arrival in the summer of 1848 wrote to London expressing his doubts about asphalt:

> "In a warm climate or even a moderately cold one I am equally an advocate for Asphalte as Mr. Owen the Surveyor, having seen it used in large quantities with great success at Maritus and Gibraltar, but in severe climates like Canada, Nova Scotia or New Brunswick, I am of the opinion it will never answer except it is well covered over, and perfectly secured from the influence of the atmosphere... and as this climate is very nearly, if not equally as cold as Kingston, Upper Canada... I am of the opinion Asphalte is more likely to fail in this province than even in Canada."82

Savage and his subordinate Lieutenant Parsons experimented with asphalt as a paving around the South Magazine between 1849 and 1854. An area was excavated to a depth of 18 inches, drains built and 11 inches of shale laid. Over this was laid two thicknesses of concrete and over this asphalt. Extensive cracks appeared after every winter. Paving on the slope of the Cavalier Barrack in 1850 failed as well.[83]

Nevertheless, on instructions from London, Savage tried asphalt over arches of casemates in 1851, 1852 and 1853. Two of the first casemates asphalted and covered with earth were soon found to have leaks where the arches met the retaining walls, but this was remedied by placing asphalted brick in the walls up to the first joint in the masonry above the asphalt covering to the arches. In 1854 Parsons reported on the casemates: "... these from being unihabitable on account of water coming in streams through the arches, are, since the application of the asphalte, perfectly dry, and are now occupied by officers and soldiers."[84] Success was also achieved in using asphalted bricks in the construction of water tanks below the surface of the parade (122,000 individually asphalted bricks).[85] All the asphalt work was carried out by a company of Royal Sappers and Miners under Corporal Penton who had been sent to learn the process at the Seyssel Asphalte Company's works in London.[86]

Savage had problems with timely delivery of asphalt from England and the quality was sometimes not the grade specified in his order. He experimented with a shipment of half a ton of 'Trinidad Bitumen' from Pitch Lake at La Brea, complete with instructions for its manufacture and use, to compare it with the product of the Seyssel Asphalte Company, but evidently did not take it up on an extensive basis.[87] The story of asphalt for fortifications in Canada is indeed an excellent case study of many of the difficulties confronted by the Corps in the diffusion of European building technology to the colonies. Even so, after extended and rigorous experimentation with the material, both Savage and Parsons felt, on the whole, that the use of asphalt had been a success. Their conclusion was premature. Within six months, the problem of damp casemates would return to plague Savages's successor.[88]

Available records do not reveal interest in Canada Province in the use of asphalt during the 1850's, but it was employed in the 1860's at the Quebec Citadel for flooring abulation rooms of barracks and in covering arches of magazines. In 1863 the Commanding Royal Engineer at Quebec, Major Hassard, recommended to the city corporation that asphalt be used to waterproof the top of the arch of St. John's Gate. He specified that the asphalt be kept at least 3 feet from the surface of the terreplein and his suggestions were implemented. By the 1860's asphalt covered over with earth became the standard waterproofing material for casemates. Even at that date, however, the Royal Engineers were the only ones using the material in Canada. New fortifications in Levis (across the river from Quebec) in 1867 required asphalt and workmen sent from England which caused delays in the project, much to the annoyance of local contractors in charge of the works.[89]

Both Greenough and Vincent have argued convincingly that it was the Board of Ordnance in London that was most enthusiastic about asphalt. Royal Engineers stationed in British North America continually urged caution in its use but London authorities were reluctant to listen.[90] This illustrates that the administrative arrangements and policy framework under which the Corps worked in the colonies often had a critical impact on its choice of building materials and techniques. It also demonstrates that engineer officers on the spot in foreign territories were able to adapt European building technology to colonial environments even when that technology proved problematic.

Design Influences in Bridge Building

Transportation technology was one of the vital tools of European imperialism in the nineteenth century. The Royal Engineers were directly involved in constructing a number of transportation facilities during the century which were conceived primarily as military works in the service of imperial defence and expansion. Two examples were the Rideau Canal (1826-1832) built to secure critical transport connections between Upper and Lower Canada in the event of future hostilities with the Americans following the War of 1812-1814, and the Sind-Pishin Railway on the Afganistan border of northwestern India constructed in the 1880's in the face of a perceived threat of Russian invasion. Such works could and did have economic benefits as well in opening up frontier areas of the empire to trade and development. Many of the land transport routes built by the Corps, however, especially in India and Australia, were conceived primarily, if not entirely, as public works. Nevertheless, regardless of purpose, roads and railways, and to some extent waterways, could not have been built without works of structural engineering, particularly bridges. It is interesting to examine design influences in the Corps' colonial bridges as yet another illustration of the Royal Engineers' role in the diffusion of building technology and its adaptation to conditions in native environments. Some bridges in Canada and India provide useful *examples*.

As a necessary part of the construction of the Rideau Canal at Bytown (renamed Ottawa in 1855), a chain of bridges was built by the Corps in order to provide access across the Ottawa River to the forge and sawmill at Hull. Contemporary sketches of the bridging work in progress show that it had all the appearance of a military operation. The longest and most significant span was over the principal chasm known as the 'Great Kettle' of the Chaudiere Falls. This 212 foot wooden through truss arched span, designed by Colonel John By (1781-1836) was completed in March 1828. The bridge consisted of three sets of arches, 12 feet apart, forming a double roadway. Each arch was formed of two concentric curves 15 feet apart, connected by braces and king posts which formed a series of trusses from end to end. The lower string pieces were made of 2 thicknesses of red pine making a rib 30 inches deep and 12 inches wide. These timbers were cut to the curve, scarfed and bolted together. The upper string pieces were made the same way only with smaller dimensioned timber. Braces were of red pine and the king posts were oak. The roadway was of white cedar logs. By's bridge failed over time because of the lack of abutment for the upper string piece and a design flaw which threw all the weight on the lower string piece. New braces and iron straps were added in 1829 but by 1835 the bridge had settled dangerously and it was proposed to strengthen it with chains. The bridge finally collapsed in May 1836 and ferries were used after this until the construction of Samuel Keefer's Union Suspension Bridge in 1843.[91] (See Figure 69).

By's wooden arch span was a type of early Palmer bridge with counter braces. Timothy Palmer (1751-1821) of Massachusetts was the most distinguished designer of the through truss with panel bracing in American wooden bridges of the 1790's. His works were characterized by a bold use of large sectioned timbers. He did not use arched reinforcing ribs, and in his first bridges made the whole truss into an arch by giving it a generous longitudinal camber. By's bridge at Ottawa was closest in design to Palmer's Washington Bridge (1796). It appears that By was familiar with American wooden truss construction from earlier experience in Canada. After training at Woolwich, By was stationed in Canada 1802-1809. He returned to England and was in charge of organizing the Enfield Small Arms Works until 1811. Following a brief spell in the Peninsular War, he was in charge of the main United Kingdom gunpowder mills, 1812-1821. During this period he made a model of a 1,000 foot span truss bridge of multiple king post arrangement and exhibited it in the Repository at the Royal Military Academy, Woolwich. Rennie and Telford thought it represented a 750 foot span by Mr. Porter, an Englishman, over the Terrebonne, a branch of the St. Lawrence River. The model was also displayed at the National Gallery of Practical Science in 1833.[92]

General Sir Howard Douglas made special note of Colonel By's celebrated model bridge in a discussion of wood truss designs in his Military Bridges (3rd edition, 1853). In referring to By's model, Douglas

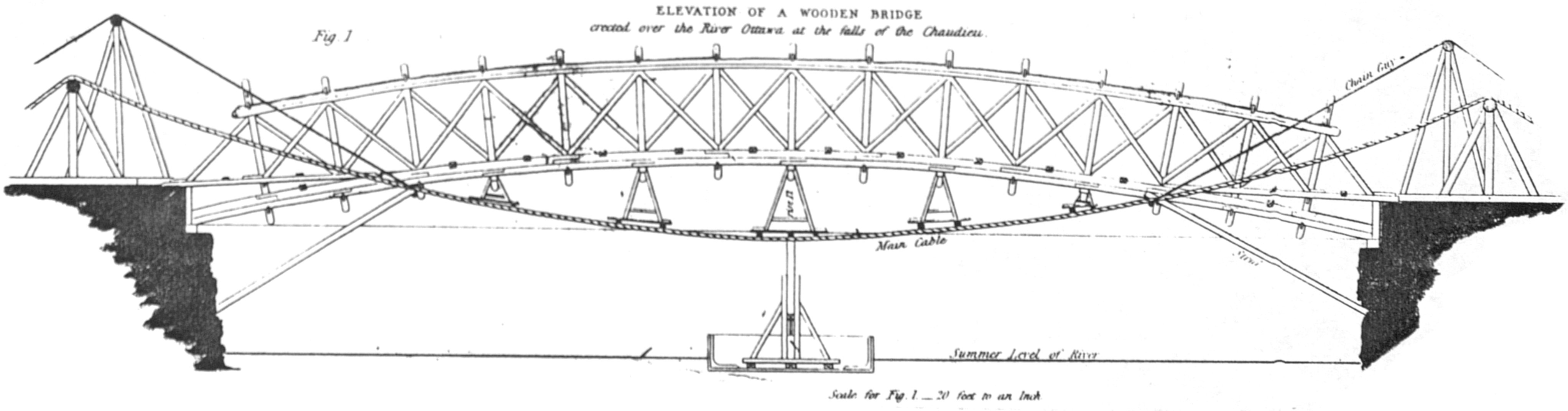


Figure 69 Colonel By's Wooden Bridge, Ottawa, 1828, Showing the Method of Erection

spoke highly of this engineer officer and of the use of the king post truss which had been a key structural element in the Ottawa bridge:

> "This principle ... has been beautifully applied by the late Colonel By, of the Royal Engineers, for a bridge of considerable span, a model of which may be seen in the Repository at Woolwich, and which does great credit to the ingenuity of that able officer."[93]

William Denison, who had served under By on the Rideau Canal project and who was probably involved in the construction of the Ottawa River bridge in some capacity, described By's 212 foot wooden truss span in an article in the Royal Engineer Professional Papers (1839). Although Denison criticised the design details of the bridge, he was much in favour of its form and materials as a logical engineering solution for the circumstances:

> "These simple forms are very well adapted to a country like America, where timber is cheap and plentiful, and can be procured of any scantling, and where labour is dear, and simplicity of form therefore very desirable."[94]

Denison expressed this theme in more explicit detail four years later when describing a simple king post truss wooden swing bridge over the Grenville Canal on the Ottawa River which had been erected during his service in that territory:

> "In Canada, timber is cheap and easily wrought; people capable of executing all the common description of carpenters' work are easily found. On the other hand, iron work, especially heavy castings, are dear, and the difficulty of transporting them to points where they are required is very great, by which, of course, the expense is much enhanced. Taking this into consideration, it was decided to adopt a wooden bridge in preference to an iron one, and the work ... has been found to answer."[95]

Timber continued to be used for bridges on the Rideau Canal exclusively until 1888.[96]

On balance, it seems fair to say that By can be credited with a work of some distinction but not adaptive genius. He had adopted American bridge technology for a Canadian situation where the advantage of wood construction was virtually the same as it was in the neighbouring country. Even so, By was the first to successfully bridge a difficult crossing of the Ottawa River near the location of the country's future capital. His chief contribution was providing the necessary supply links for the building of the Rideau Canal, a work of imperial defence.

Military engineers had long since employed the catenary rope bridge in field operations and were therefore no strangers to the suspension principle. Engineer officers in India made considerable use of rope suspension spans in the early nineteenth century, especially in the upper provinces where rivers often altered their bed making it desirable to have a bridge that could be easily dismantled and moved to a better position.[97] In 1822 Colin Shakespeare, Postmaster-General, erected at Calcutta a 125 foot long, 6 foot 6 inches wide catenary suspension bridge using a native building material called 'coir rope'.[98] Good coir rope was considered equal to hemp rope and was preferable because of its elasticity, lightness (2/3rds the weight of hemp) and resistance to rot. Coir rope suspension bridges had floors of split bamboo, fastened with slight lashings to the floor cables. The engineer officers of the East India Company experimented with the native material in the 1820's finding it very satisfactory and adopting it widely. A coir rope suspension span of 160 feet was built at Alenora by Captain Durie, and one was erected in 1825 over the River Gumber near Subathoo by Captain Kennedy, for example.[99]

For all that, East India Company officers, from the mid-1840's, adopted in place of rope catenary spans the British wrought iron chain suspension bridge. In transferring this advanced technology to India, the engineer officers became involved in the controversy over the respective merits of the 'uniform' versus the 'taper chain' system of suspension span. Their participation in the debate began when they first adopted the taper chain system which had been introduced a decade earlier in Britain by James Dredge (1794-1863), a Walcot brewer who turned to civil engineering in the 1830's.

Dredge erected his first bridge on the taper chain principle at Balloch Ferry in Scotland in 1832 and took out a patent for the system in 1836, the year he built the Victoria Bridge at Bath. In the 'uniform' system employed by Thomas Telford, Samuel Brown and others, which was the standard method of suspension bridge construction in Britain, there was an equal number of links between pins giving the chain a uniform cross sectional area throughout the span. In Dredge's design, the area of the chain decreased progressively from the points of suspension towards the centre of the span. Moreover, the 'uniform' system had vertical suspension rods but in 'Dredge' bridges they were inclined at an oblique angle. With this arrangement of the suspension system, 'Dredge' bridges depended more on the longitudinal deck beams for strength and stability. Dredge claimed a superior strength to weight ratio for his system and made experimental models to demonstrate its performance in 1838 and 1840 which were much publicised in the technical press. In 1841 William Turnbull published a treatise which attempted to demonstrate the mathematical soundness of Dredge's principle, and two years later Dredge himself published his mathematical analysis and graphic statics. Even so, the civil engineering profession remained dubious about the claims of Dredge's novelty.[100]

The engineer officer who was most responsible for introducing and adapting the Dredge taper chain system in India was Major Henry Goodwyn (- 1886) of the Bengal Engineers. He followed Dredge's example in using model tests and mathematics to prove the safety and efficiency of the taper principle, and he made his own contribution by modifying the Dredge design to what he called the 'resultant system'. Goodwyn, as well as other officers of the Bengal Engineers, designed and built or reconstructed a number of bridges on the Dredge system or on the 'resultant system'. Their experience in experiment and construction demonstrated the process of building technology diffusion and the difficulties attendant upon it in the distant overseas territories of the empire.

The first 'Dredge' bridge designed by Goodwyn was a 250 foot span structure at Ballee Khâl near Calcutta, begun in the spring of 1844.[101] On 10 July 1844 Goodwyn wrote to Dredge from Fort William, Calcutta, enclosing tracings of two taper chain bridges with specifications, one of which was the Ballee Khâl span. He was anxious for Dredge's comment on his designs and assured him that the taper chain principle had caught on in India and that Dredge need not worry that he would lose business on his patent bridge to the Bengal Engineers:

> "I want your candid opinion on my performances, and do not imagine that it is likely to detract from your employment, my making some here, for the system is now thoroughly established here, and we want so many that in a short time I hope to send you a large order."[102]

Unfortunately, in the considerable evidence examined, Goodwyn never revealed where he first learned about Dredge's taper chain principle, but the likely answer is that he had read about it in the periodicals that featured the Dredge controversy in the early 1840's - The Times, the Surveyor, Engineer and Architect, the Mechanic's Magazine and The Civil Engineer and Architect's Journal.[103] Goodwyn actually contributed to the last two, so it is assumed he had access to copies.[104]

Goodwyn's Ballee Khâl bridge partially collapsed during construction in June 1845. Following the bridge failure, a committee of Bengal Engineers was formed to investigate the incident and to report on the soundness of the principle which had been adopted in its design.[105] While the committee deliberated, Goodwyn was busy trying to find the answer to the question himself through model tests and mathematical calculations. Essentially, he was to conclude that the principle was sound and that the solution to the problem of failure in his recent project was to add material to the wrought iron longitudinal deck beam, the element upon which the strength of the 'Dredge' bridge most depended. Dredge certainly realized the critical role of this element in the working principle of his suspension bridge design. In a letter to the Mechanic's Magazine, in which he referred to his Regent's Park bridge as an example, he said that it was evident that the strength of the bridges constructed on this plan depended on the section or strength given to the side longitudinal roadway beams.[106]

As indicated earlier in a quotation from Goodwyn's letter to Dredge of July 1844, the taper chain principle had been established for suspension spans in India by the mid-1840's. Engineer officers had inspected a few of these in the course of their duties before the partial collapse of the Ballee Khâl bridge, and there is reason to suspect that they were not entirely convinced of the design's safety. Major Sir Frederick Abbot (1805-1892) of the Bengal Engineers, Superintending Engineer of the North West Provinces, was especially concerned about the soundness and safety of the 'Dredge' bridge. He explained in a letter dated 13 June 1845 to Captain Denison, who was then stationed at Portsmouth naval dockyard, that he had inspected a 120 foot span suspension bridge on the Dredge principle which had been recently erected at Meerut and was "struck by the extreme tenuity of the wrought iron girders which in those bridges profess to do so much."[107] Abbot also told Denison that he was being called upon to report on a proposal for bridging the Jumna River with a 500 foot span on the Dredge system (Goodwyn's Agra Bridge) and that therefore he had undertaken an analysis of the soundness of the principle. Through graphic statics analysis and by applying Barlow's formula for the strength of wrought iron, Abbot examined Dredge's design for the Balloch Ferry Bridge (1832). He thought that it had each half span acting independently as a lever and that the critical structural elements were the longitudinal side beams or girders which took the tension. What is most interesting about Abbot's inquiry, however, is his plea for help from the home Corps in examining this important issue and his complaint of isolation. He said in his letter to Denison:

> "If I am troubling you with views that have been already set forth, you must attribute it to the distance which separates me, as well as many others my brother officers, from the scientific world. I am utterly destitute of the means of experimenting in support of my theory. I have referred the subject to Calcutta, where there are models available, and on a large scale, but as yet I have received no reply; you must therefore be lenient to the errors which you may discover."[108]

Goodwyn too would complain of the difficulties of conducting experimental work and the proving of designs and materials in India.

Henry Goodwyn formulated his proposal for the reconstruction of the Ballee Khâl Bridge as well as for the erection of other taper chain suspension spans on the basis of model experiments and mathematical calculations in July of 1845. He explained in a letter to Dredge that same month:

> "With the assistance of a very able and first-rate mathematician here, I have studied the theory of these bridges most thoroughly; and the model that I have made, 22 feet long and 4 feet width of platform is on so large a scale, that I have been able to test it in every possible way, and it withstood the utmost efforts to derange its parts. The Governor-General, and all the scientific people here, have perfectly satisfied themselves of the efficiency of the system, and all these proofs with my models, assure me that the theory is correct. It is in contemplation to erect immediately two other bridges on the same plan, one across the wet docks at Kudderpore, near Calcutta, and the other over the Hooghly."[109]

Goodwyn's principal modifications to the Ballee Khâl bridge were to replace the outer longitudinal beams by new ones of larger section to allow for any deficiency of strength caused by the bolt-holes and to form the centre connection by wrought iron plates in lieu of the cast iron plates formerly used.[110] He explained that iron of the right dimensions was not always available in India: "The section of the outer longitudinal beam to be either 5 1/2" x 1 1/4" or 6" x 1", according to iron procurable: the first I am sure of obtaining, the latter I am not yet."[111] Like Abbot, Goodwyn demonstrated the problem of 'scientific' design in the isolation of colonial locations:

> "I beg to bring to the notice of the Committee, that (though not that I am aware of in this instance) there may be a flaw in the longitudinal beams of bridges wherein a large section of iron is used, which I have no very correct means of testing: the power of the proving machine in the iron yard is scarcely equal to the proof of 36 tons effectually; and though the portions of the platform are each separately subjected by vertical loads to much more than the actual weight they will have to carry, yet that is not the test necessary to discover a flaw in a particular piece of iron."[112]

The committee of Bengal Engineers which had been established to investigate the failure of the Ballee Khâl Bridge agreed with Goodwyn's analysis of the taper chain principle and his proposal for reconstructing the bridge. Even so, the committee expressed doubts about model experiments:

> "Useful, invaluable as models are, for rendering a particular mode of construction intelligible, all practical Engineers, as also all mathematicians who are practically as well as theoretically aquainted with mechanics, know that mere models often lead to the most fallacious conclusions; and thus from its being generally assumed (often without a shadow of satisfactory proof) that the dimensions of particular parts of the fabric only require to be increased in direct proportion to one of their linear dimensions, as for instance, in the case of bridges, directly in proportion to the spans; whereas extended on full scale experiments may be found to prove that the dimensions of some parts ought to be increased in some higher power than either the squares or the cubes of the spans."[113]

The committee recommended that the bridge be reconstructed according to Goodwyn's proposal and saw this as a fair test of the Dredge principle as well as a means for Goodwyn to work out the details for applying this suspension bridge system at stations far from Calcutta where local

Bengal Engineers would simply have to work from his instructions.[114]

Goodwyn reconstructed the Ballee Khâl Bridge in 1845. It was a graceful structure with distinctive tapering chains meeting the longitudinal deck beams at mid-span, the oblique suspender rods connected to the lightly trussed deck and with the chains extending from a stone crenellated tower and anchored underground beneath the approaches. (See Figure 70) Goodwyn subjected the bridge to proof loads, a description of which seems comic from the modern perspective; yet he was simply using what he had at hand. The tests included: a crowd of natives, up to 700 at one time, traversing the bridge for half an hour; a 4 ton elephant walking over the bridge; and a 24 pounder gun carriage and timber drawn slowly over by 36 bullocks. He pronounced the tests a success.

> "During the whole of these trials, and which tested the bridge to a greater degree than it is ever likely to again, not a bolt moved, nor was a sound of friction heard: the whole fabric seemed under dominion of tension, and the rods to be drawn fairly in the direction of their length."[115]

Goodwyn continued his model tests in 1846. He described them in detail in a letter to Major Godfrey Greene, Secretary to the Military Board, the Bengal Engineer who was later to distinguish himself as Director of Works for the Admiralty (1850-1864). Captain Goodwyn undertook his experiments at the Iron Bridge Department, Fort William, Calcutta. He acknowledged the help of communications from Colonel William Nairn Forbes (1796-1855), a former member of the committee of inquiry on the failure of the Ballee Khâl Bridge.[116] Forbes was well acquainted with structural wrought iron. He designed an iron truss for the roof of his St. Paul's Cathedral (1847), Calcutta, which at the time of its construction was one of the largest spans in existence in the buildings of India.[117]

Goodwyn undertook three sets of experiments on as many different sized models. The first was on a model of 100 foot span formed of material 1/200th of the strength of the real bridge. His object in this experiment was

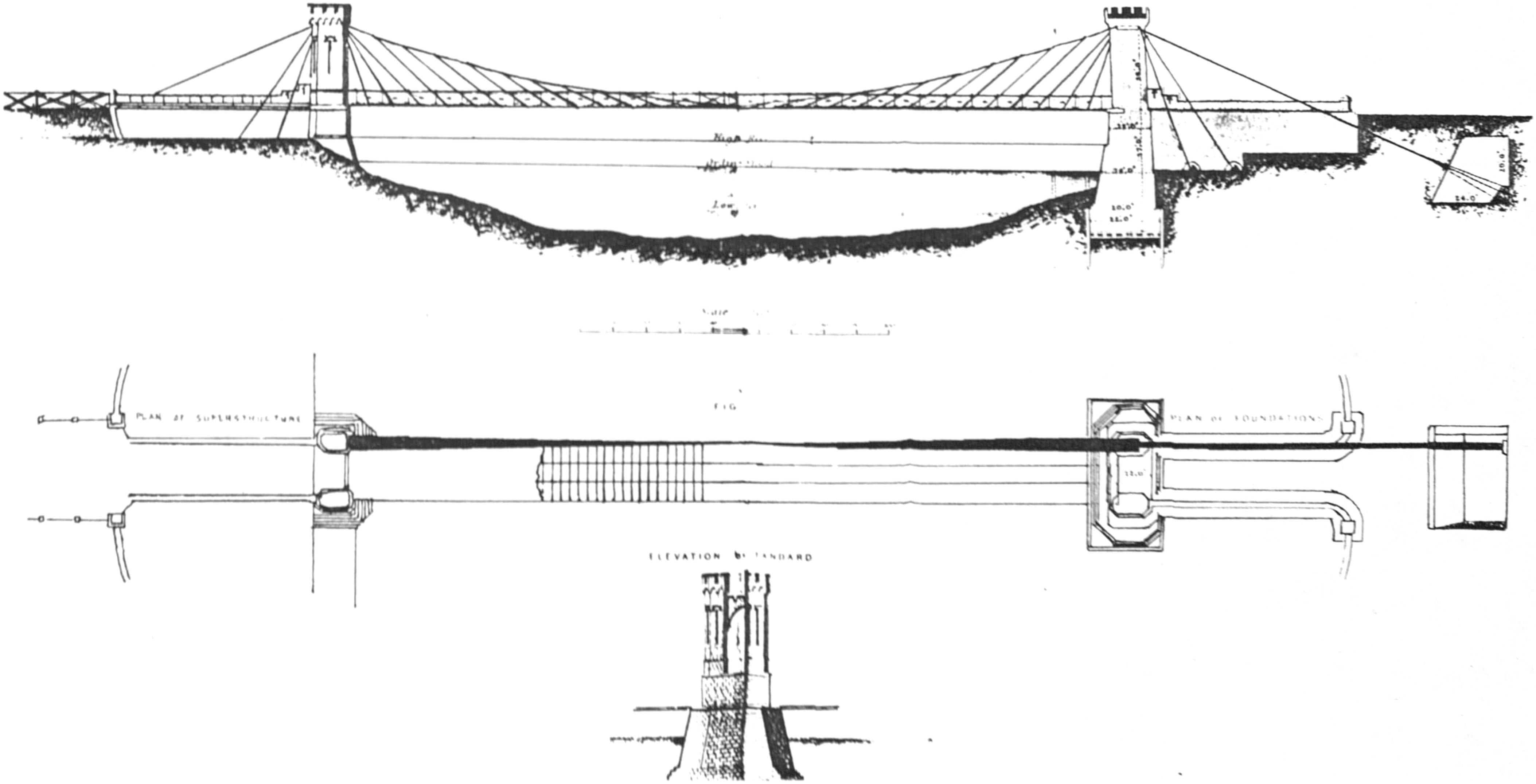
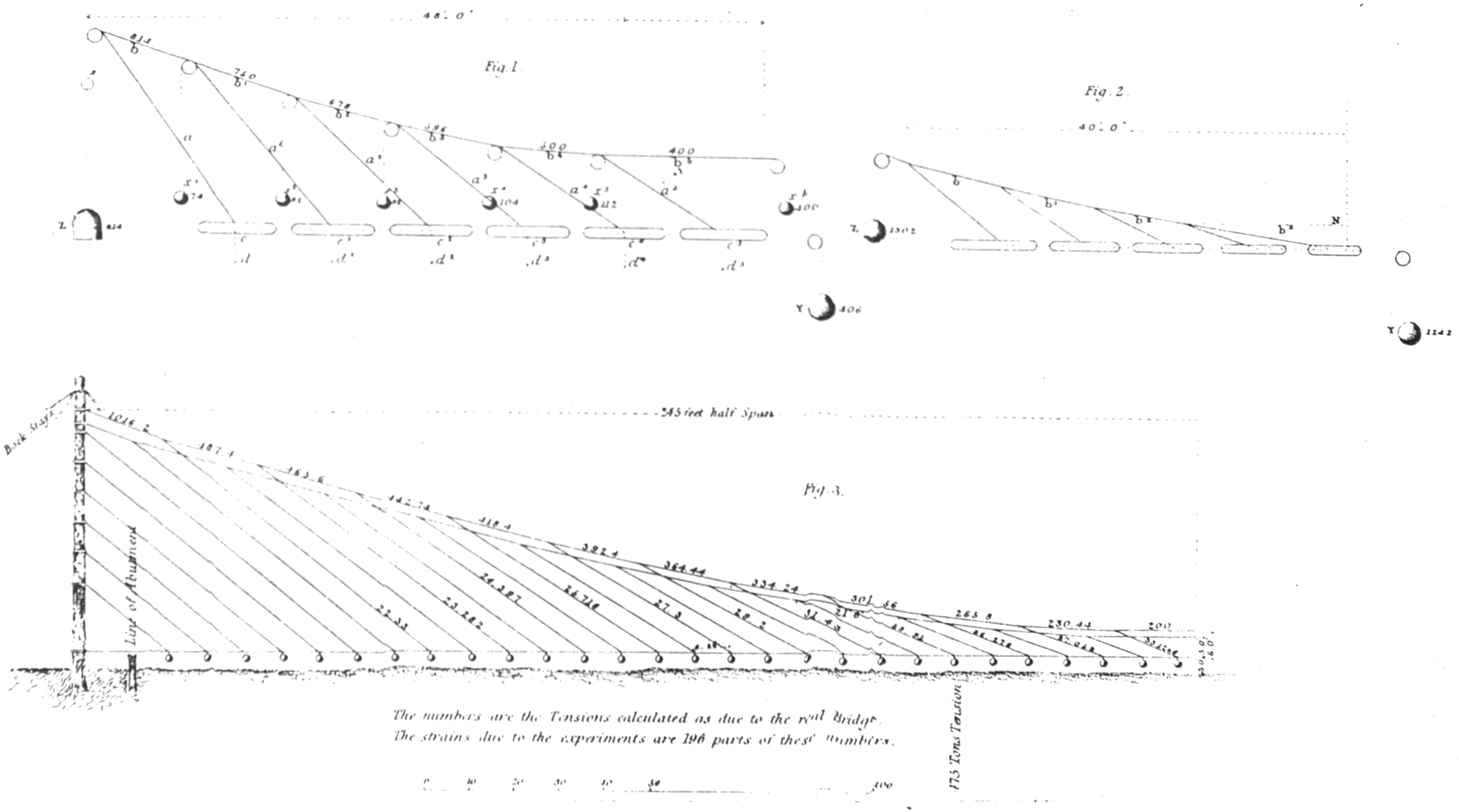


Figure 70   Ballee Khâl Bridge, Calcutta, 1845

"to test the theory of a system based on the "resolution of forces... "[118] The second was proposed by Colonel Forbes and used another fractional scale model (40 foot span). This experiment was intended to prove that "in Mr. Dredge's construction there is not iron enough in the centre of the longitudinal beam to resist tension existing there."[119] In the third experiment, Goodwyn tested his so called 'resultant system' on a 490 foot model, everything being to full scale but the sectional area of the iron being 1/196th of reality. (See Figure 71) Goodwyn compared his test results to calculations using a mathematical formula of unknown derivation. In a footnote to Goodwyn's letter to Green which was published in the Royal Engineer Professional Papers, editor Henry James, who would later work with brother officer Douglas Galton and Professor Willis of Cambridge on experiments for the Royal Commission on the Application of Iron to Railway Structures, included a note by Professor Walker of Oxford which discredited the formula presumably used by Goodwyn and doubted if the taper chain principle provided any advantage in saving on materials.[120] Smith has said of Goodwyn's model experiments and mathematical investigations that they were confused.[121] Nevertheless, this officer of the Bengal Engineers can be credited with sharing in Dredge's contribution in helping to keep alive the idea that a model, however crude, could be part of an engineer's analytical equipment.[122] Goodwyn's achievement is arguably more remarkable because it was made on the frontiers of technological civilization in India.

Goodwyn's experiments of 1845-1846 informed his construction of a number of bridges on his modified Dredge principle called the 'resultant system'. His inquiries were particularly timely and important because of the disasterous failure of a 175 foot span 'Dredge' bridge over the Kubudduk River near Jessore in the autumn of 1846 with the loss of 150 lives.[123] This bridge had been constructed under the supervision of Captain Duncan of the Royal Engineers. Dredge had manufactured the ironwork but claimed that:



The numbers are the Tensions calculated as due to the real Bridge.
The strains due to the experiments are 196 parts of these numbers.

Figure 71 Goodwyn's Suspension Bridge Model Experiments

> "the plans were made by the Indian government, and sent to me, with dimensions of every part specified, and strict injunctions given that they should be adhered to. These directions were observed in every particular, with the exception of the iron beams for the roadway, which was the part (and not the chain) that gave way; and these were made 25 per cent stronger than is depicted on the drawing."[124]

Dredge further maintained that he knew perfectly well that the longitudinal beams were weak and told Duncan to reinforce the platform to take some of the strain. Dredge even suggested sending an engineer from England to help.[125] Goodwyn in commenting on the tragedy in October 1846 reiterated the point about the cause of collapse being weak longitudinal beams.[126]

During the period 1846-1849, Goodwyn reconstructed the Kubudduk Bridge on his 'resultant system' as well as five other 'Dredge' bridges on spans varying from 120 to 200 feet.[127] His major new project was a proposal for a bridge over the River Jumna at Agra. It had four spans, the longest being 500 feet. The chains and oblique suspender rods, longitudinal and transverse beams, railing and roadway bars were all of wrought iron. Saddles for chains and rods, struts and railing staunchions were cast iron. The total weight of the wrought iron was 724 tons, the cast iron 821 tons. Suspension chains were anchored through the abutments of terminating toll houses on the roadway into 39,000 cubic feet of masonry underground. The toll houses and tower piers were of stone in the Egyptian revival style.[128] It is not known if this project was executed, but Goodwyn used it to promote his 'resultant system'. (See Figure 72)

Goodwyn's 'resultant system' essentially increased the section of the longitudinal wrought iron beams in the 'Dredge' bridge, working on the principle that what was taken away in strength of iron from the chains had to be replaced in the deck beams. Goodwyn acknowledged that this meant that no real savings were

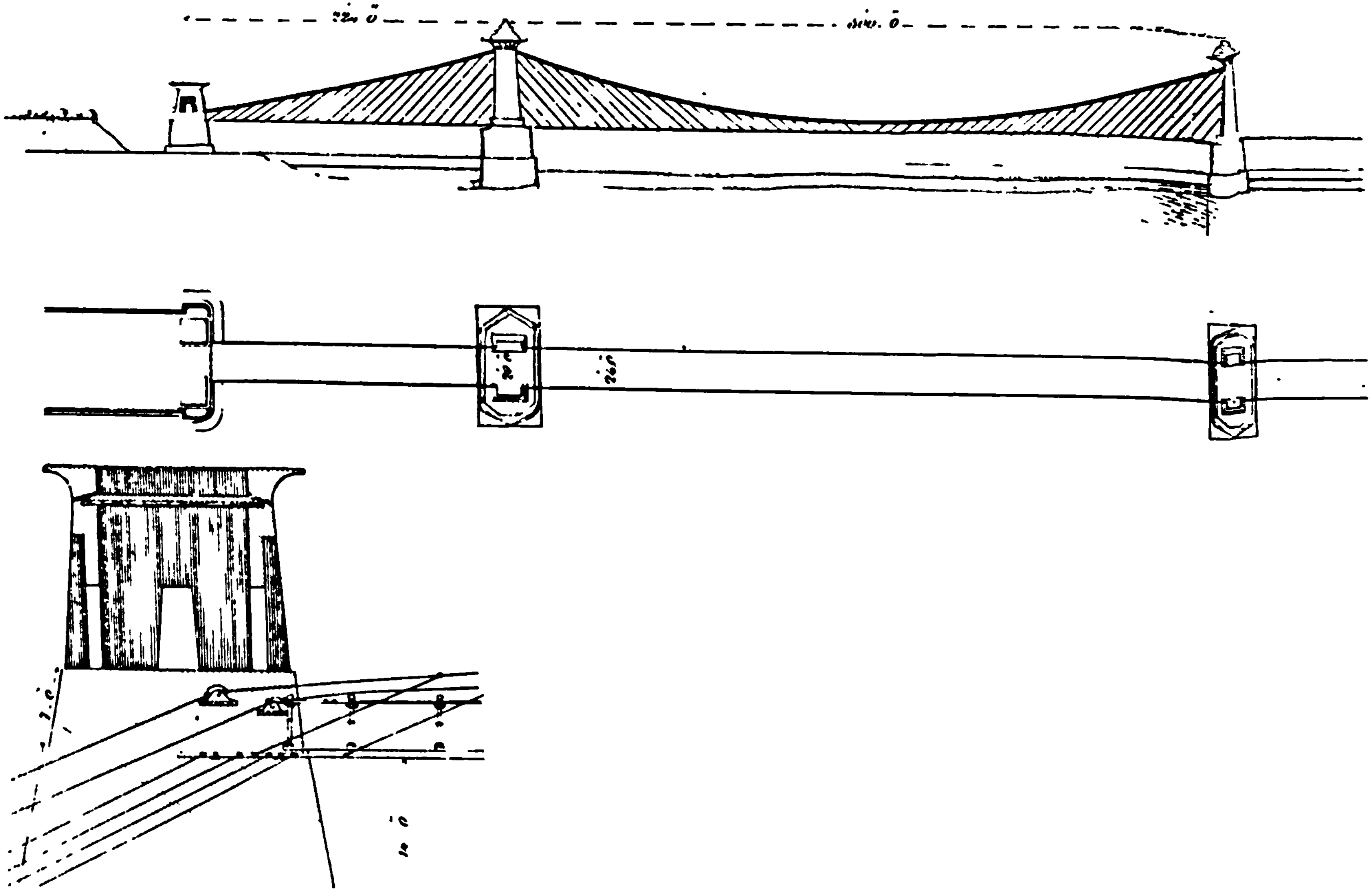


Figure 72 Goodwyn's Proposed Bridge at Agra : Elevation, Plan and Section of Toll House

made in materials. In his design for the Agra Bridge, the difference in weight of iron calculated for the 'uniform' system versus his 'resultant' system was only about 2% in favour of the latter.[129] Nevertheless, Goodwyn saw his system as superior for imparting greater stiffness, a critical factor in suspension spans:

> "If ... the quantity of iron calculated to resist a certain dead weight be the same for bridges of equal span and width, and of equal strength, whether the metal be distributed as in the uniform system, or as in the 'resultant', it surely is no small advantage in favour of the latter, that by construction it is defended from the severe trials to which all bridges, even when unloaded are exposed, from the momentum which a comparatively light body obtains when put in motion."[130]

In the 1850's the development of wide span suspension bridges of spun wire cable of uniform cross section rendered the discussion of the uniform versus the taper chain system obsolete. All the same, it is important that Goodwyn was deeply involved in the controversy at its height in the 1840's and that he built or reconstructed at least half a dozen suspension bridges on his 'resultant' system. By any measure of comparison, this was a contribution of singular ingenuity for an engineer practising in India.

The Royal Engineers played a significant role in the diffusion of iron and steel bridge technology to India in their road and railway works on the northwestern frontiers during the 1870's and 1880's. The key figure was Sir James (Buster) Browne (1839-1896). Commissioned in the Bengal Engineers in 1857 (Royal Engineers, 1862), Browne arrived in India two years later and was engaged immediately in the construction of trunk roads in the upper provinces. However, like other engineer officers in the Public Works Department, he was also responsible for barracks, fortifications and all manner of civil works. In 1871 Browne took two years furlough and travelled in Holland, Belgium and especially North America to study the art of iron railway bridge design. He also studied with Sir G. Molesworth and became an expert on steel bridges. On his return to India in 1873, Browne was placed on special duty to design iron road bridges for the Punjab and North-West Provinces. Some of these were for bridges approaching 300 foot span. Amongst his most distinguished works was a suspension bridge across the Jumna River at Kalsi (1873) with central span of 260 feet and side spans of 140 feet each. At the time, it was the largest span in India. He not only prepared the design and the estimates but also the working drawings.[131]

In 1874 Browne made a design for a 820 foot railway bridge across the Indus at Sukkur on the stiffened suspension principle with steel cable, but it was not carried out. After the Public Works Department rejected his proposal, Browne wrote to the Government of India pointing out that he had witnessed the erection of Roebling's Brooklyn Bridge and adding that the Americans had not given up on the suspension principle for railways.[132] Engineers in Britain, however, were decidedly uninterested in railway suspension bridges despite some revival of discussion in the 1860's.[133] Lansdowne Bridge (1887-1889), a cantilever span resembling the Forth Bridge, was eventually built at the location. This is an interesting case of a British engineer in India whose attitudes and practices were more influenced by American than British experience.

Browne's best known achievement, however, was with steel bridges on the Harni section of the Sind-Pishin Railway (1883-1887). A close associate in the execution of these bridges was Colonel G.K. Scott-Moncrieff. The bridges were designed as a series of short to medium span steel Warren truss girders on stone piers. An example was the Louise Margaret Bridge, Chappar Rift, in which 600 tons of girders were used.[134] There was nothing complicated about these designs. The girders were all designed and made in England, and as Scott-Moncrieff explained: "... the only work to be done in India is to put them up and rivet them together."[135] Still, this is an important example of the Corps' role in the introduction of a new material to the colonies and one which occurred at the end of the period of the present thesis. Browne was apparently highly regarded in his time. The Director of State Railways said of Brown: "... he has shown himself possessed of a rare combination of theoretical skill and practical talent."[136] This was an apt description of the character of many engineer officers who served the empire in India.

Pioneering Work in Prefabrication

Prefabrication was an ingenious and profitable solution to the building challenges of colonial expansion where local capacity could not supply needed accommodation or meet desired construction standards. This important phenomenon in the development of building technology in the nineteenth century included two distinct yet often related achievements - the wholly portable building and prefabricated frameworks and components. Pioneers of prefabrication worked with wood, corrugated iron and cast iron.[137] The Royal Engineers' contribution was a system of prefabricated cast iron frameworks for barracks and military hospitals for the West Indies which they introduced in the mid-1820's. This early event in the story of Britain's remarkable achievement in pioneering works of prefabrication has not been recognized by scholars to date and deserves to be better known and credited.[138]

Prefabricated cast iron structures for the colonies began with the export of bridges from Britain. As early as 1798 a prefabricated cast iron bridge of three arches, designed by Rennie and made in England, arrived at Lucknow, India. It remained in storage for nearly 40 years and was finally erected by Colonel Fraser of the Bengal Engineers, 1841-1844.[139] By the 1830's it had become common business to send prefabricated bridges to the colonies.[140] Cast iron components for buildings, particularly columns, were being exported to the colonies from about the beginning of the nineteenth century.[141] Cast iron building frameworks have their origin in textile mills. William Strutt made the breakthrough in 1792 with the design for the first multistorey fireproof building at Derby. In 1796 Charles Bage made the first complete iron frame. By 1818 this mode of construction was being used to heights of about eight storeys.[142] During the 1830's, the design of iron framed fireproof textile mills stabilized. The T section cast iron beam and brick arches for floors was the usual practice. In some cases, however, flagged floors were preferred supported by cast iron beams and cast iron bridging joists which slotted into the beams. Rennie used these in 1816 for a section of the Forge at Woolwich naval dockyard.[143] So too did Edward Holl, Civil Architect to the Admiralty, in the reconstruction of the ropery at Plymouth (1812) and in the lead and paint mill at Chatham (1817).[144]

Indeed, it was from the Admiralty that the first prefabricated cast iron building frameworks were to come to the West Indies. In 1817 a complete cast iron framework for a hospital was sent to Port Royal, Jamaica and built 1817-1820; and it still stands. The building is a two-storey, 400 foot long structure with six bays and encircling verandah on both floors.[145] The ironwork was by I. Sturges and Co. of Bowling Iron Works, near Bradford.[146] The design was probably by Edward Holl who is known to have designed a prefabricated Commissioner's House for Bermuda naval dockyard in 1822 (completed by his successor G.L. Taylor in 1831) where extensive use was made of cast and wrought iron for roof framing, principal floor joists and verandahs.[147] Royal Engineers would have been familiar with these buildings since they were stationed at the naval dockyards. The hospital at Jamaica shares many similarities in form with the plan adopted by the Corps for the system of cast iron building frameworks for the West Indies. Moreover, the method of making floors by slotting joists into the cast iron beams adopted by Holl from an early date was used in Corps' cast iron building frameworks. No doubt the Board of Ordnance and the Corps had access to information from the Civil Architect's Department of the Admiralty, although no evidence has been found to prove this connection.

The end of the Napoleonic Wars in 1815 saw the price of cast iron plunge from £20 to £8 per ton. It affected a second stage of wider use of the new material and stimulated more scientific design.[148] This economic incentive was important in the timing of the Corps' choice of cast iron frameworks for barracks and hospitals in the West Indies, but there were other motives. Iron was free from insect attack that plagued local timber buildings, it could better withstand the problems of hurricanes and earthquakes which troubled the West Indies and sound construction using a prefabricated iron framework could be achieved more cheaply than in other materials. Buildings could also be built quickly and the adoption of a uniform system of iron framework achieved economies over the proliferation of individually specified and manufactured cast iron elements for each new barrack or hospital project. All of these reasons were to be articulated in one way or another in the story of the development of the Royal Engineers' system of prefabricated cast iron building frameworks for the West Indies.

The Royal Engineer responsible for proposing a system of prefabricated cast iron frameworks for barracks and military hospitals in the West Indies was Colonel Sir Charles Felix Smith (1786-1858). Commissioned in 1802, Smith landed in the West Indies two years later where he served under Colonel Sir Charles Shipley (1755-1815), and was early engaged in the war with France in the Caribbean (1807-1810). Smith later fought in the Peninsular War and was Commanding Royal Engineer at Gibraltar during the French siege. In 1815 he was appointed Commanding Royal Engineer of the Sussex District in England and later that same year was Commanding Royal Engineer at Vicennes as part of the army occupation in France. Smith soon returned to his Sussex post and remained there until 1823 when he was appointed Commanding Royal Engineer of the West Indies with headquarters in Barbados. On his arrival he found that there were eleven different island colonies occupied by British troops but that he had only five Royal Engineers to do the job of building and maintaining military establishments. A commission sent from England in 1823 recommended the addition of fourteen engineer officers to properly carry out the work. Smith therefore was concerned from the outset with minimizing the work load on his small staff of trained constructors. He was to spend the next fourteen years in the West Indies, and in addition to his role as Commanding Royal Engineer was Commander of British forces in the West Indies (1836-1837) and acting governor of Trinidad (1828 and 1830-1831), Demerara and Berbice (1833) and St. Lucia (1836-1837).[149]

Mindful of his engineer officer staff shortage and the paucity of skilled building tradesmen in the West Indies as well as the factors of economy and efficiency, Smith proposed to the Board of Ordnance in 1824 "a new system of barracks that should, as far as was practicable, insure uniformity of design."[150] In the Caribbean the Corps used cast iron columns for verandahs before 1820.[151] Also, evidence suggests that the idea of employing prefabricated cast iron frameworks was a topic of interest amongst the Royal Engineers in the Bahamas and Bermuda about the time of Smith's appointment as Commanding Royal Engineer in the West Indies, but design proposals there restricted the use of structural cast iron columns and girders to galleries only.[152] It appears that Smith may have been the first Royal Engineer to propose an iron framework that effectively tied together a structure of stone bearing walls. This extended and carried to a logical conclusion the earlier use of iron components by the Corps for the distinctive encircling galleries of barracks and military hospitals which comprised an important feature of climatic adaptation in the West Indies, a topic which is discussed in the following section of this chapter.

Smith's proposal comprised a series of nine drawings with specifications.[153] In October 1824 he assigned Captain Brandreth to the job of working out the details.[154] Brandreth was in the West Indies 1816-1824 and again 1827-1828. He was to become the distinguished first Royal Engineer Director of Works for the Admiralty in 1837, and his experience with the Smith's system of cast iron frameworks for barracks was a critical formative influence in his career. The system was formally approved by the Board of Ordnance on 11 May 1825.[155]

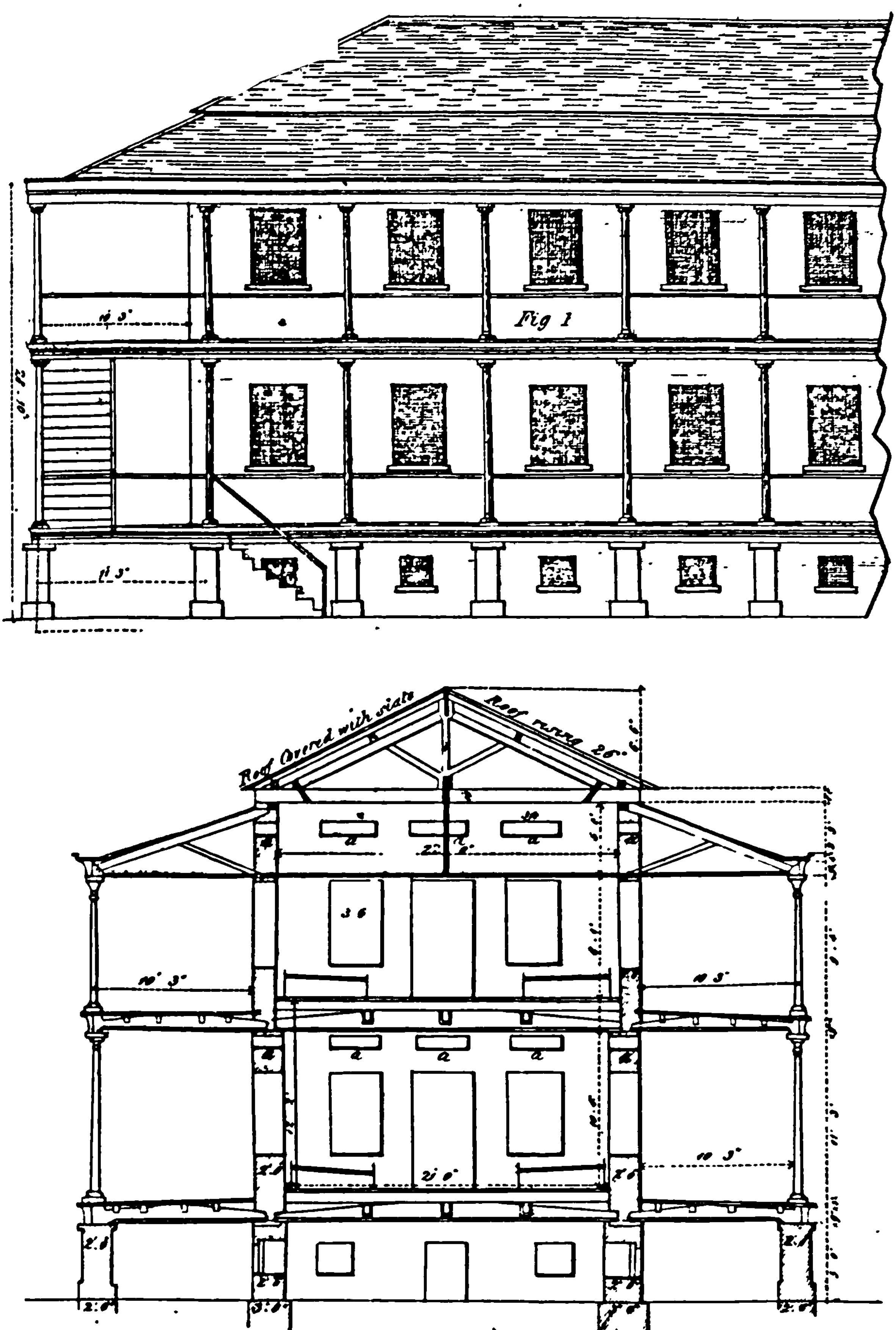
Nevertheless, it took the next three years to get the details worked out with the ironwork manufacturers, and Brandreth was stationed in Birmingham to see to this. In August and September 1825 Brandreth wrote to the Inspector General of Fortifications, General Gother Mann, explaining that he had made alterations in models of cornices, girders, joists and columns after observing castings at the foundry and taking the advice of Colonel Edward Fanshawe, Commanding Royal Engineer, London, who was responsible for planning a number of experiments on the iron work which Brandreth carried out. The experiments were crushing tests to determine the best section for cast iron elements.[156] Unfortunately, no mention was made of the ironfounder. Brandreth superintended the castings for a building designed by Colonel Fanshawe for Bermuda while engaged in work for Smith.[157] As a result of experiments made at the foundry, Brandreth slightly reduced the sections specified in Smith's original proposal. More importantly, he changed the method of connecting the parts of the iron work from flanges and bolts to dovetails and pivot joints, further secured with lead. Brandreth explained his reason for the change:

> "By this simple mode, bolts and bolt-holes, (which require nice adjustment), and the danger of any irregular pressure on flanges, are avoided. The junction of wrought iron and cast iron is also avoided, a circumstance of importance in a climate where the union of the two conditions or iron occasions greater liability to the decay of each, than when they are used separately."[158]

In June of 1826 Brandreth wrote to Smith concerning the nine drawings which comprised Smith's proposal and said that he had looked them over and corrected the errors which he enumerated. Eight of the nine are signed by Brandreth; the ninth, which is a general plan and elevation, is unsigned.[159] Five drawings based on the original nine were published by Brandreth together with an article on Smith's system in the Royal Engineer Professional Papers in 1838. The drawings show a barrack consisting of a basement and two floors, with a 10 foot gallery surrounding each floor of the 156 foot main building. Walls and piers were of brick or stone and the girders, joists, columns, and cornices or ranging plates, staircases, doors, jalousies and ventilators were of cast iron. The roof truss was hardwood but with wrought iron for the king post and transverse tie bar. Wrought iron was also used in stairway and gallery tie bars. The bridging joists in the main building floors were hardwood slotted into the cast iron girders, and the floors were covered with wood. Gallery floors were York flags. The roof was covered with slates. Interior floors were divided into rooms to accommodate 18 to 20 men each (the barracks was for 200 men). Partitions were formed with jalousies in the upper part. Barrack hospitals used the same cast iron framework system but were shorter and one was a single storey.[160] (See Figures 73, 74 and 75).

On 16 May 1826, almost exactly a year from the formal approval of Smith's system, Brandreth wrote to the Board of Ordnance from London submitting estimates for the cast iron work for hospitals at Antigua, Barbados and St. Vincent, and an officer's quarters at St. Lucia.[161] It was the Antigua project that appears to have been the prototype for the hospital system. Later that same month Brandreth acted quickly to reassure the Board of Ordnance of the soundness of Smith's plans after the failure of a cast iron roof at Maudslay's works in Lambeth. Brandreth investigated the accident and reported to the Board that it was caused, in his opinion, by the failure of the cast iron in tension due to "lateral pressure."[162] He assured the Board that the design for Smith's system was entirely different: "In the West India Iron Work all the bearings are horizontal or vertical, and the Section thro (sic) the building shows that there are every where Transverse ties to resist any outward pressure."[163]

In January 1826 Brandreth debated with the Board of Ordnance the possibility of extending the iron framework system to store houses. The Inspector General



Section thro' the line A B shewing the mode of Ventilating the Rooms a a a a. Apertures to receive the Ventilators

Figure 73 Colonel Smith's Barracks System for the West Indies : Elevation and Section

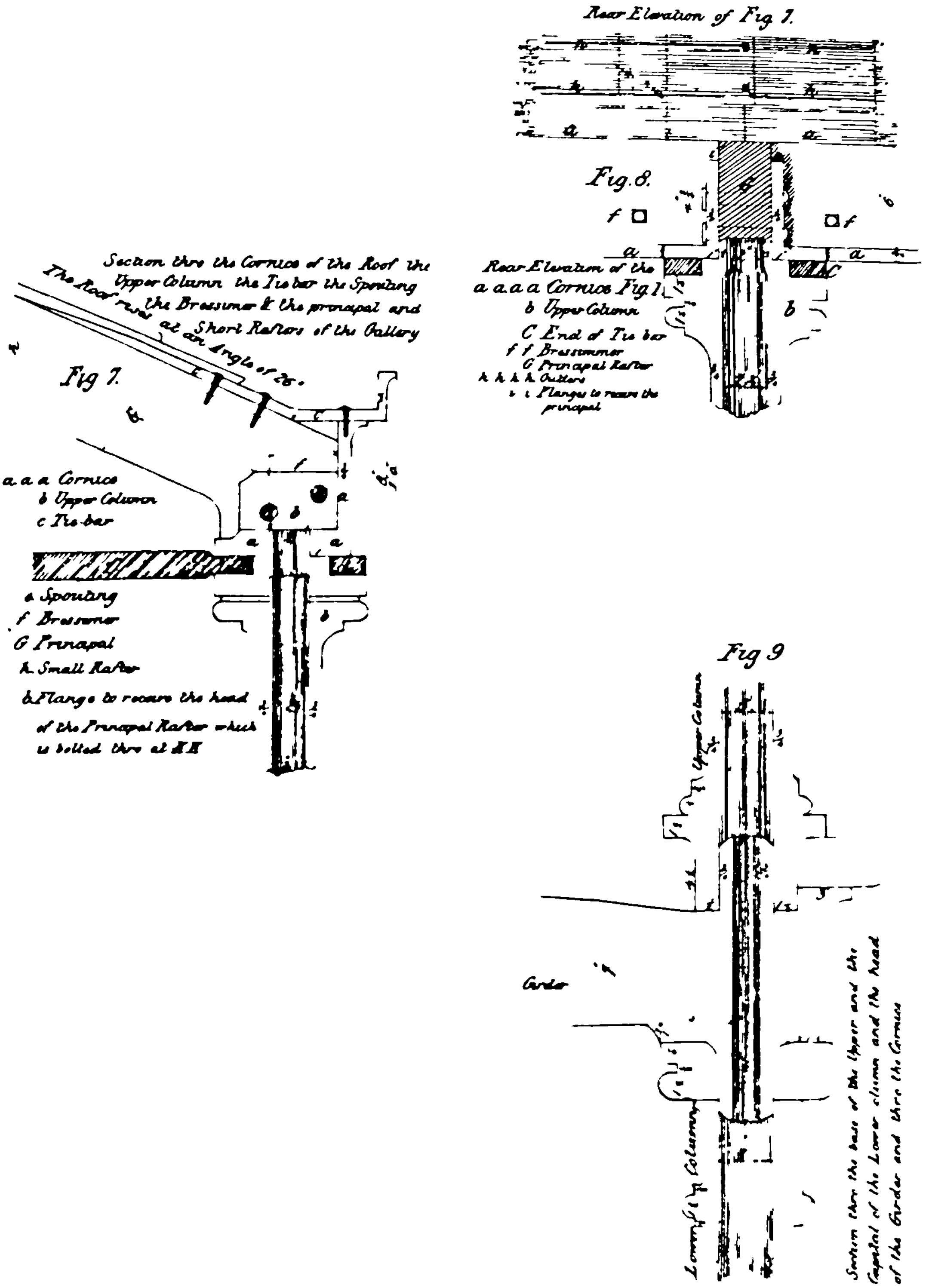


Figure 74 Colonel Smith's Barracks System : Sections Showing the Manner in Which the Iron Work Was Put Together

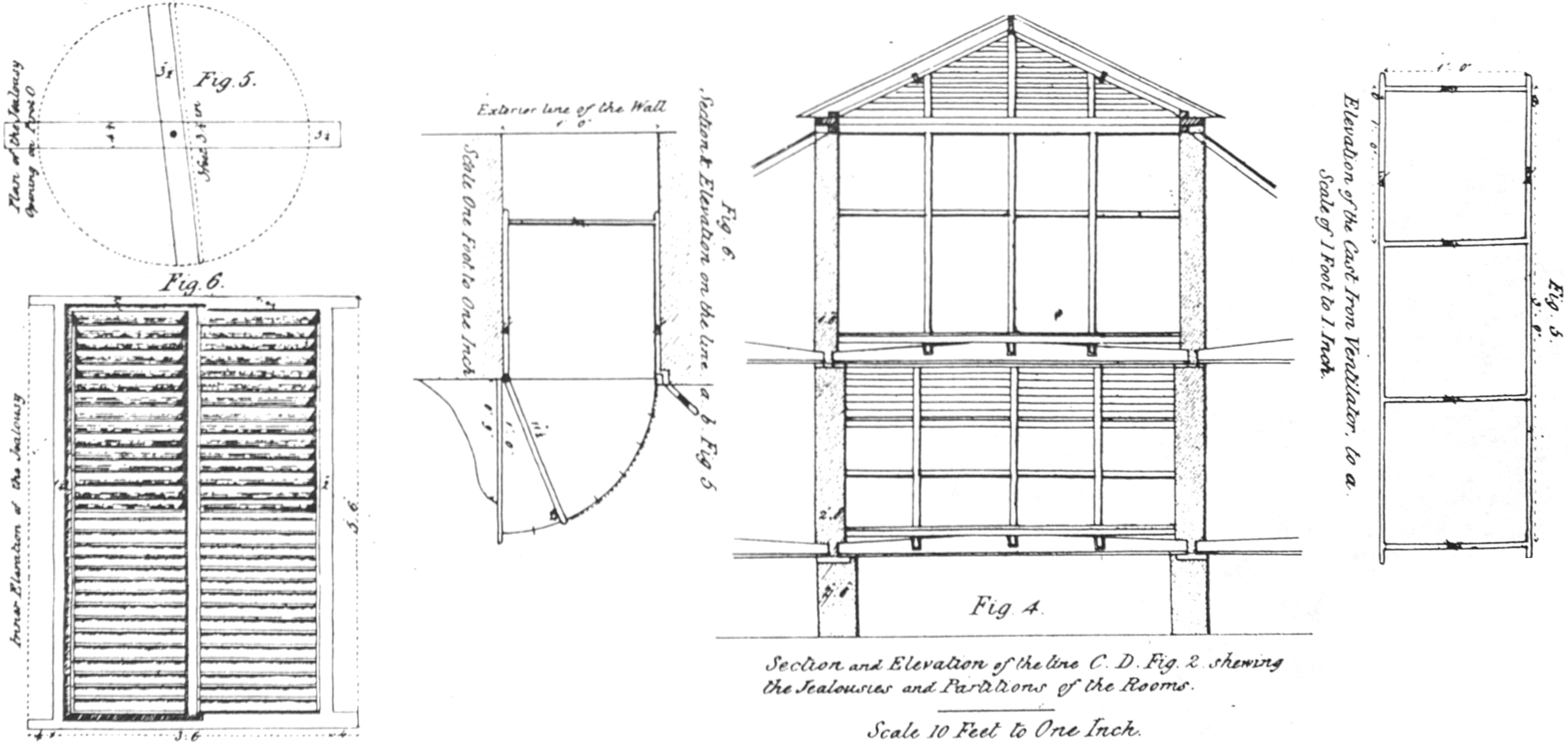


Figure 75 Colonel Smith's Barracks System : Cast Iron Jalousie, Ventilator and Ventilation in Room Partitions

of Fortifications had conveyed to him the Board of Ordnance's objection to his estimate for ironwork saying it would be too costly for a store house because new moulds and patterns would have to be made plus the expense of shipping. Brandreth replied that the same approach as the Antigua and Barbados hospitals and general barrack system could be used, it being necessary only to make "one new pattern of a building joist so that the girders may be brought nearer to each other in proportion to the weight they will have to sustain."[164] Brandreth said the new pattern would cost nothing and would serve in the making of castings for the building joists of all future store houses.[165] He urged the Board of Ordnance to let him go ahead with his proposal because in the West Indies "wood of every description is liable to injury from the insects, and vermin generated, attracted by the provisions."[166] It seems that the far-sighted Brandreth lost the argument since no evidence has been found of the adoption of his proposal.

In 1827 Brandreth supervised construction of the Antigua hospital. It was 66 feet long, 25 feet wide with an 11 foot gallery all around both of its two storeys.[167] Brandreth explained in a letter to Smith of 8 May 1827 that construction was proceeding well:

> "Not a single accident to any individual, or to any article, has occurred throughout the whole of these operations, nor any difficulty, or obstruction arisen, to retard the progress of the work."[168]

Significantly, he confirmed the success of industrial production of repetitive elements and the system of standardization and modular co-ordination:

> "At present I take leave to state that, both the bent, and strait (sic) joists are all fitted to their several girders, having their full inch bearing on each flange, and the Cornices (or ranging Plates) have accurately fitted round the whole building."169

The Barbados hospital was completed in 1828. Its ironwork was from the same moulds as that of the Antigua hospital, but it was one storey instead of two.[170] Smith, who was stationed at Barbados and supervised the work, was pleased with how well the parts fit: "I have had the parts put together, and find that they correspond so that in fact I may at once pronounce that its success is no longer problematical."[171]

In a letter to General Mann of 22 September 1828, Colonel Smith could hardly contain his delight at the success of his system:

> "... I am able to report that the Iron Work has succeeded beyond my most sanguine expectation. In an experimental Work, it would be hard to expect that perfection in all the most minute details should be stumbled upon in the first suggestions; hence some trifling deviations from the original Drawings were found by Lieut. Brandreth, when he superintended the castings, to be essential to the practical application of our propositions and some few improvements still remain to be brought forward; the latter, having the support of my recommendation, are to be submitted to you by Lieut. Brandreth, who is prepared to shew (sic) that they will not affect, in any important point, the present models."[172]

Smith ended his letter with a highly appreciative recommendation for Brandreth to the Master General and Board of Ordnance. This was only fair since it was arguably Brandreth who made Smith's system into a workable reality not only from the technical standpoint but also from the policy perspective as he steered the proposal through the often difficult to convince officialdom in the Board of Ordnance.

Following the success of the Antigua and Barbados hospitals, barracks were built at St. Lucia on Smith's system some time between 1829 and 1831.[173] Some of these still survive at Morne Fortune.[174] All of the iron framework buildings withstood the great hurricane of 1831 and another in the same decade.[175] Captain John Smyth, who served in the West Indies at the time that the iron framework buildings were first introduced, expressed a favourable opinion on the strength and economy of Colonel Smith's system:

> "... the great advantage of Sir C. Smith's iron frames, consists in their obtaining a more perfect system

> of tie through the stone-work and connextion (sic) of the parts with each other, than can be obtained, without considerable labour and expense, for roofs and galleries framed in wood."[176]

Barracks on Smith's system continued to be built into the 1840's. In January 1835 estimates were submitted to the Inspector General of Fortifications for three barracks for Barbados. The report was signed by Captain George Tait and Colonel Smith.[177] It is not known if this proposal was executed. Nevertheless, a barrack for 200 men according to Smith's system was erected at St. Ann's Garrison, Barbados seven years later. It was estimated by Lieutenant T.R. Mould in 1838, begun in January 1841 by Lieutenant H. St. George Ord and Mr. W. Walsh, Clerk of the Works, and completed in February 1842 at a cost of £8,998.[178] In this case the walls were of rubble masonry, with stock brick surrounds for openings, and the floors of the basement were of stock brick. It had pitch pine and white pine boarding for the roof with cypress shingles. Otherwise, the specifications were exactly to Smith's system design except that it had only a single room.

In 1845 Smith's iron framework barracks were still decidedly in the minority amongst the buildings of the various West Indies stations. At St. Ann's Garrison, for example, there were two brick barracks, a stone one and the iron framework structure built 1841-1842.[179] Even so, an important new building technology had been transferred to the Caribbean by the Corps over the two preceding decades. The situation in Dominica at Morne Bruce garrison in 1823 demonstrates the change. There were 35 Ordnance buildings at this station. These were mostly of stone, or brick and stone, with the exception of an old wooden soldiers' barrack and a new timber officers' quarters on stone foundation which was then under construction. For all that, the iron framework system with its distinctive cast iron gallery was not influential in the development of the typical Caribbean house type for English islands where ironwork verandahs are relatively rare.[180] The Corps' pioneering work in prefabrication was restricted it would seem to meeting the requirements of the British military establishment in the West Indies.

Barracks, Hospitals and Prisons in Tropical Lands

British military engineers were stationed from the mid-eighteenth century in hot and wet climates, especially India and the West Indies, where the adaptation or adoption of building forms and details became a practical necessity for the health and survival of Europeans. In the nineteenth century many of the techniques first developed by military engineers in the previous century were carried to new levels of sophistication by engineer officers and some fresh approaches added. The key issues were cooling, rain-proofing, and ventilation. Architectural responses in this case arguably depended more on native traditions than on advanced technology imported from Britain. Since military engineers were amongst the first British builders with some kind of formal education to work in many of the tropical colonies, their solutions to constructing healthy dwellings for Europeans are of considerable interest. These themes are explored in this section first in the West Indies, the Bahamas and Bermuda, and then in India. The chapter concludes with a brief look at the question of ventilation for prisons in the West Indies and Western Australia.

The high incidence of disease and rate of mortality were critical motivating factors for the Corps in the search for architectural solutions to the challenge of health in the West Indies. In the Caribbean theatre of the French Revolutionary and Napoleonic Wars, the British suffered 80,000 casualties, about half of them fatal, mainly from dysentry and yellow fever - twice the number killed in the Peninsular Campaign.[181] During the 1820's and 1830's military authorities were concerned with the causes which influenced the great mortality of troops in tropical climates. The miasmic theory of disease was a critical influence on the Corps' architectural contribution to measures for the prevention of disease and the control of mortality. Architecture was considered by one Royal Engineer to be even more important than the various dress and behavioural measures recommended by medical men to facilitate tropical seasoning and acclimatization in the early nineteenth century.[182] Captain Smyth explained:

> "That a proper system of diet, of exercise, and employment (which are generally too much neglected) clothing adapted to the climate for day and night, avoiding intemperance, unnecessary exposure to the night air (particularly during the unhealthy season) and a more frequent and regular relief from climates where the risk to life is so great, all form elements in the consideration of this subject I readily admit; but experience and observation convince me, that, with a comparative neglect of these, the health of the troops may be greatly preserved by the adoption of a system of building for barracks, or cantonments, adapted to, and varying with the localities in which they may be situated."[183]

Indeed, Smyth encouraged his brother officers to be more vigilant and inventive in this regard:

> "The attention of the Corps has been much called of late years to architectural requirements of convenience, strength and durability; but I do not think that sufficient attention has been given to vary the construction according to the circumstances of climate and situation, and a general and uniform system has been too much followed, not adapted to the many cases to which it has been applied."[184]

In the West Indies, Bahamas and Bermuda Royal Engineers employed a number of architectural devices in pursuit of cool, dry, well ventilated and miasma free barracks and hospitals. None of these were their invention, but the story of adoption and adaptation is important. These architectural devices included the verandah (gallery or piazza), the raised ground floor and large windows protected by jalousies (louvered shutters), all of which had been introduced in the late seventeenth century by European planters in the Anglo-Caribbean cottage.[185] The Corps also used cast iron ventilators and wire gauze mesh for windows which were products of the nineteenth century. In two cases especially, namely Colonel Charles Smith's system of barracks for the West Indies and Captain John Smyth's barracks at Demerara (1828-1833), we find interesting and revealing applications of these devices.

The open verandah, on either single or two storey structures, from eave to ground floor, usually encircling though sometimes on two or three sides only or simply on the main facade, was the standard practice in Corps designs for providing protection from the sun and partial protection from the rain.[186] (See Figure 73) However, some Royal Engineers preferred enclosed verandahs on one or more sides with jalousied windows.[187] Colonel Smith chose the former and Captain Smyth the latter approach. The subject of verandah design was much discussed by Royal Engineers serving in the West Indies. In one engineer officer's proposal, a gallery was incorporated within the main building structure rather than attached as an appendage. The masonry walls with jalousied windows were placed far enough apart to allow space for the gallery between them and the partitions which formed the walls of the rooms. These partitions were only carried up to a certain height in order to allow for circulation of air. This design was proposed by Captain West for a barrack erected in Jamaica (c 1838). It was claimed that this type of verandah provided better protection against wind and rain as well as for air circulation during the bad weather; it was also less liable to damage from hurricanes. Apparently West got the idea from buildings "adopted by planters in some of the West Indian islands."[188] (See Figure 76)

The most typical of the small vernacular Caribbean houses whose roots lie in the late seventeenth century had the whole structure raised from the ground to allow circulation of air which both cooled the air and protected the building's wood from insect attack.[189]

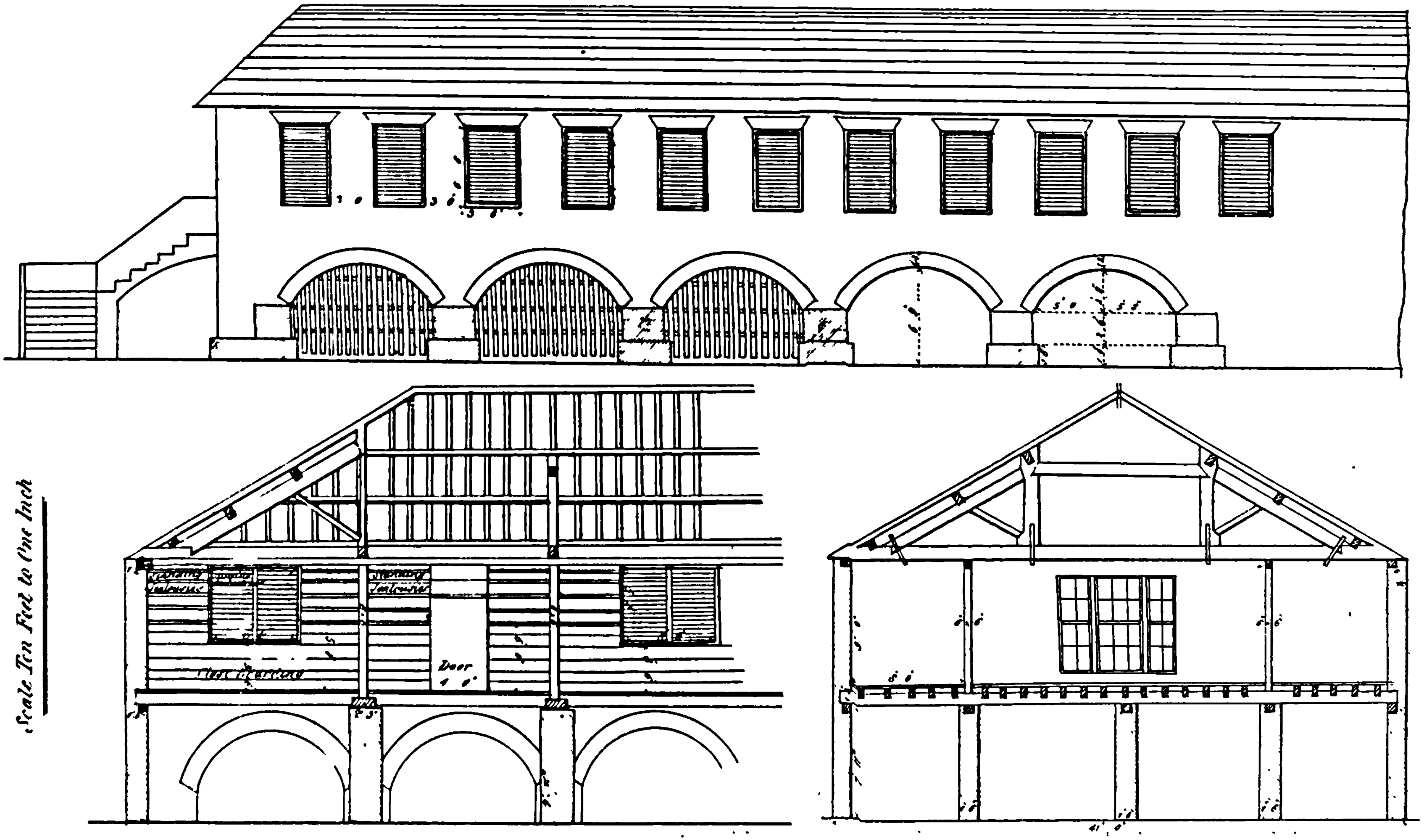


Figure 76 Captain West's Barracks at Lucea, Jamaica : Elevation and Sections

Royal Engineers adopted this technique throughout the nineteenth century. In some cases the ground floor was raised almost a whole storey on stone arches which created a large vaulted space below.[190] Most often, however, the ground floor was simply raised on stone or brick pillars a few feet off grade.[191]

Large windows were standard but methods of covering them with jalousies varied. Cast iron ventilators which were fitted in masonry walls were used to supplement window ventilation. Doors also had jalousies. In the Eveleary Barracks (c1830), George Town, Demerara, the officers' quarters had glazed double hung windows with sliding wooden jalousies provided underneath the sashes, and the gable end doorway also had jalousies. The soldiers barracks had windows fitted with cast iron jalousies which could be opened by pivoting on a central bar, and were also fitted with cast iron ventilators on the gable ends of the building on both storeys.[192] Both the cast iron jalousies and ventilators seem to have been pioneered in Smith's prefabricated cast iron frameworks. In an officers' barracks and hospital (1838) in the Bahamas, Captain Alderson used casemate windows rather than sash windows because the latter gave way too early from decay, in his experience, and the former he found better for air circulation because "the whole or a small portion of the Window may be opened as required."[193]

The jalousie was universal as the method of blinding the sun, letting in air and keeping out rain from openings. Initially these were of wood but cast iron was common by the 1830's.[194] All the same, Brandreth made an interesting proposal in 1830 for the introduction of copper wire gauze in openings as protection against malaria bearing mosquitos as well as miasma. He suggested that the gauze be put in the cast iron window frames then in use in place of the jalousie louvres.[195] In 1838 he urged the adoption of gauze in an article in the Royal Engineer Professional Papers and explained that "notwithstanding the precautions of raising the ground floor four or five feet, surrounding the building with galleries, and the ordinary modes of ventilation, the influence of the malaria has been very fatal."[196] Brandreth thought a mesh or interstice of 1/24th of an inch would be best and recommended copper over iron because of the exposure of the West Indies' buildings to the sea. He quoted Dr. Arthur of the army medical staff as the authority on using wire gauze to prevent or mitigate the effect of marsh malaria. Brandreth also advocated the use of mosquito nets in barracks and hospitals since they had not yet been adopted in the West Indies for soldiers' barracks.[197] His proposals were endorsed by Colonel Smith and by Dr. Arthur. Copper wire gauze had also been recommended by Dr. Trail, Professor of Medical Jurisprudence at Glasgow, in response to a request from the Horse Guards for information on preserving health in tropical climates.[198] It was used in several hospitals in Italy.[199] Brandreth also thought that gauze blinds would provide for a more moderate and equable diffusion of wind throughout the barracks since soldiers were in the habit of closing jalousies on the windward side thus interrupting the free circulation of air.[200] His proposal was apparently adopted for a new hospital at Demerara in the late 1830's.[201]

Colonel Smith's prefabricated iron framework barrack system incorporated a variety of devices for climatic adaptation. Barracks had a raised ground floor, open verandahs, cast iron jalousies with pivot opening in the windows, as well as cast iron ventilators with adjustable doors on the intake to control air flow. The roof was slate covered for thermal insulation unlike the usual barracks in the West Indies before the introduction of Smith's system which were covered with wood shingles on laths.[202] (See Figures 73 to 75).

No evidence has been found, however, on how well Smith's design worked in promoting health. Nevertheless, in Captain John Smyth's barracks at Demerara (1828-1833) the design's effectiveness was documented. The barracks had enclosed encircling verandahs. Windows were glazed and opened by moveable jalousies only on the sides and ends facing the sea. Roofs were boarded and slate covered with louvered ventilators at the ridge and jalousies in the gables. Smyth's system managed to reduce the death rate from a high of 22% in 1828 to a low of 5 1/4% in 1832 during his six years at Demerara.[203] Smyth had taken the principles for ventilation and temperature control from his observations of native 'trooly' sheds. As he explained:

> "The huts formerly built for the negroes in Guiana, of hardwood, and thatched or covered with trooly palm, afford nearly all the advantages for which I seek. They were lofty, with steep roofs, and, from the palm-leaves much overlapping each other, were perfectly dry; were kept at a uniform temperature, cool by day and warm by night: good ventilation was obtained in them..."[204]

Some Royal Engineers realized that local vernacular traditions in building often worked far better than construction practices suitable for English conditions.

In India the story of the *engineer officers'* response to the challenge of designing dwellings for Europeans in a tropical climate begins with the matter of the bungalow. King has traced the origins of the bungalow to the adaptation of the indigenous Bengali hut by military engineers of the East India Company in the eighteenth century. The salient characteristics of the type were a free standing and single storey structure, on a plinth, and with pitched, thatched roof and a verandah. It was sited in a large compound located at a distance from other buildings or places of settlement thus affording a controlled environment.[205] Later in the eighteenth century the military engineers in India introduced architectural ideas to transform the native design into the more substantially built, flat roofed 'classical' bungalow used particularly to house Company officials including army officers on the cantonment. This evolved by the mid-nineteenth century into what was widely known as the Public Works Department's 'Military Board' style which became a standard form for official government buildings.[206]

The work of the nineteenth century military engineers in India therefore was one of extending and modifying the adaptive work of earlier times. Even critics of the Royal Engineers in the mid-Victorian period acknowledged their contribution to architecture in India. In an address to a meeting of the Royal Institute of British Architects in 1867, T. Roger Smith, an architect who had advised Henry Scott on acoustics for the Albert Hall, said of the Corps' activities in the India Public Works Department:

> "... any one who has had experience of it will fully understand that neither architecture nor building is the proper function of military engineers, and that it hardly seems giving military officers their proper position to employ them upon the carrying out of any work except from designs prepared by the officer engaged. At the same time that I make these remarks I must add that this corps contains individual officers who have distinguished themselves in India as architects by their designs and executed works; and they have been pioneers in the work of constructing in that country buildings for European use."[207]

Notwithstanding the beneficial effects of constructional features such as the verandah and raised ground floors, the main method of controlling the thermal environment of the bungalow and other Anglo-Indian buildings of the nineteenth century was by canopies, blinds, screens and various devices for fanning the air.[208] The engineer officers serving in India made use of these, occasionally with some inventiveness. The 'jhilmil', a projecting wooden fretwork canopy for windows which had no glass, just louvred shutters, was used effectively both as a cooling device and as an architectural feature by Colonel T. Cowper in the Town Hall (1825), Bombay, which Davies has called "the finest neo-classical building in India..."[209] Jhilmils as well as louvered screens between columns enclosing a central verandah were used by Major W.N Forbes in the 1820's in his Greek revival Mint Master's House in Calcutta.[210]

The issue of ventilation and healthy buildings was much more important, however, in barracks and hospitals designed by engineer officers. This matter was sharply focussed by the investigations and report of the

Commission on the Sanitary State of the Army in India, 1859-1863. The mortality rate of British soldiers serving in India was staggeringly high compared to experience at home and abroad. Barrack conditions were responsible for much of the problem according to the Commission.[211] With few exceptions, the barracks in India at the time of the Commission's enquiries were constructed as a hut with doors on opposite sides protected by verandahs. In some of the recent ones, the centre hut was raised some height on arches dividing the centre and two sides. The Commission was critical of the fact that very few barracks were raised off the ground.[212] Doors and windows were the main means of ventilation, the openings being covered either by venetian blinds or shutters. Many of the barracks had louvres in the roof for ventilation. The Commissioners concluded that ridge ventilation, together with free admission of air under the eaves, was the best solution to the problem of efficient ventilation of barracks in India.[213] Similar suggestions were made for the ventilation of barrack hospitals.[214]

The usual means of cooling the air in both barracks and hospitals was by 'punkahs', a heavy cloth hung from the ceiling and fixed to a wooden beam and pulled to and fro by natives, and in very hot stations also by 'tatties', mats of grass fitted in doors or windows and wetted down by servants to moderate hot breezes.[215] Also used at some very hot stations were 'thermantidotes' which operated like a winnowing machine in which air entering to supply the fan was made to pass through a wetted mat.[216] These devices, however, were not unique to barracks and military hospitals in India.

Not all the Royal Engineers stationed in India agreed with the observations and recommendations of the Commission. Moreover, there were isolated examples of barracks which displayed a much higher standard of design for climatic adaptation than the barracks visited by the Commissioners. The major objection appears to have come from Public Works Department engineer officers from Upper India. Major J.G. Medley, editor of the Professional Papers on Indian Engineering and a member of a committee on ventilation and the cooling of barracks, complained that only one member of the Commission had ever been in Upper India and that "the recommendations of the Commission lay such stress on the evils of dampness, that it is clear they had the climate of Bengal in view, rather than that of Upper India."[217] Medley included in the first volume of Professional Papers on Indian Engineering (1863-1864) an article on the European Barracks, Nowshera, Punjab, which had been erected in 1855 by Lieutenant F.S. Taylor. He said of this building: "It is believed that no Barracks, as yet constructed in India, are better built or surpass these in comfort and healthiness."[218] This single storey barrack featured double verandahs (inner 12 feet, outer 10 feet) with 22 foot high main walls, and was topped by a pitched roof on iron trussed frames which was not ceiled. It had a ventilator at the ridge, windows hung on the centre, punkahs hung on iron rods at a height of 15 feet from the floor, and in the inner verandah the iron tubular beams were left open at the extemities to admit a current of air through them into the building.[219] The constructional and mechanical arrangements for cooling and ventilation in this building were indeed works of engineering virtuosity. (See Figure 77)

As discussed in Chapter 6, Joshua Jebb, Surveyor-General of Prisons and Inspector of Military Prisons, made a significant contribution to ventilation and heating services technology for prisons in the nineteenth century. It is interesting to observe what he thought about the adaptation of his ideas in the tropical colonies and how this compared with the design ideas of his brother officers stationed there. For the West Indies, Jebb suggested a two storey structure with encircling verandahs, with the cells placed back to back and doors facing the galleries. For ventilation, he specified iron ventilators, hooded to prevent transmission of sound, placed in the cell walls above the doors as well as hollow iron beams for the first floor and a passage above the ceiling, both communicating with the outside atmosphere and with connecting flues for ingress and egress of air to cells. He also suggested a passage beneath the ground floor for

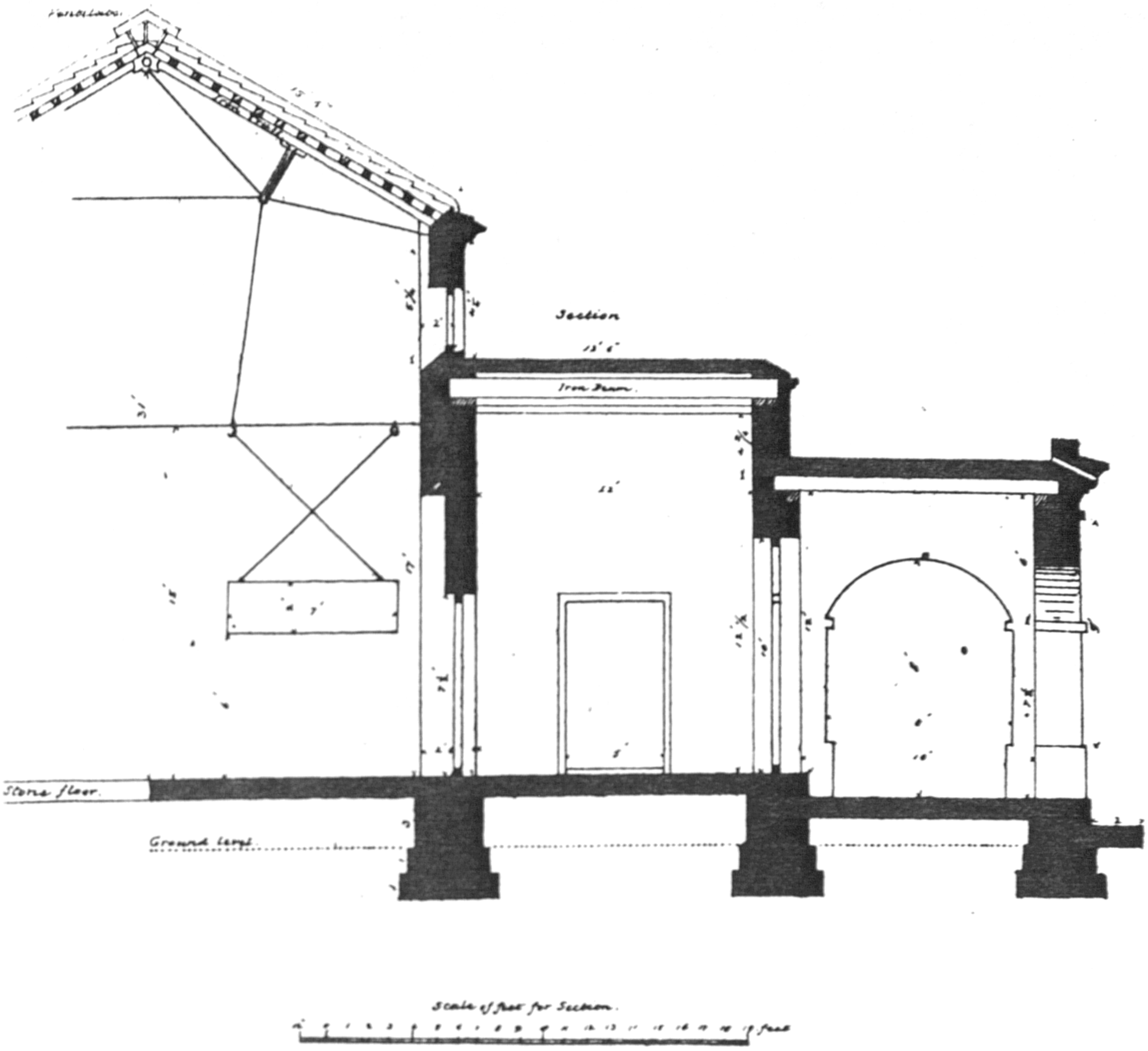


Figure 77 Nowshera Barracks, India, 1855

the circulation of air under the cells.[220] (See Figure 78)

The West Indies provides an interesting example of the interaction of Jebb and the Royal Engineers stationed in the colonies on the matter of prison design. The Mutiny Act of 1844 authorized for the first time the use of military prisons.[220] In July 1845 Lieutenant-Colonel Thomas Moody (- 1849) designed two military prisons for St. Ann's Garrison, Barbados - Provost or Barrack cells and cells at the dockyards. The Provost cells were arranged on opposite sides of a walled courtyard in single storey blocks with shed roofs. Each cell was 7 feet by 6 feet 10 1/2 inches with a door facing the courtyard. It had a small window over the door and an air brick under it, and a small vent was located on the opposite wall. The cells rested on the ground with an earth floor. The cells at the dockyard were arranged in a single storey block with shed roof. Doors faced a walled courtyard. The cell was 8 feet x 6 feet and for ventilation had only a single window over the cell door, hooded by sheet iron on the outside to prevent the prisoner seeing out. The boarded floor rested directly on the ground.[221]

Jebb was asked to comment on Moody's designs in his capacity as Inspector General of Military Prisons. Jebb wrote on 5 September 1845: "Under any circumstances the external walls should be protected by Galleries, and there should be free ventilation in every direction."[222] Jebb recommended that "a new Provost Prison, of a construction adapted to the Climate should be created, containing sufficient accommodation for soldiers sentenced to imprisonment by a Court Martial."[223] Notwithstanding a detailed report by Moody which argued for his design, the Board of Ordnance ordered a new prison design to be prepared on the request of the War Office dated 16 September 1845. It seems that Jebb won the day but records of the new design appear not to have survived.

Royal Engineers in Western Australia did not adopt Jebb's ventilating and heating arrangements for English convict prisons since the climate made these

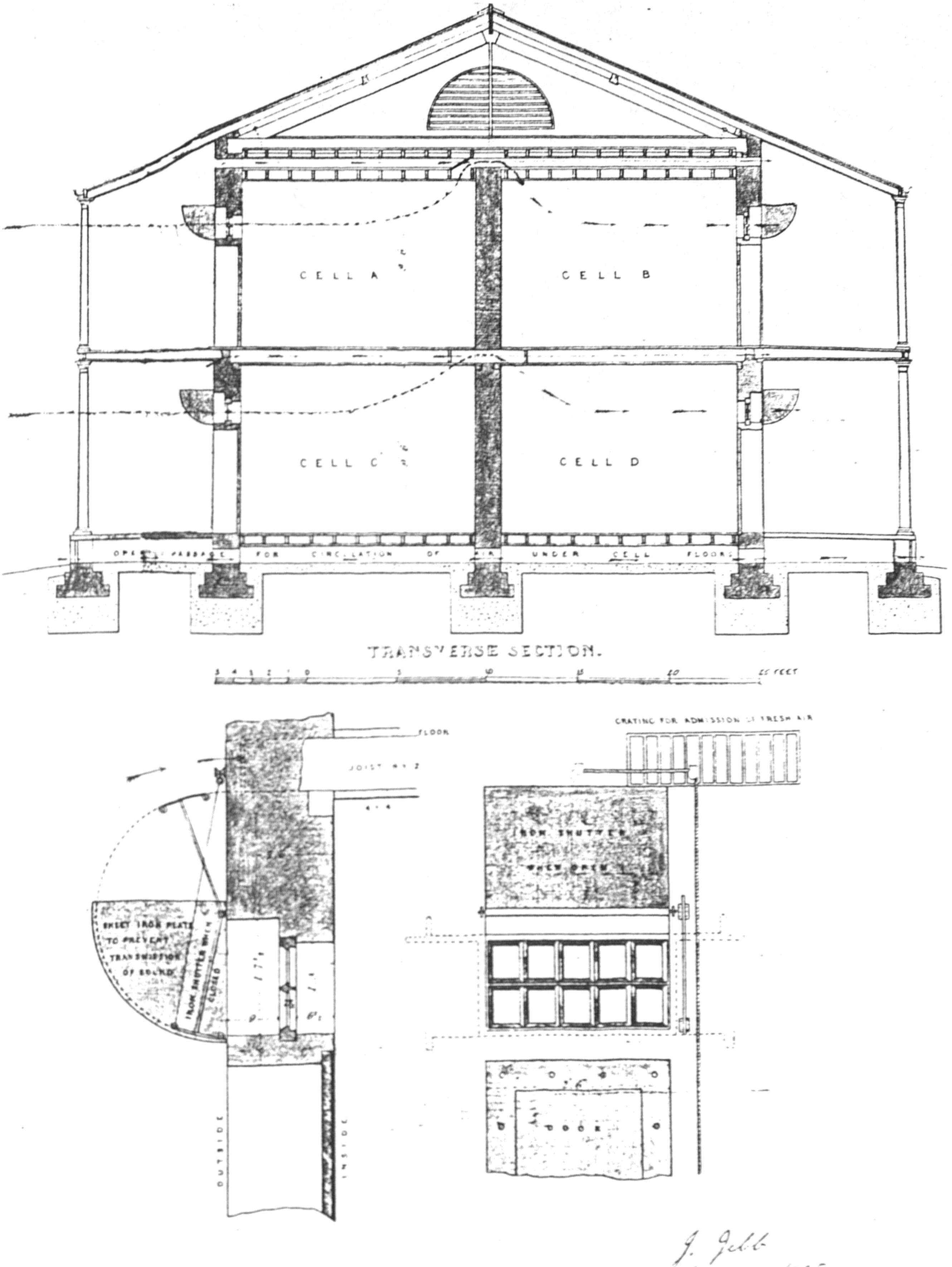


Figure 78 Jebb's Principle of Prison Construction for Tropical Climates

inappropriate, but little thought went into a suitable system and cells were poorly serviced by comparison. In Freemantle Prison (1852-1857) Captain E.Y.W. Henderson used stone walls for 7 foot by 4 foot sleeping cells, the size used at Portland Prison. Jebb had recommended the prefabricated corrugated iron system of internal walls used at Portland which had a decided advantage for ventilation and free circulation of air. Henderson's reason for stone was that the material was ready at hand and would save on construction expenses.[224] In this case the engineer officer on the spot seemed to be more concerned with cost effectiveness than the optimum efficiency in ventilation. Jebb was also concerned with economy but arguably he had the two in better balance. The matter of prison design in the colonies illustrates that advanced technology was not always embraced by Royal Engineers stationed in foreign territories even when it was proposed by brother officers at home.

9. CONCLUSIONS

A number of conclusions can be drawn from the present study of the Royal Engineers and the development of building technology in the nineteenth century. These are examined below under three general headings. The categories of analysis are not mutually exclusive and there is necessarily some overlap. First to be discussed are the fundamental formative factors which shaped the Royal Engineers' position and contributions. These include the interaction of their formal education and on-the-job training, the climate of support and incentive in their duties and their relationships with others. Next is an appraisal of the Royal Engineers' contributions made with reference to the five evaluation criteria delineated in the introduction and according to three levels of achievement - the Corps, the civil office or station, and the individual. Finally, some observations are offered on the nature of nineteenth century building technology, architecture and society.

Formative Factors

Formal Training Versus On-the-Job Experience

Compared with civil engineers and architects, the Royal Engineers had a superior theoretical education but an inferior practical training. They learned principally on-the-job and arguably best in civil employment as opposed to military duty. Their sound theoretical education, albeit not as good in some respects as foreign military engineers, especially the French, seems to have been a major factor in their considerable versatility and ability to learn a succession of new jobs quickly and well. It also served as excellent background for an experimental aptitude. The case of the Corps seems to prove that learning by doing brought results - the basis of British achievement in the nineteenth century.

The East India Company engineer officers were arguably better trained in practical architecture and engineering because they served a type of apprenticeship immediately following their formal education, unlike the Royal Engineers who went straight into regular duty. In some cases this had an effect on their design capabilities. For example, whilst important contributions were made to the development of structural iron in the naval dockyards by Royal Engineers working for the Admiralty Works Department, notably Brandreth, Denison, James and Beatson, it was a former Bengal Engineer, Godfrey Greene who designed distinguished buildings, especially the Boat Store at Sheerness. Engineer officers in both the Imperial and Indian corps constantly sought improvement through on-the-job training and a tradition of experiment, the results of which were reflected in their professional journals. On the other hand, there is little evidence of interest in the pursuit of further theoretical education in mathematics and science.

In the colonies, engineer officers had to adjust their thinking and practice based on English training and conditions to the requirements of local environments. By and large they made the adjustment well. They learned the local ways of building and modified advanced technology which they brought from Britain or adopted from European or American practice. Sometimes they had trouble convincing fellow officers and officials in London of the need to adapt materials, structural forms, plans or services. The case of asphalt in British North America is a good example. On a few occasions, however, it was the view of Royal Engineers at home that proved more enlightened. Perhaps the best example is the debate between Jebb and Moody over the design of military prisons in the West Indies. Theory and practice were much influenced by differing standards of construction as well as expectations of comfort and convenience at home and abroad.

Support and Incentives

Promotion for Royal Engineers in the army was by strict seniority only and therefore there was no incentive to seek advancement by meritorious works. Nevertheless, no explicit evidence has been found that this situation discouraged excellence. The call of duty seems to have been a strong substitute. It was best articulated by Pasley and Denison but others bore witness to this too.[1] The motivation of duty was particularly strong in military works both for the War Office and the Admiralty. Changing technology of war, especially in artillery and naval vessels, furnished not only a perceived threat which had to be thwarted but also a professional challenge.

Army officers' pay was not enough to live on and civil service remuneration, although better and desirable enough for engineer officers to seek, did not constitute a significant incentive to pursue excellence. It was not uncommon for army officers during the nineteenth century to be engaged in private business. Scott and Baddeley patented their discoveries with new cements but neither became rich as a result. Moreover, there is some evidence that the practice of Royal Engineers patenting inventions in the expectation of profit was not encouraged by the Inspector General of Fortifications and that it was resented by competing interests in the private sector. One of the railway inspectors, Tyler, was a director of a railway company while still an inspector, but there is no evidence that this affected his work. It seems safe to conclude, therefore, that financial gain did not constitute a major motive for Royal Engineers' contributions to building technology development.

From the perspective of social motivations, Royal Engineers were less likely to be driven to perform and excel in built works as a means of gaining public recognition leading to a rise in status than were civil engineers and architects. They already enjoyed high standing by virtue of their military position.

Nevertheless, no concrete evidence has been found to suggest that engineer officers were complacent because of their position. The Royal Engineers' status allowed them to work on a level of complete social equality and sometimes superiority with other building professionals. Though this did not guarantee respect from their contemporaries, it was usually forthcoming. It has been said, however, that engineer officers in the India Public Works Department were snobbish and condescending towards civil architects, although much of this may be a reflection of professional jealousy on the part of the latter.[2]

The army regulation specifying that an engineer officer could be seconded to civil service employment for only ten consecutive years and then had to rejoin military service or resign his commission was a retrograde rule as far as encouraging long term commitment and special achievement in civil works. Cole was an important critic of this regulation. Hawkshaw and others commented on the ill effects of the rule on the railway inspectorate. Even so, there is little evidence that the precept seriously retarded the contribution of the Corps or individual engineer officers to building technology development. An officer could always choose to resign his commission. Scott did, for example, and made important contributions after leaving the Corps.

The Royal Engineers were supported by clerks of the works for barrack and military hospital construction and to an extent in fortifications too. This was much criticised by contemporaries as reducing the engineer officers' incentive and competence. It will be remembered, however, that the situation was different in India where the engineer officers were clearly in charge of the design and construction process and clerks of the works entirely in a subordinate role. Moreover, critics of the Royal Engineers also pointed out that constant moving of officers from station to station, with only a few years in each appointment, discouraged familiarity, continuity and commitment in built works. There is something in these criticisms, but reliance on clerks of the works and short term assignments did not prevent talented individuals from making important contributions to progress in the technology of building.

The public treasury was the usual patron of the Corps' works and it was unfailingly niggardly with project budgets. Working under severe financial constraint forced Royal Engineers to be experimental and ingenious in finding cheap but effective solutions. Sometimes they fell short of the mark and produced shoddy buildings but often design excellence was achieved, especially in the choice of materials and their employment. Fowke was probably the best example of a Royal Engineer's ability to combine economy and effectiveness.

Relationships with Others

The Royal Engineers' relationships with others included: those to whom they referred as authorities on particular technical subjects; those they consulted for opinion and advice; those they contracted and directed or superintended and for whom they set the design brief or provided constructive criticism in the design, manufacture or construction process; those they collaborated with in design, experiment or other act related to building or building materials; those who assisted them in carrying out experiments, preparing drawings, specifications and estimates; and those from whom they took orders. These people represented a wide variety of occupations: some were fellow engineer officers, men of the Royal Sappers and Miners or civilian clerks of the works; others were civil servant colleagues; a few were scientists, inventors, mathematicians or technical writers; many were engineers and engineering contractors; a few were architects, builders or building contractors; several were manufacturers; some were from the medical profession; and finally, there were some foreign military engineers as well as officers of the Royal Artillery and Royal Navy.

There were a number of collaborations between Royal Engineers but one stands out above all others in significance - C.F. Smith and Brandreth in the system of prefabricated cast iron barrack frames for the West Indies. Other examples were: Brandreth and Fanshawe in testing castings for barrack frames; Pasley and Streatford, Scott and Moncrieff as well as J.T. Smith and Sims in testing cement and limes; Best and Elliot in testing Malay woods; Goodwyn and Forbes in model tests for suspension bridges; and Henderson and Wray on Freemantle Prison. With the notable exception of the Smith/Brandreth team, engineer officers did not often produce meritorious works in collaboration though they commonly shared ideas, information, attitudes and opinions. This may be partly explained by the frequent moving from station to station which rarely allowed enough time for teamwork to develop to maturity. It was more likely to happen in the colonies because engineer officers generally had only their army and civil servant colleagues to work with whereas at home collaboration was overwhelmingly with top people in the private sector.

The Royal Sappers and Miners provided important assistance in materials experiments and testing, and some deserve recognition in the undertaking of built works. In cement experiments, Pasley acknowledged the help of Menzies and Down, and Scott credited Hartley and Grey. Henderson, Du Cane and Wray worked closely with the 20th Company of Royal Sappers and Miners in Western Australia in the construction of convict establishments and bridges as well as other public works.

Clerks of the works, especially at home, had a leading role in the design of barracks and military hospitals. They were occasionally responsible for important designs on their own, the best example being Stent's early pavilion hospital proposal for Aldershot. The most important work of collaboration with clerks of the works was that between Pasley and Howe in cement experiments and teaching at the Royal Engineer Establishment. A notable team of engineer officers and a clerk of the works was Henderson, Wray and Manning in Western Australia. Their most important work was Freemantle Prison.

Engineer officers' relationships with fellow civil servants were of considerable importance especially in the Admiralty Works Department and in the Science and Art Department. These mostly comprise collaborations with building professionals or technicians but sometimes were with persons whose expertise lay in other fields, including public administration. A number were of the highest order of significance in shaping engineer officers' contributions to building technology development. Scamp's collaborations with Greene in pioneering works in structural iron in the naval dockyards, including the celebrated Boat Store at Sheerness, and later with Clarke in the early large scale use of Portland cement for mortar and concrete in the Portsmouth and Chatham dockyard extensions are of especial importance. Other examples of collaboration in the Admiralty Works Department, though of a lower order of significance, were that of Bernays with Denison in works of iron, and later with Clarke and C. Pasley in the use of Portland cement concrete for the Chatham dockyard extension project. In the Science and Art Department the most important collaborative works were those of Fowke and Sykes in terracotta, and Fowke and Grover in iron. Fowke's architectural assistants helped too, but mainly on stylistic interpretation and decorative details rather than building technology. Fowke also worked closely with R. Redgrave on the design of lighting for picture galleries. Scott collaborated with Gamble and Townroe on terracotta, following the Fowke/Sykes team formula, but his closest assistant was G.R. Redgrave who helped with a wide variety of building matters at South Kensington. A notable one-off collaboration was that between Galton and Mennie in the Herbert Hospital. The most significant relationships with a non-building expert were those of Cole with Fowke and later Cole with Scott at South Kensington. Another example was Jebb and Crawford and Russell in the design of prisons.

Relationships with scientists, mathematicians and technical writers were interesting, although few were of critical importance. Both Pasley and Scott consulted Faraday on cement experiments, and Scott also sought the advice of Able in this regard. Grain consulted Able on the insect resistance properties of jarrah timber. The most important collaboration was that of James and Galton with Willis on experiments for the Royal Commission on the Application of Iron to Railway Structures. Warren de la Rue was a partner in Scott's sewage cement company.

Royal Engineers' relationships with engineers were many and varied and often of critical importance in contributions to developing building technology. In this are included civil engineers, engineering contractors and building services engineers. At the naval dockyards, Denison's proof testing and design alterations for Baker and Sons' wide span composite iron slip roofs at Portsmouth and Greene's collaboration with Fox, Henderson are very important. Of even greater significance is Scott's work in the Albert Hall roof with Fowler, Hawkshaw, Grover and Ordish, particularly the last engineer. Jebb's work with Haden in Pentonville Prison and Scott's with W.W. Phipson in the Albert Hall were important collaborative achievements in heating and ventilation. Pasley and M. Brunel appear to have followed closely each others work with reinforced brick beam experiments. Railway inspectors collaborated with civil engineers in important investigations and reports. Examples include Simmons and Walker on the Dee Bridge disaster and Yolland, Hawkshaw and W.H. Barlow on a steel strength standard and later a wind design factor for railway bridge construction. Hawkshaw and Hayter worked closely with Royal Engineers on the design and construction of foundations for the Spithead iron forts. J.T. Leather also worked with Royal Engineers on coastal defences of the Commission Forts era, and he and E.P. Smith played an important role in the use of Portland cement by Clarke in the Portsmouth dockyard extension. And finally, in the colonies the most important collaborative effort was that of Dredge with the Bengal Engineers, especially Goodwyn, in the design and manufacture of taper chain suspension bridges.

Architects played a relatively insignificant role in working with Royal Engineers on building technology developments. They mostly helped with the design of building facades and decorative details, a good example being Barry's work on Jebb's Pentonville Prison. Nevertheless, in working with Scott on South Kensington Museum buildings, J.W. Wild contributed to planning interiors as well as stylistic interpretation and decorative details on exteriors, and advised Scott on the velarium for the Albert Hall roof which affected the ceiling's appearance and acoustics. Even so, the relationship between Wild and Scott was exceptional.

Builders and building contractors played only a small role too. A couple of examples merit mention though. Most important was Ranger's collaboration with Harding in the experimental concrete model casemate at Woolwich. Also of interest was Kelk's work in the manufacture and erection of Fowke's timber truss roofs for the 1862 International Exhibition building.

Manufacturers were of especial significance. Pasley was in close touch with Frost, his rival in the early development of artificial cement. Scott worked closely with Lee, Son and Smith in making practicable the commercial manufacture of his selenitic cement. Others also took up the manufacture of Scott's cement. Scott and his partners became manufacturers in Scott's Sewage Cement Company. Grissell played an important role in Greene's virtuoso works in iron in the naval dockyards, especially in the Boat Store at Sheerness. Inglis and English collaborated with Brown and Company in developing large, thick wrought iron plates for fort shields. Fowke worked indirectly with Handyside in the conservatory for the Royal Horticultural Society at South Kensington. In works in terracotta at South Kensington, Fowke employed Blanchard, and Scott used Gibbs and Canning. Together they helped advance the art of construction in this new material.

Relationships with the medical profession concerned the design of healthy prisons, barracks and military hospitals. Jebb worked with Dr. Rees, medical officer of health at Pentonville, in testing the effectiveness of the model prison's ventilation and heating arrangements for cells. Brandreth used Dr. Arthur as an authority to endorse his proposal for copper mesh window coverings to counteract malaria and 'miasma' in the West Indies' barracks. Dr. Parkes tested Galton's ventilating stove. But most important was the collaboration of Galton, Sutherland and Nightingale in the design of barracks and military hospitals, especially in the promotion of the pavilion principle for hospital planning, construction and services. Collaboration furthered the interests of both the building and medical professions.

Finally, Royal Engineers had some interesting relationships with foreign military engineers and with colleagues in the Royal Artillery and the Royal Navy. Pasley and Scott both consulted the works of General Treussart of the French military engineers in their experiments with limes and cements, and Scott used Treussart as well as Colonel Raucourt de Charleville as authorities on concrete construction. Inspector General of Fortifications, Burgoyne, corresponded with General Totten of the U.S. Corps of Engineers, an expert on iron in fortifications. Fox consulted General Q.A. Gillmore's publications in undertaking works in Portland cement concrete at Bermuda. Gillmore of the U.S. Corps of Engineers was a leading American authority on the subject of limes, cements and concrete. General Morin, a French military engineer, tested Galton's ventilating stove. Captain Schuman of the Prussian Engineers lectured at the Royal Engineer Establishment on iron fortifications. Nelson got his idea for a laminated timber arch for a proposed bridge in South Africa from the practice of the Royal Prussian Engineers which he had observed while on a trip to Germany. Last, but not least, Royal Engineers worked with the Royal Artillery in testing a model concrete casemate at Woolwich, and with the Royal Artillery and Royal Navy in experiments with iron shields for warships and forts. This all goes to show that during the long Victorian peace there was a good deal of exchange of technical information amongst European and American military engineers as well as between various military services in Britain on the subject of building and not necessarily restricted to fortifications, and that it had some important influences on the Corps. It would be interesting to know how much the Royal Engineers influenced foreign military engineers. The only hard evidence found relating to this question was concerning Pasley's 1838 publication on limes and cements, and this suggested that his work was mainly national in its impact.

Contributions

The Corps

The Corps of Royal Engineers was small in numbers compared to civil engineers as a profession, and its contribution was arguably considerable for its size. Moreover, the Corps' achievements were particularly notable considering the extremely low percentage of engineer officers whose fathers were engineers or from other building professions or occupations, in marked contrast to civil engineers and architects where the percentage was high. It was probably an advantage to be from a building profession family in times when the apprenticeship system prevailed as the usual route to knowledge and skill. Even so, Royal Engineers, by virtue of their 'scientific' education and social position as military officers, were highly regarded as professionals. This was reflected in the remarkable number of engineer officers who were members of the Institution of Civil Engineers and other engineering organizations as well as the Royal Society and many other learned and scientific societies. Some Royal Engineers were awarded medals and prizes by engineering and scientific associations. It was because of their social and professional status that engineer officers were entrusted by the state with important civil appointments, notwithstanding the fact that their services could be obtained more cheaply than civilians of comparable knowledge and skill.

The Corps was extraordinarily versatile in its abilities in construction and otherwise, and many individual officers were polymaths. There was nearly always someone at every station who could do the job no matter what it was. These qualities were extremely handy on the frontiers of the empire where often engineer officers were the only formally educated builders on the spot. It is for this reason that one of the Corps' chief contributions was in the diffusion of building technology to the colonies.

On balance, however, it was probably the Corps' collective contribution to increasing knowledge of new building materials that constitutes its foremost achievement, especially with respect to limes and cements, colonial woods and asphalt. All of these were developed or tested in both Britain and the colonies, demonstrating the importance of the imperial connections of the Corps and its global building experience. The Corps' contribution to the knowledge of materials was based on informed observation, systematic experimentation and practical verification.

Civil Office or Station

Of the various civil offices or military stations that engineer officers staffed, the most significant in contributions were the Admiralty Works Department and the Science and Art Department. Next in importance were the Inspectorate of Railways and the colonial stations of India and British North America. Also of some note as a group contribution was the Fortifications Department of the War Office. In the office of Surveyor-General of Prisons the contributions were essentially those of individuals, most especially Jebb whose achievements will be discussed in the following section.

As directors and superintendents of the Admiralty Works Department, engineer officers commanded a high position of trust given the fact that the dockyards represented the nation's greatest capital investment in defence. Their contributions matured with accumulated experience. In pioneering wide span roofs in the 1840's, they mainly supported the work of the private sector engineering contractors, but by the 1850's Greene was acting more on his own initiative and skill in design and by the end of the decade was on an equal footing in collaboration with his civilian colleague, Scamp, and the private sector contractors and manufacturers who worked with them. The engineer officers also contributed to the development of functional workplaces in the dockyards, an achievement of vital importance to the maintenance of British naval power. Their proof testing of iron slip roofs seems to have influenced the private sector to adopt this practice for trainshed roofs where the maturation of wide spans for buildings was achieved. Engineer officers managed well the Works Department contracts, awarding them on a competitive basis to top engineering contractors of proven ability. They also collaborated with engineer contractors and manufacturers in the early large scale use of corrugated galvanized iron, helping to establish in the 1840's the credibility of the material for roofing; albeit it was challenged in the 1850's. Engineer officers working with the private sector in the naval dockyards provided a proving ground for the use of new materials and forms of construction which provided valuable experience for industrial buildings and civil engineering works and helped establish confidence in the materials' application to civil works generally. They helped advance progressive ideas in the use of concrete in marine works in the mid-1840's and two decades later pioneered the large scale use of Portland cement and concrete in docks thereby helping to establish greater confidence in these materials in Britain. The work of the engineer officers in the Admiralty Works Department stands out as the greatest group contribution of British military engineers serving or retired.

In the Science and Art Department there were only two Royal Engineers of note - Fowke and Scott - although others played supportive roles in the Department or with related works at South Kensington. Nevertheless, the office of Architect or Director of Works as it was later called was an exemplary case of the Royal Engineers' remarkable ability to co-operate with other building professionals as well as others involved in the design and construction process. The principal achievement was in marrying technology and architectural taste, particularly in the use of new materials, namely terracotta and Scott's cement, to produce the characteristic appearance of the 'South Kensington' style. Moreover, the other notable contributions to building technology in timber roof trusses, in structural iron and in lighting, ventilation and heating services in the buildings which comprise the South Kensington cultural complex were also products of the remarkable co-operative instinct and skill of Fowke and Scott and the architectural office which they in turn headed.

At another, slightly lower level of significance were the contributions of the railway inspectors. Their collective achievement was to provide by way of accumulated experience and a singular concern for safety, a salutary check on civil engineers to counteract the tendency to move too far in the direction of economy and efficiency in the design of railway bridges. They helped establish public confidence in new railway bridge technology. Moreover, they were largely responsible for the government's decision to appoint a Royal Commission on the Application of Iron to Railway Structures, for which two Royal Engineers conducted important experiments. The major consequence of the experiments was to foster a better understanding of the structural testing and specification of cast iron, and of the effects of dynamic loads on bridges. The railway inspectors were largely responsible for the Board of Trade's strength standards for iron and later steel. They also contributed to design excellence by challenging engineers and manufacturers in the design process, especially in structural wrought iron.

Engineer officers of the East India Company staffed the most important of the colonial stations. Their key contributions in the technology of building included the adaptation of the bungalow as a tropical house for Europeans, experiments with magnesia cement and its application to irrigation structures beginning in the 1830's and the diffusion to India of the taper chain suspension bridge in the 1840's and of the steel Warren truss for railway bridges in the 1880's. Royal Engineers stationed in British North America also made some important corporate contributions. In Halifax, Nova Scotia, the Royal Engineers were very early users of Portland cement, probably amongst the first in North America, and were pioneers in the Corps in the use of Portland cement concrete for fortification superstructures. Royal Engineers at Fort Henry, Kingston, Upper Canada (Ontario) pioneered asphalt for building in North America, and its use there was the first for the Corps in fortifications. Engineer officers at the Quebec Citadel and Halifax Citadel were also early users of asphalt in North America.

The corporate contributions of the Fortifications Department of the War Office are also worthy of recognition. Together with the Board of Ordnance, the Department enthusiastically endorsed asphalt as proposed by Oldfield and its use soon became widespread in Britain as a waterproofing material for casemates and other applications in works of fortification. Nevertheless, the Department was slow to take the advice of the Royal Engineers on the spot in Canada that the application of asphalt needed to be adapted to the cold Canadian winters. The development of iron shields and forts is also of some note with respect to the collaboration of the Department with other military services and the private sector.

Individuals

Eight engineer officers made outstanding personal contributions to the development of building technology. It is believed that each of them compares favourably with some of the highly accomplished civil engineers and architects of the nineteenth century. Collectively their contributions embraced virtually the entire spectrum of British achievement: experimentation with and testing of materials and structural forms; the development of artificial cements; wide span roofs in wrought iron; prefabrication in cast iron structures; new developments in heating and ventilation systems; prison and hospital planning and servicing; the diffusion of building technology through imperial expansion; and technical literature on engineering and architecture.

Henry Rowland Brandreth was jointly responsible with C.F. Smith for the pioneering of prefabricated cast iron barrack frameworks for the West Indies. He can also be credited with specifying iron for fireproof, durable construction in the naval dockyards and with the idea of using iron for dockyard slip roofs - pioneering wide spans for buildings which predate those well known achievements for railway trainsheds. Brandreth was partly responsible for the government's decision to appoint the Royal Commission on the Application of Iron to Railway Structures shortly before his sudden death.

Sir William Thomas Denison was an accomplished experimenter with materials who won the Telford Medal from the Institution of Civil Engineers for his work on Canadian woods. He later experimented with Ranger's concrete blocks at Woolwich naval dockyard, undertook proof tests on the principals for a pioneering wide span iron roof at Portsmouth which led to the modification of the design and also tested the strength of a new fireproof floor design at Woolwich. Denison contributed a progressive proposal for the use of concrete in the Dover breakwater which influenced the final design executed by the private sector. He made an early use of mechanical forced air central heating and ventilation in the Royal Marine Barracks, Woolwich. And finally, Denison founded and edited the Royal Engineer Professional Papers, an important and early contribution to British technical literature on building.

Francis Fowke made important experiments on colonial woods at the Paris International Exhibition of 1855, and established the Museum of Building Materials and Construction at South Kensington which acted as an important showcase for new materials and techniques. He developed a new timber roof truss, a work of adaptive genius. Fowke helped establish confidence in the durability, strength and economy of architectural terracotta by his experiments and works at South Kensington.

He also had some notable success in the use of iron as a structural and decorative material and produced a record size dome of iron and glass. Fowke combined his considerable mechanical and constructional skills in advancing the art of natural lighting in picture galleries and in pioneering their gas lighting and effective ventilation.

Sir Douglas Strutt Galton contributed to important experiments for the Royal Commission on the Application of Iron to Railway Structures. He also invented a new ventilating fireplace grate and stove which were widely adopted in barracks and military hospitals. Galton designed the Herbert Hospital, the first pavilion hospital completed in Britain, in which his special contribution was in the engineering services, particularly in ventilation and heating arrangements. He was a distinguished lecturer, writer and well respected advocate of the pavilion plan in hospitals and of the design of healthy dwellings in late Victorian Britain.

Godfrey Thomas Greene was responsible for the mature works in structural iron at the naval dockyards in the 1850's. He deserves outstanding status alone for his much celebrated Boat Store at Sheerness. Greene is perhaps the best example of the considerable contribution made by engineer officers of the East India Company. Yet, in the case of this distinguished Bengal Engineer, the achievement for which he deserves a notable place in structural history was made after his retirement from the army, and in England.

Sir Joshua Jebb designed the model prison at Pentonville which, while not an innovative concept, constituted an ingenious refinement of details subsequently adopted as the standard for a major rebuilding of British prisons in the Victorian age and acted as a pervasive influence in penitentiary construction abroad. Jebb's special contribution was the development of ventilation and heating engineering for prisons.

Sir Charles William Pasley founded and developed the Royal Engineer Establishment as well as its architectural course. He wrote two important publications on the nature, manufacture and use of limes, cements and concrete and he himself produced an artificial cement that was adopted by some manufacturers in Britain and was made in India. Pasley also helped establish the use of reinforced brickwork. His work as Inspector-General of Railways was more important as part of the corporate achievement of the railway inspectors than a personal contribution.

Henry Young Darracott Scott helped improve the Royal Engineers' knowledge and skill with cement and concrete in his position as an instructor at the Royal Engineer Establishment. He invented selenitic cement, an important new material of the nineteenth century, which was used fairly widely including by Scott himself and by Fowke at South Kensington. Scott also developed sewage cement, a contribution to sanitary engineering as much as to building technology, although it proved not to be a success commercially. He helped to establish the architectural use of terracotta by his works at South Kensington and was partly responsible for the important wide span wrought iron roof in the Albert Hall.

Some twenty-two other engineer officers made notable contributions at various levels of significance short of outstanding. Sir John Charles Ardagh designed the earliest mass concrete walls in fortification works in Britain. Frederick Henry Baddeley experimented with and patented some of the earliest natural cements made in Canada. Roger Stewart Beatson designed an early cast iron trussed beam for the floors of a boat house as well as a freestanding cast iron watertower. Sir James (Buster) Browne designed important iron and steel bridges for roads and railways in India, diffusing to the colony the latest European and American technology. Sir Andrew Clarke pioneered the large scale use of Portland cement for mortar and concrete in British dock and harbour works. Arthur Thomas Cotton experimented in India with magnesia cement, a new material of the early nineteenth century, and applied it in important irrigation works. Sir Edmund Frederick Du Cane promoted the jarrah timber of Western Australia and later as Surveyor-General of Prisons designed Wormwood Scrubs, the first prison in Britain built on the pavilion plan. Henry Goodwyn, in India, undertook model tests and designed and constructed a number of taper chain suspension bridges, a distinctive form of bridge technology which he helped diffuse to the colony. Sir George Judd Harding made the earliest experiment in Britain with mass concrete for the superstructure of fortification works, in collaboration with William Ranger, the patentee of the novel concrete preparation and application processes employed. Sir Henry Drury Harness was partly responsible for the government's appointment of the Royal Commission on the Application of Iron to Railway Structures but more importantly reformed the architectural and engineering courses at the Royal Engineer Establishment as its director. Sir Edmund Yeamans Walcott Henderson experimented with jarrah timber in Western Australia and used the new material for an early laminated timber roof in the colony. Thomas Inglis became an international expert on the subject of iron in coastal forts and was mainly responsible for the British iron shield design for fortifications. William Innes developed expertise in Portland cement concrete for fortifications and helped improve the Corps' knowledge of this aspect of building technology. Sir Henry James undertook experiments for the Royal Commission on the Application of Iron to Railway Structures and his discoveries led to revised strength standards for cast iron in railway bridges. Sir William Francis Drummond Jervois, as Assistant Inspector General of Fortifications and Director of Works of Fortification, had considerable managerial responsibility for the development of the British iron coastal forts and iron shields for fortifications. Richard John Nelson undertook important experiments on colonial woods while stationed in Bermuda. John Oldfield pioneered works in asphalt for the Corps, first in Canada and then in England. Sir John Lintorn Arabin Simmons, a railway inspector, seems to have been mainly responsible for initiating the safety factor for wrought iron based on a stress factor which was adopted by the Board of Trade as the standard for railway bridge construction. Sir Charles Felix Smith was an early British pioneer in the development of prefabricated cast iron frameworks for buildings in the colonies. John Thomas Smith translated into English and published Vicat's treatise on limes and cements which proved influential, and undertook important experiments on limes and cements in India. Henry Wray tested jarrah timber in Western Australia and used it extensively in buildings, jetties and bridges in the colony; he later became instructor of construction at the School of Military Engineering where he greatly improved the Royal Engineers' education in building. William Yolland, a railway inspector, was partly responsible for committee recommendations concerning a stress factor for steel and a wind pressure standard which were adopted by the Board of Trade for railway bridge construction.

Building Technology, Architecture and Society

A number of observations can be made on the nature of building technology, architecture and society in the nineteenth century from this study of the Royal Engineers. These include: the social character of Britain's achievements in building technology development; the quality of British education in building science; the role of experiment in the adoption of new materials; the connection between social reform and architecture; attitudes toward environmental control in architectural design; the relationship between technology and taste; and the importance of building technology in imperial expansion.

The development of building technology in Britain was founded on complex relationships among various building professions, the building industry, manufacturers, entrepreneurs, government officials and others. The Royal Engineers' corporate contributions and their relationships with others suggest that Britain's achievements were as much collective accomplishments as they were the responsibility of individual genius. Personal contribution by way of discovery, initiative or virtuosity was indispensable, but it would not have flourished single handed.

The Royal Engineer Establishment was one of the earliest institutional education opportunities in Britain for engineering, building technology and architecture. Still, its history reveals the weakness of British technical training compared to the Continental experience. Efforts to reform the Royal Engineer Establishment from the 1860's reflected the debate in the British engineering and architectural professions after mid-century concerning the best balance between formal theoretical education and practical training viz. the apprenticeship system.

Experiments with cements and concrete at the Royal Engineer Establishment and by engineer officers in the colonies confirm and reflect the remarkable British contribution to the development of stronger and more durable bonding agents and renders for traditional masonry construction and to concrete for foundations. Yet these experiments also demonstrate the country's conservatism concerning the use of mass concrete and artificial stone in building superstructures and in marine works. This serves to illustrate that in assessing achievements in building technology development it is important to remember that 'scientific' knowledge can inhibit as well as stimulate further endeavour. On balance, the Royal Engineers' experimental tradition more often induced progressive practices than caution in the use of new materials.

The Royal Engineers' role as railway inspectors, Surveyors-General of prisons and army sanitary reformers reflected the increasing intervention of government in the life of the nation and was part of the roots of the British welfare state. All of these activities involved seeing science and progress as social ideal. For Royal Engineers and other agents of social reform, architecture was viewed as becoming more socially useful through advanced building technology. In railway bridges progress meant safer structures through inspection and Board of Trade strength standards; in prisons, barracks and hospitals improvement was achieved through advances in planning, servicing and the details of construction.

Contrary to the traditional view, the nineteenth century was not uninterested in environmental control in design. An incredible variety of heat-aided or mechanical forced ventilation and central heating systems were employed in all types of buildings. For all that, there was an equally significant counter-current of reliance on modified traditional 'low' technology - the fireplace and open windows. The Royal Engineers' experience demonstrated a decided preference for the latter. This seems to suggest that, though widely available, new building technology was not necessarily applied if improvements to old technology proved reasonably satisfactory. Expense, reliability and familiarity were all factors tending to slow the acceptance of new technology in building.

The work of Fowke and Scott at South Kensington shows that an interdisciplinary team approach to architecture which combined advanced technology and the canons of architectural taste was possible in mid-Victorian Britain, albeit not without criticism. Nevertheless, the dictates of fashion in appearance clearly dominated. This can be seen best in the engineer officers' use of concrete and iron. Although both Fowke and Scott were keen advocates of mass concrete for fortifications, including superstructures, Fowke used it for complete buildings at South Kensington in only two minor works - a powder magazine and an entrance lodge - and Scott not at all. Concerning works of iron, Fowke's conservatory for the Royal Horticultural Society as well as his roof for the South Courts of the South Kensington Museum, both of decorative ironwork, were well received whereas his functional, undecorated pyramidal roofs for the museum's North Courts and his twin record span domes for the 1862 International Exhibition building were widely condemned. Scott's distinctive wrought iron dome for the Albert Hall was appreciated as a work of structural engineering virtuosity but concern was expressed for its interior appearance. The material which proved the ideal medium for the successful combination of technology and taste in the engineer officers' works at South Kensington was terracotta. This is not surprising since it was based on historical precedent in buildings of the early northern Italian Renaissance. Tensions existed between the forces of technology and history in Victorian architecture but it was not beyond the power of able designers to achieve a workable compromise. Scholars have perhaps over-emphasized the tensions and failed to appreciate the compromises because their criteria of judgement have been those of the twentieth century and particularly those of sympathizers with the rise of the modern movement in architecture.

Hobsbawm has shown that Britain in the nineteenth century developed as an essential part of a global economy, more particularly as the centre of a vast formal or informal 'empire' on which its fortunes largely rested.[3] Moreover, Headrick has demonstrated that technology was a vital force in imperialism, and Buchanan has explored how British engineers were agents of the diffusion of technology occasioned by imperial expansion.[4] The Royal Engineers participated in all this as individuals for short periods at various colonial stations, but more so as a Corps presence in all the major colonies throughout most of the nineteenth century and in India well into the twentieth. This phenomenon was marked not only by technology transfer but also by adaptation to local conditions and even by the adoption of native traditions. Of especial importance are the development and use of building materials and the role of prefabrication, both of which are rooted in economic motivations as well as building needs. Also of considerable significance was the climatic adaptation of structural form, constructional details and building services to suit European expectations of health, comfort and convenience - a prime example of the cultural influences on architecture and technology. This subject has received too little attention from scholars, and a fuller understanding of it is vital to a comprehensive and critical appraisal of the development of British building technology in the nineteenth century. In particular, an examination is needed of the relative importance of European and American influence in building technology diffusion. The present thesis points to the desirability of a comparative study on the contributions of military engineers from all advanced Western nations.

APPENDIX A - BIOGRAPHIES OF ENGINEER OFFICERS

The following brief biographies of the thirty engineer officers who comprise the core group studied in this thesis are intended primarily to support data presented in Appendices B and E on social origins and early education respectively. They also serve to highlight each officer's building related career with respect to major positions held as well as membership in professional associations, especially the Institution of Civil Engineers (ICE). Each biography closes with references to the principal sources of biographical information on the individual concerned.

Ardagh, Sir John Charles (1840-1907)

The son of Rev. W.J. Ardagh, vicar of Rossmire, he was educated at an endowed school in Waterford under Dr. Price and Trinity College, Dublin in 1857. Ardagh was commissioned in 1859. His major work was in the construction of fortifications, most notably Newhaven Fort (1865). In 1874 he joined the Intelligence Department of the War Office and ceased involvement in building. See: Watson, History of the Corps of Royal Engineers, pp 380-387; DNB (1901-1911), pp 50-53.

Baddeley, Frederick Henry (1894 -)

Little information has been found on Baddeley. He was commissioned in 1814 and served in Canada 1821-1839 where he undertook experiments with natural cements at Quebec and Kingston, taking out a patent on one of them. He retired from the army in 1856. See: Connolly, T.W.J., Roll of Officers of the Corps of Royal Engineers 1660-1898, Chatham, 1898, p. 427.

Beatson, Roger Stewart (1812-1896)

The son of Captain Henry Dundas Beatson of Campbeltown, Scotland, he was commissioned in 1832. Beatson was superintendent for the Admiralty Works Department at Portsmouth (1839-1845) and Woolwich (1845-1848). He later served as Commanding Royal Engineer in Canada (1849-1854), Woolwich (1856), Gibraltar (1856-1859), Newcastle (1859-1865), and New Zealand (1865-1869). He retired in 1869. See: Boase, Vol. IV, p. 327.

Brandreth, Henry Rowland (1794-1848

Commissioned in 1813, Brandreth served in the West Indies (1816-1824; 1827-1828). He was Director of the Admiralty Works Department 1837-1846 and Commissioner of the Railway Board 1846-1848. He was a member of the ICE. See: PP, Vol. X (1849), pp 1-35; PP, Vol. VIII, (1848), pp 12-14.

Browne, Sir James (Buster) (1839-1896)

The son of Robert Brown, M.D., he was educated by his father and in local schools in France and Germany and at Cheltenham College (1855). He was commissioned in the Bengal Engineers in 1857 and landed in India two years later. Browne was an executive engineer in the north-west provinces of India where he made significant contributions to road and railway construction from the 1860's to the late 1880's. See: Innes, General Sir James Browne; Vibart, Addiscombe, pp 637-643; and Watson, History of the Corps of Royal Engineers, pp 375-379.

Clarke, Sir Andrew (1824-1902)

The son of Lieutenant Colonel Andrew Clarke of the 4th Regiment, he was educated at The King's School, Canterbury and at Portora School, Enniskillen, Ireland. Clarke was commissioned in 1842 and served in various posts in Australia 1846-1859. He was Director of the Admiralty Works Department 1864-1873. Clarke was head of the Public Works Department in India 1875-1880, Commandant of the School of Military Engineering 1881-1882 and Inspector General of Fortifications 1882-1886. See: Vetch, Lieutenant-General Sir Andrew Clarke; Watson, History of the Corps of Royal Engineers, pp 299-304; Australian Dictionary of Biography, Vol. 1, p. 228 and Vol. 3 pp 409-411; DNB, (1901-1911), pp 362-365.

Cotton, Arthur Thomas (1803-1899)

The son of H.C. Cotton Esq. of Woodcot House, Oxfordshire, he was commissioned in the Madras Engineers in 1821. Cotton was an irrigation engineer principally and a distinguished dam builder. He returned to England in 1861. See: Vibart, Addiscombe, pp 343-351.

Denison, Sir William Thomas (1804-1871)

The s n of John Wilkerson, a London merchant who took the surname of his cousin William Denison of Kirkgate, Leeds, whose property he had inherited, W.T. Denison was educated at a private school in Sunbury, at Eton and under a private tutor,Rev. C. Drury. Denison was commissioned in 1826 and first served in Canada in the construction of the Rideau Canal 1827-1831. He was superintendent for the Admiralty Works Department at Woolwich/Deptford (1837-1845) and Portsmouth (1845-1846). Denison was a member of the ICE and was on its council in 1838; he was also a Fellow of the Royal Society (1838). Denison's later career was spent as a colonial governor in Van Dieman's Land, New South Wales and Madras. See: DNB, Vol. 5, pp 805-807; PPNS, Vol. XX (1872), ix-xxi; Boase, Vol. 1, p. 858; Porter, History of the Royal Engineers, pp 466-471; MPICE, Vol. 33 (1871), pp 251-259.

Du Cane, Sir Edmund Frederick (1830-1903)

The son of Major Richard Du Cane of the 20th Light Dragoons, he was educated at grammar school, Dedham, Essex and at a private coaching establishment at Wimbledon (1843-1846). Du Cane was commissioned in 1848 and served at the International Exhibition of 1851 in London. He was employed in Western Australia 1851-1856 and later served in the Fortifications Department of the War Office 1856-1863. Du Cane was appointed Director of Convict Prisons in 1863 and Surveyor-General of Prisons in 1869. He retired from the army in 1887 and from the civil service in 1895. See: DNB (1901-1911), pp 528-529.

Fowke, Francis (1823-1865)

Fowke was educated at Dungannon College and by a military tutor in Woolwich. Commissioned in 1842, he served in Bermuda and at Devonport until 1854-1855 when he was a British official at the Paris International Exhibition of 1855. Fowke joined the Science and Art Department in 1856 as an inspector but soon was appointed the Department's architect and engineer. He became the Corps' most accomplished designer of monumental public architecture. Fowke was an associate member of the ICE (1863). See: DNB, Vol. VII, pp 519-520; PPNS, Vol. XV (1866), pp ix-xv; Porter, History of the Royal Engineers, pp 494-497; MPICE, Vol. 30 (1865), pp 468-470.

Galton, Sir Douglas Strutt (1822-1899)

The son of John Howard Galton of Hadzor House, Droitwich, he was educated at Birmingham, Geneva and at Rugby. Galton was commissioned in 1840 and later was appointed secretary to the Railway Commission and the Royal Commission on the Application of Iron to Railway Structures. He served the Railway Department until 1857. The following year he was appointed to the Barrack and Hospital Improvement Committee (Army Sanitary Commission) which he served until his death in 1899. Galton was Assistant Inspector General of Fortifications in charge of barracks (1859-1862), Assistant Permanent Under Secretary for War (1862-1870) and Director of Public Works and Buildings (1869-1875). He retired from the army in 1862. Galton was a member of the Institution of Mechanical Engineers (1862) and its vice-president (1892), a member of the Sanitary Institute of Great Britain, a member of the Institution of Electrical Engineers (1872) and a Fellow of the Royal Society (1859). See: DNB, Vol. XXII, pp 691-694; Proceedings of the Institution of Mechanical Engineers, 1899, pp 129-134.

Goodwyn, Henry (- 1886)

Very little is known of Goodwyn's background. He was commissioned in 1823 in the Bengal Engineers and served initially in Calcutta and later as an executive engineer in the northern provinces. He returned to England after a long career and died at Bournemouth. See: Vibart, Addiscombe, p. 668; Connolly, Roll of Officers of Royal Engineers.

Greene, Godfrey Thomas (1807-1886)

The son of Major Anthony Greene of East India Company service, he was commissioned in the Bengal Engineers in 1825. Greene served in a variety of military and civil posts in India until 1850 when he retired from the Bengal Engineers to take up the position of Director of the Admiralty Works Department which he held until 1864. See: Vibart, Addiscombe, p. 667; The Times, 30 December 1886; Skempton, TNS, Vol. XXXII (1959-1960), pp 57-78

Harding, Sir George Judd (1788-1860)

Commissioned in 1802, Harding served in military positions during the Napoleonic Wars. He was Commanding Royal Engineer at Woolwich where he tested Ranger's concrete for use in fortifications in 1835. Harding was an Assistant Inspector General of Fortifications (1850-1855) and Governor of Gurnsey (1855-1859). See: Boase, Vol. 1, p. 1326.

Harness, Sir Henry Drury (1804-1883)

The son of John Harness, M.D., he was commissioned in 1827. Harness served as an instructor in fortification at the Royal Military Academy (1834-1846) and as an instructor in surveying at the Royal Engineer Establishment (1840-1846). He was secretary to the Railway Commission (1846-1850), Commissioner of Public Works in Ireland (1852-1854) and in charge of the fortification branch of the War Office (1854-1855). Harness was Director of the Royal Engineer Establishment 1860-1865. See: DNB, Vol. VIII, pp 1298-1299; Collinson, General Harness.

Henderson, Sir Edmund Yeamans Walcot (1821-1896)

The son of Vice Admiral George Henderson, Royal Navy, he was educated at Bruton, Somerset. Henderson was commissioned in 1838 and served in Western Australia building convict establishments and public works 1849-1856 and as the colony's head of public works 1856-1863. He was Surveyor-General of Prisons 1863-1869. See: DNB, Vol. XXII, pp 834-836; Australian Dictionary of Biography, Vol. 4, pp 376-377.

Inglis, Thomas (- 1888)

Commissioned in 1843, after several years service in South Africa, Inglis was in charge of works at the armaments factories in England (from 1853) and in 1857 was appointed Inspector of Works of the Manufacturing Departments. He was Inspector of Iron Fortifications in the War Office 1867-1884. See: BSP/1862/XXXIII/531-533.

Innes, William (1841-1875)

The son of Colonel Thomas Innes, commander of the Royal Aberdeenshire Highlanders Militia, he was educated at the Ordnance School of Carshalton, a prepatory school for the Royal Military Academy. Innes was commissioned in 1858 and worked in the construction of fortifications in England and at Halifax, Nova Scotia 1859-1872. He then became Assistant Colonial Engineer of the Straits Settlement where he was employed almost exclusively in public works (1872-1875). He was elected an associate member of the ICE in 1869. See: MPICE, Vol. 43 (1875-1876), pp 312-317.

James, Sir Henry (1803-1877)

The son of John James, a Truro attorney, he was educated at grammar school in Exeter. Commissioned in 1826, James was appointed initially to the Ordnance Survey where he remained until 1846 when he took up the position of superintendent for the Admiralty Works Department at Portsmouth which he held until 1850. He was a member of the Royal Commission on the Application of Iron to Railway Structures (1847-1849). In 1850 James returned to the Ordnance Survey and served as its Director-General 1854-1875. He was elected an associate member of the ICE (1849) and was a Fellow of the Royal Society (1848). See: DNB, Vol. X, pp 647-650.

Jebb, Sir Joshua (1793-1863)

The son of Joshua Jebb of Walton, Derbyshire, he was commissioned in 1812. Jebb served initially in Canada (1813-1820). He was seconded to the Home Office in 1837 to serve as architectural advisor to the inspectorate of prisons. Jebb was Surveyor-General of Prisons and Inspector-General of Military Prisons from 1844 and Director of Convict Prisons from 1850, until his death in 1863. See: DNB, Vol. X, pp 698-669.

Jervois, Sir William Francis Drummond (1821-1897)

The son of General William Jervois, K.H., Colonel of the 76th Foot, he was educated at Dr. Burney's academy at Gosport and Mr. Barry's school at Woolwich. Jervois was commissioned in 1837 and served initially in Cape Colony where he built fortifications. In 1856 he was appointed Assistant Inspector General of Fortifications and in 1862 Director of Works for Fortifications, where he served until 1875. Jervois ended his career as a colonial governor at Straits Settlement (1875), and South Australia 1877-1882 and New Zealand (1882-1890). He was an associate member of the ICE 1857) and a Fellow of the Royal Society 1888). See: DNB, Vol. XXII, pp 912-915.

Nelson, Richard John 1803-1877

The son of General Richard Nelson, he was educated at a private school at Tamerton Foliott near

Plymouth. Nelson was commissioned in 1826 and served initially at Bermuda (1827-1835) and the Cape of Good Hope (1835-1838). He later served in the British Isles, Canada and Nassau and retired in 1864. See: DNB, Vol. XIV, pp 209-210.

Oldfield, John (1789-1863)

The son of Lieutenant John Nicholls Oldfield, Royal Marines, he was educated at Great Marlow, a junior cadet school, before entering the Royal Military Academy. Oldfield was commission in 1806 and served in Canada, Newfoundland, England, Ireland, Jersey and the West Indies. He retired in 1854. See: DNB, Vol. XIV, pp 994-996.

Pasley, Sir Charles William (1780-1861)

The son of Charles Pasley, a London merchant, he was educated by Andrew Little of Langholm and at Selkirk in Scotland. Pasley was commissioned in 1797. He was the founder and director of the Royal Engineer Establishment (1812-1841) and Inspector-General of Railways (1841-1846). Pasley was a Fellow of the Royal Society (1816), a member of the ICE (1820) and a member of the Institute of British Architects (1842). See: Pasley Papers, MS 41766, British Library; MPICE, Vol. 21 (1861), pp 545-560; Kealy, Sir Charles Pasley; Proceedings of the Royal Society, Vol. 12 (1863), pp xx-xxv; DNB, Vol. 15, pp 439-442; Porter, History of the Royal Engineers, pp 433-436.

Scott, Henry Young Darracott (1822-1883)

The son of Edward Scott, an extensive quarry owner, he was educated privately. Scott was commissioned in 1840 and in 1848 was appointed instructor in field-works at the Royal Military Academy. He also became instructor in surveying, practical astronomy, chemistry and civil works at the Royal Engineer Establishment in 1855. In 1864 Scott was seconded to the Science and Art Department and the next year became the Department's Director of Works, a position he held until 1883. He was elected an associate member of the ICE (1874) and a Fellow of the Royal Society (1875). See: MPICE, Vol. 75 (1884), pp 319-322; DNB, Vol. 17, pp 964-965.

Simmons, Sir John Lintorn Arabin (1821-1903)

The son of Captain T.F. Simmons, Royal Artillery, he was educated at Elizabeth College, Gurnsey. Simmons was commissioned in 1837 and served in Canada 1839-1845. He was appointed a railway inspector in 1847 and was secretary to the Railway Department (1848). Simmons left the inspectorate in 1853 and served in a variety of civil and military appointments including Inspector General of Fortifications (1875-1880) and Governor of Malta (1884-1888). He retired from the army in 1888. See: Watson, History of the Corps of Royal Engineers, pp 259-266.

Smith, Sir Charles Felix (1786-1858)

The son of George Smith of Burn Hall, Durham who became a lieutenant colonel in the army, he was commissioned in 1802. Smith served in the West Indies (1804-1810 and 1823-1837) where he was Commanding Royal Engineer for fourteen years. He was later stationed in Gibraltar and Ireland. See: DNB, Vol. XVIII, pp 429-432.

Smith, John Thomas (1805-1882)

The son of George Smith Esq. of Edwalton, Nottinghamshire, he was educated at Repton and at Edinburgh High School. Smith was commissioned in the Madras Engineers in 1824 and was principally engaged in lime and cement experiments, mintage and lighthouse construction in India. After 1856 he was a consulting engineer to an irrigation company and a director of a railway company. Smith was elected a Fellow of the Royal Society (1837). See: DNB, Vol. XVIII, pp 498-499.

Wray, Henry (- 1900)

Commissioned in 1848, Wray served in Western Australia 1852-1858 in construction of convict establishments and public works. In 1866 he was appointed instructor in construction at the School of Military Engineering. See: McNicoll, Royal Australian Engineers, pp 172 and 107-111.

Yolland, William (1810-1885)

Yolland was educated at Trueman's mathematical school at Exeter and by George Harvey of Plymouth. He was commissioned in 1828 and served in the Ordnance Survey 1838-1854. Yolland joined the railway inspectorate in 1856 where he enjoyed nearly thirty years service and became chief inspector. He retired from the army in 1863. Yolland was a Fellow of the Royal Society (1859). See: DNB, Vol. XXI, pp 1237-1238.

APPENDIX B - OCCUPATION OF ENGINEER OFFICERS' FATHERS - AN ANALYSIS OF SOCIAL ORIGINS

The following analysis is based on data in Appendix A on the occupation of engineer officers' fathers. Information was found on 19 of the 30 engineer officers who comprise the core group studied in the present thesis.

Classification of Occupations			No.	%
I.	Upper Class			
	A.	landowner - peer	-	-
	B.	landowner - gentry	1	5
	C.	army or navy officer	11	58
		Total	12	63
II.	Professional Middle Class			
	D.	clergy (established church)	1	5
	E.	lawyer	1	5
	F.	doctor	2	11
	G1.	surveyor	-	-
	G2.	civil engineer	-	-
	G3.	architect	-	-
	G4.	land agent	-	-
		Total	4	21
III.	Merchants and Traders			
	H.	banker and 'capitalist'	-	-
	I.	merchant or large retailer	2	11
	J.	shopkeeper or small businessman	-	-
		Total	2	11
IV.	Manufacturers and Industrialists			
	K.	manufacturer-owner/head	-	-
	L.	non-manual employees	-	-
	M.	independent craftsman	-	-
		Total	-	-
V.	The Land and Mining			
	N.	yoeman or farmer with other activity	-	-
	O.	tenant farmer or other cultivator	-	-
	P.	quarrymaster, coalmaster	1	5
		Total	1	5

Continued ...

APPENDIX B - CONTINUED

Classification of Occupations		No.	%
VI.	Working Class		
	Q. skilled workman	-	-
	R. workman in domestic industry	-	-
	S. unskilled workman, 'poor', servant etc.	-	-
	Total	-	-
VII.	Various		
	T. occupations other than above	-	-
	Total	-	-
	TOTAL	19	100

Classification on Social Class		No.	%
1.	Upper Class = A,B,C.	12	63
2.	Middle Class = D,E,F,G,H,I,K.	6	32
3.	Lower Middle Class = J,L,M,N,O,P.	1	5
4.	Working Class = Q,R,S.	-	-
5.	Various = T.	-	-
	TOTAL	19	100

APPENDIX C - OCCUPATION OF CIVIL ENGINEERS' FATHERS - ANALYSIS OF SOCIAL ORIGINS

The sample of 57 civil engineers analysed below represents individuals who were born before 1840 and practised after 1810. Information is from obituaries in the Minutes of the Proceedings of the Institution of Civil Engineers and Colvin's Biographical Dictionary of British Architects.

Classification of Occupations

I. Upper Class

A.	landowner - peer		-
B.	landowner - gentry		2
C.	army or navy officer		6
		Total	8 or 14%

II. Professional Middle Class

D.	clergy		2
E.	lawyer		2
F.	doctor		2
G1.	surveyor		2
G2.	civil engineer		7
G3.	architect		5
G4.	land agent		2
		Total	22 or 38%

III. Merchants and Traders

H.	banker or 'capitalist'		-
I.	merchant or large retailer		2
J.	shopkeeper or small businessman		1
		Total	3 or 5%

IV. Building and Civil Engineering Industry

K.	builder		-
L.	civil engineering contractor		1
M.	non-manual employees		1
N.	millwright		1
O.	craftsman		1
P.	skilled trades		-
		Total	4 or 7%

V. Manufacturers and Other Industries

Q.	manufacturer-owner/head		3
R.	non-manual employees		-
S.	independent craftsman		5
		Total	8 or 14%

Continued ...

APPENDIX C - CONTINUED

Classification of Occupations

VI. The Land and Mining

T.	yoemen or farmer with other activity	1
U.	tenant farmer or other cultivator	3
V.	quarrymaster, coalmaster	-
	Total	4 or 7%

VII. Working Class

W1.	skilled workman	-
W2.	workingman in domestic industry	-
W3.	unskilled workman, 'poor', servant etc.	1
	Total	1 or 2%

VIII. Various

X.	occupations represented in sample other than the above.	7 or 12%
	Total	7

Classification on Social Class

1.	Upper Class = A,B,C.	8	or 14%
2.	Middle Class = D,E.F,G,H,I,K,L,Q.	28	or 49%
3.	Lower Middle Class = J,M,N,O,R,S,T,U,V.	13	or 23%
4.	Working Class = P,W.	1	or 2%
5.	Various = X.	7	or 12%
	TOTAL	57	100%

Persons engaged in Professions, Business, Craft, or Worker related to Building or Civil Engineering (G,K-P.)	20	35%

APPENDIX D - OCCUPATION OF ARCHITECTS' FATHERS - AN ANALYSIS OF SOCIAL ORIGINS

The sample of 261 architects analysed below represents individuals who were born before 1840 and practised after 1810. Information is from Colvin's Biographical Dictionary of British Architects, Dixon and Muthesius' Victorian Architecture and Derek Linstrum, West Yorkshire Architects and Architecture, London, 1978.

Classification of Occupations

I. Upper Class

A.	landowner - peer	-	
B.	landowner - gentry	5	
C.	army or navy officer	2	
	Total	7	or 3%

II. Professional Middle Class

D.	clergy	7	
E.	lawyer	3	
F.	doctor	6	
G1.	surveyor	19	
G2.	civil engineer	4	
G3.	architect	85	or 33%
G4.	land agent	3	
	Total	127	or 48%

III. Merchants and Traders

H.	banker or 'capitalist'	2	
I.	merchant or large retailer	14	
J.	shopkeeper or small businessman	3	
	Total	19	or 7%

IV. Building Industry

K.	speculative builder	4	
L.	builder	25	
M.	clerk of works/draughtsman	3	
N.	mason	17	
O.	carpenter/joiner	10	
P.	bricklayer	2	
Q.	cabinet-maker	3	
R.	plasterer/stuccoist	3	
S.	painter/decorator	5	
	Total	72	or 28%

Continued ...

Classification of Occupations

V. Manufacturers and Other Industries

T.	manufacturer-owner/head	3	
U.	non-manual employees	1	
V.	independent craftsman	3	
	Total	7	or 3%

VI. The Land and Mining

W.	yoeman or farmer with other activity	1	
X.	tenant farmer or other cultivator	3	
Y.	quarrymaster, coalmaster	-	
	Total	4	or 1.5%

VII. Working Class

Z1.	skilled workman	1	
Z2.	workman in domestic industry	-	
Z3.	unskilled workman, 'poor', servant	3	
	Total	4	or 1.5%

VIII. Artists

Ar.		5	
	Total	5	or 2%

IX. Various

Va.	occupations represented in sample other than above.	16	or 6%
	Total	16	

Classification or Social Class

1.	Upper Class = A,B,C.	7	or	3%
2.	Middle Class = D,E,F,G,H,I,K,L,T,Ar.	180	or	69%
3.	Lower Middle Class = J,M,N,O,Q,U,V,W,X,Y.	44	or	17%
4.	Working Class = Z,P,R,S.	14	or	5%
5.	Various = Va.	16	or	6%
	TOTAL	261		100%

Persons engaged in Professional Occupation, Business, Trade, etc. related to Building (G,K-S).	189	or	72%

APPENDIX E - ENGINEER OFFICERS' EARLY EDUCATION

The following analysis of engineer officers' education before entry to the Royal Military Academy is based on data presented in Appendix A. Information was found on 18 of the 30 engineer officers who comprise the core group studied in the present thesis. The highest level of education attained is recorded in each case only.

Type of Education	No.	%
1. Grammar School	1	6
2. Private Tuition	2	11
3. Private School, Academy, College or High School (including Scotland and Ireland)	10	55
4. Public School	4	22
5. University	1	6
TOTAL	18	100

APPENDIX F - SHIPBUILDING SLIP ROOFS IN THE NAVAL DOCKYARDS 1844-1857

Date	Slip No.	Location	Designer	Span	Sources
1844-45	8 and 9	Pembroke	Fox, Henderson	80 ft. 7 5/8 in.	Williams, PP, Vol. 9, p. 51; PRO, ADM/12/460
1844-45	?	Woolwich (moved to Chatham in 1869)	Fox, Henderson	?	BSP/1844/XXXIII/260; Sutherland, Second Interim Report
1845-46	3 and 4	Portsmouth	G. Baker & Sons	84 ft. 6 in.	Cumberland, PP, Vol. 9, and 62-63; PRO ADM/140/633.
1845-46	2 and 3	Deptford	G. Baker & Sons	?	PRO, ADM/12/460; PRO, ADM/12/476.
1846-47	4	Woolwich	Fox, Henderson	84 ft.	PRO/ADM/12/460; MPICE, Vol. XIV (1854-55) p. 264.
1846-47	7	Pembroke	Fox, Henderson	?	PRO, ADM/12/476.
1847-48	4, 5 and 6	Chatham	G. Baker & Sons	?	PRO, ADM/12/476; PRO, ADM/12/492.
1847-49	1 and 2	Pembroke	G. Baker & Sons	?	PRO, ADM/12/476; PRO, ADM/12/508.
1852-54	7	Chatham	G. T. Greene	82 ft.	PRO, ADM/140/66.
1856-57	5	Woolwich	G. T. Greene/ Fox, Henderson	?	PRO, ADM/12/619; PRO, ADM/12/636.

NOTES

Introduction

1. See especially: Rolt, L.T.C., Victorian Engineering, Harmondsworth, 1970; Rolt, L.T.C., George and Robert Stephenson, Harmondsworth, 1978; Rolt, L.T.C., Isambard Kingdom Brunel, Harmondsworth, 1980; Vignoles, K.H., Charles Blacker Vignoles, romantic engineer, Cambridge, 1982; Straub, H., A History of Civil Engineering, London, 1960; Armytage, W.H.G., A Social History of Engineering, London, 1961; Smiles, S., Lives of the Engineers, London, 1862.

2. The scholars most responsible for this point of view are Nikolas Pevsner, J.M. Richards and Henry Russell Hitchcock. See: Pevsner, N., Pioneers of Modern Design, Harmondsworth, 1974; Richards, J.M., An Introduction to Modern Architecture, Harmondsworth, 1944; Richards, J.M., The Functional Tradition in Early Industrial Buildings, London, 1968; Hitchcock, H.R., Early Victorian Architecture in Britain, New Haven and London, 1972.

3. This interpretation has been articulated by Sigfried Giedion in Space, Time and Architecture, 5th Edition, 1967, and by Peter Collins in Changing Ideals in Modern Architecture 1750-1950, London, 1965.

4. Boyd, D., Royal Engineers, London, 1975; Connolly, T.W.J., History of the Royal Sappers and Miners, 2 Vols., London, 1857; McNicoll, R., The Royal Australian Engineers 1835 to 1902: The Colonial Engineers, Canberra, 1977; Porter, W., History of the Corps of Royal Engineers, 2 Vols., London, 1889; Sandes, E.W.C., The Military Engineer in India, 2 Vols., London, 1935; Watson, C.M., History of The Corps of Royal Engineers, 2 Vols., Chatham, 1915.

5. See especially: Spiers, E.M., The Army and Society 1815-1914, London, 1980; Skelley, A.R., The Victorian Army at Home, London, 1977; Harries-Jenkins, G., The Army and Victorian Society, London, 1977.

6. Parris, H., Government and the Railways in Nineteenth Century Britain, London, 1965.

7. Hogg, I.V., Coast Defences of England and Wales 1856-1956, Newton Abbot, 1974; Hughes, Q., Military Architecture, London, 1974.

8. Evans, R., The fabrication of virtue: English prison architecture 1750-1840, Cambridge, 1982; Tomlinson, M.H., Victorian Prisons: Administration and Architecture 1835-1877, PhD Dissertation, University of London, Bedford College, 1975.

9. Physick, J., *The Victoria and Albert Museum; The history of its buildings*, Oxford, 1982; Survey of London, *The Museums Area of South Kensington and Westminster*, Vol. XXXVIII, London, 1975.

10. Hamilton-Baillie, Brig. J., 'Nineteenth Century Concrete and the Royal Engineers'', *Concrete*, March/April, Vol. 14, 1980, pp 12-16 and pp 18-22; Vincent, E., *Military Construction Techniques in the Use of Building Materials in British North America, 1820-1870*, Parks Canada Microfiche Report Series 156, 1985.

1. The Corps: Background, Training and Duties

1. Boyd, D., *Royal Engineers*, London, 1975, p. xxii; Smyth, J., Sir, *Sandhurst: The History of the Royal Military Academy, Woolwich, the Royal Military College, Sandhurst, and the Royal Military Academy, Sandhurst 1741-1961*, London, 1961, p. 17.

2. Smyth, *Sandhurst*, p. 32.

3. Boyd, *Royal Engineers*, p. 9.

4. Vibart, H., *Addiscombe: Its Heros and Men of Note*, Westminster, 1894, pp. 3 and 9.

5. These artisan soldiers were founded originally as the Soldier-Artificer Company(1772)but became the Corps of Royal Military Artificers (1787) and the Royal Sappers and Miners (1812). Connolly, T.W.J., *History of the Royal Sappers and Miners*, London, 1857, Vol 1, pp 1-185.

6. Ahlström, G., *Engineers and Industrial Growth*, London, 1962, pp.21 and 27; Artz, F.B., *The Development of Technical Education in France 1500-1850*, Cambridge, Massachusetts, 1966, p. 161; Emmerson, G.S., *Engineering Education: A Social History*, Newton Abbot, 1973, p. 22; Mainstone, R., 'Introduction', in Collins, A.R., (Editor), *Structural Engineering: Two Centuries of British Achievement*, London, 1983, pp. 11-14; Sutherland, R.J.M., 'Pioneer British Contributions to Structural Iron and Concrete: 1770-1855', in Peterson, C.E. (Editor), *Building Early America*, Radnor, Pennsylvania, 1976, p. 96.

7. Spiers, E.M., *The Army and Society 1815-1914*, London, 1980, p. 11.

8. Porter, W., *History of the Corps of Royal Engineers*, Vol 1, London, 1889, pp. 397, 399, 400, 406, 407, 408.

9. BSP/1857/Sess1/V1, 1, Report of the Commission Appointed to Consider the Best Mode of Re-Organizing the System of Training Officers for the Scientific Corps, p.388.

10. Vibart, *Addiscombe*, p. 315.

11. BSP/1871/XIV/139, Report of a Committee Appointed to Inquire into the Employment of Officers of the Royal Engineers in Civil Departments of the State, pp. 158 and 149.

12. Buchanan, R.A., 'Institutional Proliferation in the British Engineering Profession, 1847-1914', *Economic History Review*, 2nd Series, Vol 38, 1985, p.43.

13. Buchanan, R.A., 'Diaspora of British Engineering', *Technology and Culture*, Vol 27, No 3, July 1986, p. 508.

14. Ibid, p. 507. Buchanan has shown how British engineers remained isolated until after 1830, military engineers being a notable exception.

15. Otley, C.B., 'The Social Origins of British Army Officers', Sociological Review, New Series Vol 18, No 2, July, 1970, p. 214; Smyth, Sandhurst, pp. 31 and 90. It was not until 1863, however, that all cadets at the Royal Military Academy were products of the new system of admission by open competition.

16. Otley, Sociological Review, p.214; Spiers, The Army and Society, p. 1.

17. Spiers, The Army and Society, p. 1; Burn, W.L., The Age of Equipoise, London, 1964, p. 257.

18. Quoted in Otley, Sociological Review, p. 216.

19. Ibid, p. 231; Spiers, The Army and Society, pp. 6-7.

20. The upper classes comprised 24% in the period 1805-1834. Razzell, P.E., 'Social Origins of Officers in the Indian and British Home Army:1758-1962', British Journal of Sociology, Vol 14, 1963, pp. 248-249 and 250-251.

21. Crouzet, F., The First Industrialists: The problem of Origins, Cambridge, 1985, pp64 and 126. As Crouzet has pointed out, his analytical model is not strictly speaking 'scientific'. According to the usual method of statistical study, sampling is done from a corpus of data and consists in selecting some of those data according to rules previously decided upon (for example, every tenth household in a census list or all the individuals whose name begins with B in parish registers). The sample should also be stratified in order to take into account the relative importance of various activities as well as the size and duration of activity. The group which I have used is extremely small and the samples, like Crouzet's, are not scientific because they are neither random nor stratified, although they are random in the sense that availability of biographical information has some, but only some, random character. On the limitations of the analytical model see Crouzet, pp 55-56. Crouzet's model was selected over those used by scholars for analysis of the origins of British army officers because it provided a more practical and detailed list of occupational categories for my purposes.

22. Spiers, The Army and Society, p. 14.

23. Otley, Sociological Review, p. 215.

24. Spiers, The Army and Society, p. 20; Porter, History of the Royal Engineers, p. 407.

25. Reader, W.J., Professional Men: The Rise of the Professional Classes in Nineteenth Century England, London, 1966, p.75.

26. Ibid, p.98

27. Spiers, The Army and Society, p.23.

28. Emmerson, Engineering Education, p. 249; Buchanan, Economic History Review, pp. 46-47; Reader, Professional Men, pp. 70, 147, 149, 163-166; Wilton-Ely, J., 'The Rise of the Professional Architect in England', Kostof, S. (Editor), The Architect: Chapters in the History of the Profession, New York, 1977, pp. 199 and 202.

29. Buchanan, R.A., 'Gentleman Engineers: The Making of a Profession', Victorian Studies, Vol 26, Summer 1983, pp. 407-429; Wilton-Ely, The Architect, pp 117 and 199.

30. These are also based on Crouzet's model and are subject to the same limits concerning scientific validity as explained in note 21 above.

31. H. Brandreth, W.T. Denison, F. Fowke, H.D. Harness, W. Innes, H. James, W. Jervois, C.W. Pasley and H.Y.D. Scott were members of the Institution of Civil Engineers. C.W. Pasley was elected to the Institute of British Architects in 1842. See biographies in Appendix A.

32. This was C.W. Pasley. Gibb, Sir A., The Story of Telford, London, 1935, p. 200; Buchanan, Victorian Studies, p. 42o.

33. This was F. Fowke. See chapter seven.

34. W.T. Denison, H.Y.D. Scott and J. (Buster) Browne won the Telford prize for papers delivered to the Institution of Civil Engineers. D. Galton was an example of an engineer officer who distinguished himself in another engineering association. He became vice president of the Institution of Mechanical Engineers. Galton was also a member of the Institution of Electrical Engineers. See biographies in Appendix A.

35. Smyth, Sandhurst, p. 17; Harries-Jenkins, G., The Army in Victorian Society, London, 1977 , pp. 114-115.

36. BSP/1857/Sess 1/ VI, 1, p.287. Admission age after 1870 was fixed at 16 to 18. See Smyth, Sandhurst, p. 115.

37. Ibid, p.287

38. See Appendix E.

39. BSP/1857/Sess 1/VI/1.

40. Ibid,p. 290 and pp. 403-404.

41. Ibid, p. 294.

42. DNB, Vol.10, pp. 351-353; DNB, Vol. 8, p. 546.

43. Dictionary of Scientific Biography, Vol IV, pp 527-539; Chambers Biographical Encyclopedia of Scientists, p.1.

44. Barlow, P., A Treatise on the Strength of Materials, Edited by William Humber, London, 1867, pp iii-viii; Smyth, Sandhurst, p.38.

45. Hogg, O.G.F., The Royal Arsenal, Vol 1, London, 1963, p. 191, note 50; Colvin, H., A Biographical Dictionary of British Architects 1600-1840, New York, 1978, p. 501.

46. Smyth, Sandhurst, p. 34.

47. MPICE , Vol 75, p. 319.

48. Smyth, Sandhurst, p. 63.

49. Ibid, p. 63.

50. Harries-Jenkins, The Army in Victorian Society,pp. 116-117.

51. In the period 1841-1855 there were 36 final exams with 525 cadets going to the Royal Artillery and 205 to the Royal Engineers. On 31 occasions the top cadet chose the Engineers and on 23 occasions the top 1/3 of the class joined the top cadet in choosing the Engineers. BSP/1857/Sess1/VI, pp 388 and 390; Harries-Jenkins, The Army and Society, p. 117.

52. BSP/1857/Sess1/VI,1, pp 266 and 280; Vibart, Addiscombe, pp 17-18.

53. Vibart, Addiscombe, pp 43 and 140.

54. Ibid, pp 80-81.

55. Pasley, C.W., Course of Instruction Originally Composed for the Use of the Royal Engineer Department, Vol 1, London, 1814, pp. iv-v; Porter, History of the Royal Engineers, pp 170-171; Pasley, C.W., Course of Military Instruction Originally Composed for the Use of the Royal Engineer Department, Vol II, London, 1817, p. vi.

56. Porter, History of the Royal Engineers, p.172; Conolly, History of the Royal Sappers and Miners, p.185.

57. Kealy, P.H. Lieut-Col. RE (retired), Sir Charles Pasley 1780 to 1861, London, 1930, ppp 2-12; DNB, Vol 15, pp 439-442; Harries-Jenkins, The Army and Victorian Society, pp 105-107.

58. Lancaster was a son of a soldier and established a primary school in London on his father's property in 1798. He published a book on improvements in education (1803). Bell had served for nine years as an army chaplin in Madras, India where he was superintendent of a school for soldiers' sons. There he introduced a method of using older boys to teach the younger ones. Bell also published a pamphlet on his educational experiment. Both systems used a simple instruction card or textbook, divided the children into groups or squads and had a more advanced child act as tutor, each child working in his squad until he had learnt the required work and then was promoted. Lancaster went much farther and introduced monitors, children of superior ability and character who examined the different squads and saw who was ready for promotion. Sturt, M., The Education of the People: A history of primary education in England and Wales in the nineteenth century, London, 1967, pp 19-37; Pasley, Course of Instruction, Vol I, 1814, p.vi.

59. Pasley, C.W., Course of Instruction Originally Composed

for the Use of the Royal Engineer Department, Vol I, London, 1814; Pasley, C.W., Course of Military Instruction Originally Composed for the Use of the Royal Engineer Department, Vo II & III, London, 1817.Pasley said he published these works to diffuse knowledge to the " lower classes" in as much as they would increase the ingenuity of masons and carpenters without whose aid the designs of architects and civil engineers could not be executed. The books were also aimed at young gentlemen who had received a classical education, for self improvement. Pasley, Course of Instruction, Vol I, 1814, p. iv-vii

60. Pasley, C.W., Standing Orders for An Establishment for Instructing the Junior Officers and the Non-Commissioned Officers and Soldiers of the Royal Engineer Department in Their Duties in the Field, Chatham, 1818, pp 129-133 .

61. Pasley, C.W., Course of Instruction,Vol I, p.iv. Peter Nicholson (1765-1844) published The New Carpenters Guide (1792), The principles of Architecture (1795-8), The Carpenter's and Joiner's Assistant (1797), The Architectural Dictionary (1812-19 in two volumes), The Student's Instructor in Drawing and Working the Five Orders of Architecture (1795) and Mechanical Exercises or the Elements and Practice of Carpentry, Joinery, etc (1811). See Colvin, Dictionary of British Architects, pp 593-594.

62. Pasley, Course of Instruction, Vol I, pp v-vii.

63. Sandeman, E.E.N., Lieut-Col, RE, Notes on the History of School of Military Engineering and the Royal Engineers Depot at Chatham, Unpublished manuscript, Corps Library, Institution of Royal Engineers, Chatham, 1961, p. 5.

64. Pasley, C.W., Outline of a Course in Practical Architecture, Chatham, 1862, p. 2.

65. Ibid, pp 1-12.

66. Sandeman, History of the School of Military Engineering,p.5.

67. BSP/1862/XXXIII/507, Report of the Barrack Works Committee, p. 570.

68. Ibid, p.370. It later decreased to about 20 working days by 1860. The average number of engineer officers instructed per year was 6.3 (1825-35 ,9.6 (1835-45)and 17.8 (1845-56). BSP/1857/Sess 1/VI, 1, p. 379.

69. Pasley, Course of Instruction, Vol I, p.218.

70. Pasley, C.W., Course of Practical Architecture, Lithograph, Chatham, 1826, pp 7-27, 40-45.

71. Crook has suggested that the connection may possibly be traced to the fact that General Sir John Malcolm, one of Smirke's leading Tory patrons, was also Pasley's cousin. See Crook, J.M.,'Sir Robert Smirke: Pioneer of Concrete Construction', Transactions of the Newcomen Society, Vol 38, 1965/66, p.11.

72. Pasley, Course of Practical Architecture, 1826, pp 178-182, 183-184, 229-237, 252-254.

73. Smith, F. Sir, Abstract of Orders for the Officers Doing Duty at the Royal Engineer Establishment, Chatham, Lithograph, Chatham, June 1847, pp 30-31.

74. BSP/1857/Sess1/VI,1, pp 377-378

75. Collinson, General, General Sir Henry Drury Harness, London, 1903, pp 2-7 and 201.

76. Ibid, p.214.

77. Ibid, p. 217.

78. Ibid, pp 212 and 242; BSP/1862/XXXXIII/507, p. 570.

79. Sandeman, History of the School of Military Engineering p. 18; McNicoll, R., The Royal Australian Engineers 1835 to 1902: The Colonial Engineers, Canberra, 1977, pp 107-11 and 172.

80. Sandeman, History of the School of Military Engineering,p.18.

81. Simmons, J.L. Col RE, Standing Orders of the SME, Chatham, 1875, p. 41; Edwards, J. B., Col RE, Standing Orders of the SME, Chatham, 1887, p.32

82. BSP/1862/XXXIII/682 Report of the Barrack Works Committee. pp 684-685. This description is from the testimony of Lieut. Col. Richard Strachey (1817-1908) of the Bengal Engineers, an important contributor to canal works for irrigation, railways and the reform of the Public Works Department. Originally commissioned in the Bombay Engineers in 1836, Strachey arrived in India that same year. He was transferred to the Bengal Engineers in 1839. From his testimony it appears that the training programme for engineer officers in India which he described had been in place since his arrival. For details of his career see DNB (1901-11), pp 439-442.

83. Spiers, The Army and Society, pp 151-152.

84. BSP/1862/XXXIII/507, pp 507-510.

85. The Builder,Vol 14 (1856), p.405. The journal kept up this line of criticism in editorials from time to time over the next two years.

86. Burnell, G.R., The Annual Retrospect of Engineering and Architecture, Vol I, January to December 1861, London, 1862, p. 276. George Rowden Burnell (1814-1868) practised civil engineering mainly abroad but also built some buildings in England. He is best known, however, for his extensive contributions to technical literature on engineering and architecture. See Boase, Vol 1, p.485.

87. Ibid, p. 289.

88. BSP/1857/Sess 1/VI,1, pp i-lxxxv; Spiers, The Army and Society , p. 152.

89. BSP/1857/Sess 1/VI, 1, pp lxxxxiii-lxxxiv.

90. Ibid. p. lxxxv.

91. Ibid. p. lxxx.

92. Ibid, pp 354-355.

93. Ibid. pp 368-369.

94. Ibid, p. 363.

95. Ibid, pp 363-364.

96. Ibid, p.364.

97. BSP/1862/XXXIII/507, p. 570.

98. Ibid, p.571.

99. Ibid, p. 581.

100. Ibid, p. 583.

101. Ibid, p. 582.

102. Ibid, p.583.

103. Ibid, p. 687. On Strachey's career background see note 82.

104. Reader, *Professional Men*,pp 117-125; Ahlstrom, *Engineers and Industrial Growth*, pp 82-85; Emmerson, *Engineering Education*, pp 54-56, 60-64 and 118-120; Musson, A.E. and Robinson, E., *Science and Technology in The Industrial Revolution*, Manchester, 1969, pp 72-76; Cardwell, D.S.L., *The Organization of Science in England*, Revised Edition, London, 1972, p. 58; Buchanan, R.A.,'Science and Engineering: A Case Study in British Experience in the Mid-Nineteenth Century', *Notes and Records of the Royal Society*, Vol 32, 1978, pp 215 and 221; Buchanan, *Victorian Studies*, pp 422-429; Wilton-Ely, *The Architect*, pp 197-199; Harries-Jenkins, *The Army in Victorian Society* , pp 148 and 150-51.

105. BSP/1857/Sess 1/VI, 1, p. 376.

106. Ibid , p. 380.

107. Collinson, *Harness* , p. 197.

108. As explained in the introduction, the *Professional Papers* were published more or less annually from 1837 until after 1900, in several series and under different titles. The principal new architectural and civil engineering periodicals of the 1830's and 1840's were *The Civil Engineer and Architect's Journal* (1837), *Transactions and Minutes of the Proceedings of the Institution of Civil Engineers* (1837), *Transactions of the Institute of British Architects* (1837), the *Surveyor, Engineer and Architect* (1840) and *The Builder* (1842). See Jenkins, F., 'Nineteenth-Century Periodicals', in Summerson, J., (Editor), *Concerning Architecture*, London, 1968.

109. Denison, W.T., 'Introduction', PP, Vol. 1 (1837), p. 1.

110. Ibid, pp 3-4.

111. PP, Vol. 2 (1838), pp v-vi.

112. Ibid, p. xi.

113. James, H., 'Preface', PP, Vol. IX (1847), pp vi-viii.

114. Ibid, p. vii.

115. CEAJ, Vol 1 (1837-38), p. 5.

116. CEAJ, Vol VIII (1845), p. 60.

117. Ibid, p. 93.

118. BSP/1857/Sess 1/VI, 1, p. 351

119. Professional Papers on Indian Engineering, Vol i (1863-1864), p. 1; Sandes, E.W.C., The Military Engineer in India, Vol II, London, 1935, pp 358 and 362.

120. The earliest engineering education institution in India was the Madras Surveying School (1794) which was placed under the Engineers Department of the Board of Revenue in 1846 and eventually became part of the Public Works Department. Civil engineering colleges were also established at Calcutta (1856), Madras (1859) and Poona (1868). Also, in 1823 Colonel G.R. Jervis (1794-1851) founded at Bombay the 'Engineers Institution' to train native assistants for engineer officers. This lead to the foundation of Elphinstone College (1827) which in 1843 established a class of civil engineering to which Willian Pole was appointed professor (1844-47). Sandes, Military Engineer in India, p. 362; Brown, J.M., 'Contributions of the British to Irrigation Engineering in Upper India in the Nineteenth Century', Transactions of the Newc men Society Vol 55, 1983-84, pp 86-87; MPICE, Vol 11 (1851-52), pp 105-109.

121. Aide Memoire to the Military Sciences Framed from Contributi ns of the Different Services, and Edited by a Committee of the Corps of Royal Engineers. 2nd edition, London, 1853-62. For a good description of the content of the Aide Memoire see: Vincent, E., A Select Annotated Bibliography Applicable to the Study of the Royal Engineers' Building Technology in Nineteenth Century British North America, Parks Canada, Research Bulletin No. 190, March 1983. For a late edition see: Seddon, H.C., Lieut. Col. RE, Aide Memoire for the Use of Officers of the Royal Engineers, Vol II, London, 1883.

122. Anon, Notes on the History of the RE Corps Library 1813-1971, RE Corps Library, Chatham, n.d., pp 1-3; Corps Papers, Vol 1 (1849-50), p. x.

123. Catalogue of the Library of the Corps of Royal Engineers, London, 1847, p.3.

124. Catalogue of Books, Maps and Plans in the General Corps Libraries of the Royal Engineers, London, 1866; Vincent, E., Military Construction Techniques in the Use of Building Materials in British North America, 1820-1870, Parks Canada Microfiche Report Series 156, 1985, p.7.

125. Quoted in Harries-Jenkins, The Army in Victorian Society, p.118.

126. Porter, History of the Royal Engineers, p. 4 .

127. BSP/1862/XXXIII/507, pp 511-514.

128. Porter, History of the Royal Engineers, pp 2-3; Roderick, G. and Stephens, M., Where Did We Go Wrong? Industrial Performance, Education and the Economy of Victorian Britain, Barcombe, 1981, pp 176-177; Cardwell, The Organization of Science, p. 116; Burn, Age of Equipoise, p.224.

129. Porter, History of the Royal Engineers, p. 408; BSP/1871/XIV/139, Report of a Committe appointed to inquire into the Employment of Officers of the Royal Engineers in Civil Departments of the State, pp 147-148.

130. The first Inspector-General of Railways, Lieut. Col. Sir Frederic Smith was paid only £900 a year of which £570 was his military pay. This was cheaper than hiring a civil engineer for the job. Parris, H., Government and the Railways in Nineteenth Century Britain, London, 1965, p. 32. Railway inspector F.H. Rich's salary in 1872 was only £1,000. BSP/1872/XXXVII/747. The salary of the Director of the Admiralty Works Department in 1838-39 was only £403 plus service pay. By 1847-48 it had risen to £1,000 total. BSP/1837-38/XXXVII/185, Navy Estimates;BSP/1847/XXV/125, Navy Estimates. In 1872 C. Pasley (son of C.W. Pasley), superintendent of Admiralty works at Chatham received only £750 per year and the director of the Works Department, Sir Andrew Clarke, got the modest sum of £1,300. BSP/1872/XXXVII/747, Return of number etc of Royal Engineers in Civil Service Employment.

131. BSP/1872/XXXVII/747

132. BSP/1871/XIV/139, Extract from a memorandum from Sir John Burgoyne, 22 March 1857,onthe Advantages of the Royal Engineers in Civil Service

133. Cole, H. Sir, Fifty Years of Public Works, Vol. II, London, 1884, p. 327.

134. Tyler, H.W. Capt., PP, NS, Vol. XIII (1863), pp xiii-xiv.

2. Experiments at the Royal Engineer Establishment

1. On the relationship between science and engineering and the British empirical tradition see: Buchanan, R.A., 'In Memoriam: Stanley Baines Hamilton 1889-1977', TNS, Vol. 51, pp 1-5; and Buchanan, R.A., 'Science and Engineering: A Case Study in British Experience in the Mid-Nineteenth Century', *Notes and Records of the Royal Society*, Vol. 32, (1978) pp 215-23.

2. Pasley, C.W., *Course of Instruction Originally Composed for the Use of the Royal Engineer Department*, Vol. III, London, 1817, p. 493 et seq. Pasley's *Course of Elementary Fortification* was the first fully comprehensive English work on fortification in the nineteenth century: see, Hughes, Q., *Military Architecture*, London, 1974, pp 158-159. Pasley also referred to these model experiments in his monumental work on limes and cements as an argument in favour of the adhesive strength of cement mortar which ensured the stability of wharf walls built without counterforts. See, Pasley, C.W., *Observations on Limes, Calcareous Cements, Mortars, Stuccos and Concrete and on Puzzolanas, Natural and Artificial etc.*, London, 1838, p. 261. The prevailing theory of the line of thrust or pressure which influenced the design of retaining walls was that developed by Frenchman Charles Augustin de Coulomb (1736-1806) in 1773. Notwithstanding Pasley's experiments, or later the theoretical work of W.S. Macquoren Rankine (1820-1872), Coulomb's theory continued to be used well into the nineteenth century. See, Timoshenko, S.P., *History of Strength of Materials*, London, 1953, p. 211.

3. Smith, D., 'Structural Model Testing and the Design of British Railway Bridges in the Nineteenth Century', TNS, Vol. 48 (1976-77), p. 73; Smith, D., 'The Use of Models in Nineteenth Century British Suspension Design', *History of Technology*, 2nd Annual Volume, 1977, p. 169.

4. In 1843 Lieut. Hope undertook similar experiments to Pasley's also using wooden models and with the objective of testing Coulomb's theory to determine which form of revetment would resist the pressure of earth behind it with the least quantity of masonry. He also tried experiments on a full scale brick wall when he became dissatisfied with the results of the wooden model experiments. Unfortunately, Hope's sudden and premature death in 1844 put an end to these experiments before solutions were found to the optimum design for retaining walls. See, 'Experiments carried on at Chatham by the late Lieutenant Hope, Royal Engineers, on the Pressure of Earth Against Revetments, and the Best Form of Retaining Walls', PP, Vol. VIII (1845) pp 69-86.

5. Draffin, J.O., 'A Brief History of Lime, Cement, Concrete and Reinforced Concrete', in Newlon, H.J., A Selection of Historic American Papers on Concrete 1876-1926, Publication SP-52, American Concrete Institute, Detroit, 1976, pp 6-8; Halstead, P.E., 'The Early History of Portland Cement', TNS, Vol. 34, 1961-62, pp 37-54; Thurston, A.P., 'Parker's Roman Cement', TNS, Vol. 19, 1938-39, pp 193-206; Skempton, A.W., 'Portland Cements', TNS, Vol. 35, 1962-63, pp 146-148; Crook, J.M., 'Sir Robert Smirke: A Pioneer of Concrete Construction', TNS, Vol. 38, 1965-66, pp 5-22.

6. Skempton, TNS, Vol. 35, pp 117-128 and 138-139; Brown, J.M., 'W.B. Wilkinson (1819-1902) and his place in the History of Reinforced Concrete', TNS, Vol. 39, 1966-67, pp 129-142.

7. Pasley, Observations, 1838, p. 1.

8. Pasley, C.W., Outline of a Course of Practical Architecture, Chatham, Lithograph, 1826; Nilsson, S., European Architecture in India 1750-1850, London, 1968, p. 170.

9. It was not only British military engineers that had these concerns in the early nineteenth century. General Joseph Gilbert Totten (1788-1864) of the U.S. Corps of Engineers undertook artillery resistance experiments on limes, cements and concrete in fortifications at Fort Adams, Rhode Island, in 1836. See, Gillmore, Q.A. Lieut. Col., Practical Treatise on Limes, Hydraulic Cements and Mortars, New York, 1874, pp 80, 184-185 and 252-253.

10. Francis, A.J., The Cement Industry 1796-1914: A History, Newton Abbot, 1977, p. 13; Hudson, K., Building Materials, Chatham, 1972, pp 49-50.

11. Draffin, Selection of Historic American Papers on Concrete, p. 6.

12. Ibid, p. 7.

13. Ibid, p. 7.

14. Thurston, TNS, Vol. 19, pp 193-206.

15. Skempton, TNS, Vol. 35, p. 131.

16. Ibid, p. 148; Draffin, Historic American Papers on Concrete, p. 6.

17. Pasley, Observations, 1838, p. iii.

18. Pasley, C.W., 'Letter to Dr. Garthe on Portland Cement', Polytechnisches Journal, Vol. CXXXIV, p. 27, quoted in Redgrave, G.R. and Spackman, C., Calcareous Cements, London, 2nd Edition 1905, pp 33-34.

19. Pasley, Observations, 1838, p. 1.

20. Ibid, p. 1. Reid was commissioned in 1809. He is best known for his meteorological work, especially his publication of Law of Storms (1838) which went through several editions and was translated into many languages. Reid had first studied this phenomenon while in the West Indies, during which time he also undertook the repair of buildings damaged by hurricanes and developed methods to strengthen structures against this natural calamity. He was elected a fellow of the Royal Society in 1839. Reid also acted as the Chairman of the Executive Committee of the Great Exhibition of 1851. DNB, XVI, pp 883-887.

21. Pasley, Observations, 1838, pp 3, 64, 67 and 70-72.

22. Pasley, C.W., Observations Deduced from Experiment Upon Natural Water Cements of England and on the Artificial Cements that May be Used As a Substitute for Them, Chatham, 1830, p. ii.

23. Pasley, Observations, 1838, p. 122.

24. MPICE, Vol. 1 (1837), pp 17-19.

25. Pasley, Observations, 1838; Pasley, C.W., Observations on Limes, Calcareous Cements, etc., 2nd Edition, Part 1, London, 1847. The second part which promised up-dated information was never produced. Pasley told Dr.Garthe of Cologne in a letter of 3 March 1852 that following his term as director of the Royal Engineer Establishment in 1841 he had "neither assistants, materials, nor appliances at my disposal" and was therefore "no longer in the position to prosecute researches of a similar nature to those formerly carried on... which resulted in the discovery of an artificial cement but little inferior to the best natural cement." See, Pasley, Polytechnisches Journal, Vol. CXXIV, p. 27.

26. Pasley, Observations, 1830, p. ii.

27. Pasley, Observations, 1838, pp 101 and 109.

28. Williams, E.P., The Selected Correspondence of Michael Faraday, Vol. 1, Cambridge, 1971, pp 311-312.

29. Pasley, Observations, 1838, p. 67. Nash's kiln was 4 feet in diameter at the top and 6 feet deep. It had been chiefly built for experimental purposes. Pasley used it to make four batches of 140 cu. ft. each of raw cement in 1830. He also used it in 1831 and 1832. Ibid, pp 67-69.

30. Ibid, Appendix, pp 14-16.

31. Ibid, Appendix, p. 15.

32. Ibid, Appendix, p. 16.

33. Mechanic's Magazine, Vol. 36 (1842), p. 311. Frost went to America after selling his works in 1833.

34. Pasley, Observations, 1838, pp 79-80 and 107-109; Skempton, TNS, Vol. 35, p. 133; Draffin, Historic American Papers on Concrete, pp 13-14.

35. Pasley, Observations, 1838, p. 80.

36. Ibid, pp 112 and 125; Draffin, Historic American Papers on Concrete, p. 14.

37. Ibid, pp 145-154.

38. Ibid, pp 82-84.

39. Redgrave and Spackman, Calcareous Cements, p. 205; Draffin, Historic American Papers on Concrete, p. 14.

40. Redgrave and Spackman, Calcareous Cements, pp 206-207; Skempton, TNS, Vol. 35, pp 119-121.

41. Grant, J., 'Further Experiments on the Strength of Portland Cement', MPICE, Vol. 32 (1870-71), pp 319-324; Innes, Capt. W., 'Notes on the supply, storage and testing of Portland Cement, PPNS, Vol. 21 (1873), pp 1-8.

42. Draffin, Historic American Papers on Concrete, p. 14.

43. Ibid, p. 13. Vicat, L.J. (Translation by J.T. Smith), A Practical and Scientific Treatise on Calcarious Mortars and Cements, Artificial and Natural, London, 1837, p. 303 and Plate 2.

44. Pasley, Observations, 1838, p. 152.

45. Mechanic's Magazine, Vol. 28 (1837-38), p. 22.

46. Pasley Papers, Add MS 41766, British Library, Tyler, John Charles, Col., General Sir Charles William Pasley, his family and career, 1929.

47. Vignoles, K.H., Charles Blacker Vignoles: romantic engineer, Cambridge, 1982, p. 38. Vignoles' plan was turned down and Marc Brunel completed the tunnel with the assistance of his famous son Isambard Kingdom Brunel.

48. Pasley, Observations, 1838, pp 170-180.

49. Ibid, p. 175.

50. Ibid, p. 175.

51. Skempton, TNS, Vol. 35, p. 131; Draffin, Historic American Papers on Concrete, p. 10.

52. Skempton, TNS, Vol. 35, pp 129-132.

53. Francis, The Cement Industry, p. 12.

54. Pasley, Observations, 1838, Appendix, p. 17.

55. Pasley, Observations, 1847, p. XIV. Sir William Tite, Vice President of the Institute of British Architects, made the same point in May 1845 while endorsing the manufacture of Portland cement. See, Redgrave and Spackman, Calcareous Cements, p. 36.

56. Pasley, Observations, 1847, p. XIV; CEAJ, Vol. X (1847), p. 310.

57. CEAJ, Vol. X (1847), p. 311.

58. White, G.F., 'Observations on Artificial Hydraulic or Portland Cement etc.', MPICE, Vol. Xl (1852), p. 480.

59. Quoted in Redgrave and Spackman, Calcareous Cements, p. 42.

60. Skempton, TNS, Vol. 35, p. 137.

61. He mentioned the firm (and its Portland cement) as one of three manufacturers of artificial cement in 1847. See Pasley, Observations, 1847, p. XIV.

62. He told Dr. Garthe of Cologne in a letter of 3 March 1852 that his attention had been drawn to the alleged superiority of Portland cement over Roman cement by a display of the former at the Great Exhibition of 1851 but said it was "neither more nor less than my own artificial cement, compounded of chalk and clay". See Redgrave and Spackman, Calcareous Cements, p. 34.

63. MPICE, Vol. XVI (1857), pp 443-444.

64. Seddon, H.C., Lieut. Col. RE, Aide Memoire for the Use of Officers of Royal Engineers: Vol. II Permanent Engineering Works, London, 1883, p. 422.

65. Francis, Cement Industry, p. 47; Brunel also used reeds, straw, hemp and lathes of wood as reinforcement materials.

66. Ibid, p. 48.

67. Pasley, Observations, 1838, pp 161-163; Brunel, M.I. 'Particulars of Some Experiments on the Mode of Building Brick Construction', Transactions of the Institute of British Architects, Vol. 1, Part 1, (1835-36), pp 61-64.

68. Pasley, *Observations*, 1838, pp 162, 240 and 273; Francis, *Cement Industry*, pp 51-52; Francis, C.L., 'On the Brick Beam at Nine Elms', MPICE, Vol. 1 (1838), p. 16.

69. Francis, C., MPICE Vol. (1838), p. 16.

70. Brunel, M., 'Cement and Iron Hooping', MPICE Vol. 1 (1838), p. 20.

71. Pasley, *Observations*, 1838, p. 233; *Mechanics Magazine*, Vol. 28 (1837-38) p. 16 and pp 22-23. The first beam was broken down 27 September 1837.

72. Pasley, *Observations*, 1838, pp 233-234. Brunel's was 22 feet 9 inches between bearings; Francis' was 21 feet 4 inches.

73. Sutherland, R.J.M., 'Pioneer British Contributions to Structural Iron and Concrete: 1770-1855', Peterson, C.E. (Editor), *Building Early America*, Radnor, Pennsylvania, 1976, p. 113.

74. Pasley, *Observations*, 1838, p. 235.

75. Ibid, p. 239.

76. Ibid, pp 243-244.

77. *Mechanic's Magazine*, Vol. 28 (1837-38), p. 16.

78. Pasley, *Observations*, 1838, p. 117; Francis, *Cement Industry*, p. 49. Brunel recommended coating hoop iron with hot pitch and dusting it over with sand or brick dust. Brunel, *Transactions of the Institute of British Architects*, Vol. 1, Part 1, (1835-36), p. 64.

79. Pasley, *Observations*, 1838, p. 169.

80. B, Vol. V (1847), p. 33.

81. Sutherland, *Building Early America*, p. 113.

82. *Mechanic's Magazine*, Vol. 28 (1837-38), p. 23.

83. BSP/1844/XXVIII/129, Report of the Surveyor General on the Construction, Ventilation and Details of Pentonville, Prison, p. 146; Galton, D., *Report on the Herbert Hospital at Woolwich*, HMSO, London, 1865, p. 27 Art. 30; Colson, C. 'Portsmouth Dockyard Extension Works, MPICE, Vol. 64 (1880-81) Part 2, pp 124-125.

84. Sutherland, *Building Early America*, p. 113.

85. Hamilton-Baillie, J.R.E., Brig., 'Nineteenth Century Concrete and the Royal Engineers', *Concrete*, Vol. 14, 1980, p. 14.

86. Francis, *Cement Industry*, p. 127; on Wilkinson see: Brown, J.M., 'W.B. Wilkinson (1819-1902) and his place in the History of Reinforced Concrete', TNS, Vol. 39 (1966-67) pp 129-142. Wilkinson was more likely to have got the idea from J.B. White and Sons' reinforced brick beam test at the Great Exhibition of 1851 but this too is far fetched. See: White, G.F., MPICE, Vol. 2 (1852), pp 478-510.

87. The patents were taken out by Johann Franz Kleine for reinforced brick floors as an alternative to reinforced concrete. Hamilton, S.B., 'The History of Hollow Bricks', *Transactions, British Ceramic Society*, Vol. 58, No. 2, Feb. 1959, p. 56.

88. Collins, P., *Concrete: The Vision of a New Architecture*, London, 1959, pp 24-25; Crook, TNS, Vol. 38 (1965-66), pp 5-22; Reid, Lt. Col., 'Description of the Concrete Sea Wall at Brighton etc.' PP, Vol. 1 (1837), pp 43-47, Taylor, G.L., 'An Account of the Methods Used in Underpinning the Long Storehouse at Her Majesty's Dock Yard, Chatham, in the Year 1834' *Transactions of the Institute of British Architects*, Vol. 1, Part 1 (1836), pp 40-43.

89. Francis, *Cement Industry*, p. 56.

90. Pasley, *Observations*, 1838, pp 265-269.

91. Ibid, pp 23-270; Reid, Lieut. Col., 'Description of the Concrete Sea Wall at Brighton and the Groins which defend the Foot of it, PP, Vol. 1 (1837) pp 43-47; Denison, Lieut., 'Notes on Concrete', PP, Vol. 2 (1838), pp 263-266.

92. Pasley, *Observations*, p. 19; Harding, George, J. 'Description of a Concrete Bomb-Proof Erected at Woolwich With Detailed Experiments as to the Effect Produced on it by Artillery Fire', PP, Vol. 1 (1837), pp 33-42.

93. Pasley, *Observations*, 1838, p. 84.

94. Ibid, pp 85-86.

95. Hamilton-Baillie, *Concrete*, Vol. 14, 1980, p. 13.

96. Pasley, *Observations*, 1838, p. 144.

97. Denison, PP, Vol. 2 (1838), pp 263-264; Pasley, *Observations*, 1838, p. 254.

98. Denison, PP, Vol. 2 (1838), p. 266.

99. Pasley, *Observations*, 1939, p. 145.

100. Ibid, pp 21-22.

101. Ibid, p. 22.

102. CEAJ, Vol. 1 (1837-38), p. 6.

103. Scott, Capt. H. 'On Concrete as a Substitute for Brick and Stone Masonry in Works of Fortification', PPNS, Vol. 11 (1862), p. 227.

104. Crook, TNS, Vol. 38 (1965-66), pp 5-22.

105. Pasley, Observations, 1838, p. viii.

106. Mahan, D.H., An Elementary Course of Civil Engineering, Edited by Peter Barlow, Edinburgh, 1845.

107. Burnell, G., Rudimentary Treatise on Limes, Cements, Mortars, Concretes, Mastics, Plastering Etc., London, 1850, p. 71.

108. Ibid, p. 77. Burnell mentioned the artificial stone of Frederick Ransome of Ipswich patented 1844.

109. Pasley, Observations, 1838, p. iii.

110. Ibid, p. iii.

111. Ibid, pp iii and ix.

112. Ibid, p. iv.

113. White, G.F., MPICE, Vol. 2 (1852), pp 503 and 507.

114. Mechanic's Magazine, Vol. 36 (1842), p. 311.

115. CEAJ, Vol. X (1847), p. 310.

116. Ibid, p. 310.

117. B, Vol. V (1847), p. 521.

118. Burnell, Rudimentary Treatise on Limes and Cements, pp iii, v, 40-41.

119. Scott, H.Y.D., Capt. 'Observations on Limes and Cements; their Properties and Employment', PPNS, Vol. XI (1862), p. 26.

120. Seddon, H.C., Lieut. Col., RE, Aide-Memoire for the Use of Officers of the Royal Engineers, Vol. II - Permanent Engineering Works, London, 1883.

121. Mahan, Elementary Course of Civil Engineering, p. vii.

122. Gillmore, Q.A., Practical Treatise on Limes, Hydraulic Cements and Mortars, New York, 1874. (Original in Professional Papers of the Corps of Engineers U.S.A., No. 9, 1863).

123. Faija, H., *Portland Cement for Users*, 3rd edition, London, 1890, p. 105.

124. DNB, Vol. 17, pp 964-965; MPICE, Vol. 75, p. 319-322; Scott, Capt. H., 'Account of a New Cement, And of the Experiments Which Led to Its Discovery', PPNS, Vol. VI (1857), pp 143-145.

125. Scott, PPNS, Vol. VI (1857), pp 146-148; Scott, H. Capt., 'Account of the Manufacture of a New Cement Invented by Captain H. Scott, RE', PPNS, Vol. X (1861), pp 132-158: Scott, H.Y.D., Capt., RE., 'A Short Account of Scott's Patent Cement', *Papers read at the Institute of British Architects 1856-57*, 1857, pp 152-155; Redgrave and Spackman, *Calcareous Cements*, pp 249-250; Francis, *Cement Industry*, pp 241 and 181-182; *Mechanic's Magazine*, Vol. 68 (1858), p. 253; *Royal Institute of British Architects Sessional Papers 1871-72*, p. 180.

126. Francis, *Cement Industry*, p. 241; Redgrave and Spackman, *Calcareous Cements*, p. 250; MPICE, Vol. 32 (1871), p. 311.

127. Scott, PPNS, Vol. X (1861), pp 144-149; Redgrave and Spackman, *Calcareous Cements*, p. 252.

128. Scott, PPNS, Vol. X (1861), pp 151-153.

129. Redgrave and Spackman, *Calcareous Cements*, p. 251.

130. *Mechanic's Magazine*, Vol. 68 (1858), p. 253.

131. Scott, PPNS, Vol. X (1861), pp 153-155.

132. Watson, J., *Cements and Artificial Stone*, Cambridge, 1922, p. 101; *Mechanic's Magazine*, Vol. 68 (1858) p. 253; B, Vol. 29 (1871), p. 689.

133. Scott, PPNS, Vol. 10, p. 151; Scott, *Papers read at the Institute of British Architects (1856-57)*, 1857, p. 155; Watson, *Cements*, pp 100-101.

134. MPICE, Vol. 75 (1884), pp 319-322; On Q.A. Gillmore see: *Dictionary of American Biography*, Vol. IV, p. 295 and Chamberlin, W.P. 'The Cleft-Ridge Span: America's First Concrete Arch', *IA Journal of Society for Industrial Archeology*, Vol. 9, No. 1, 1983, pp 29-44.

135. Burnell, G.R., *The Annual Retrospect of Engineering and Architecture*, Vol. 1 (Jan to Dec. 1861), London, 1862, pp 284-285.

136. Physick, J., *The Victoria and Albert Museum: The history of its building*, Oxford, 1982, p. 160.

137. Redgrave and Spackman, Calcareous Cements, p. 49.

138. Scott, Capt. H.Y.D., 'Observations on Limes and Cements, their Properties and Employments', PPNS, Vol. XI (1862), pp 15-94.

139. Ibid, p. 94.

140. Scott, Capt. H. 'On Concrete as a Substitute for Brick and Stone Masonry in Works of Fortification', PPNS, Vol. XI (1862), pp 220-239. On Coignet see: Collins, Concrete, pp 27-35.

141. MPICE, Vol. 75 (1884), p. 321.

142. Francis, Cement Industry, p. 242. On Warren de la Rue see: DNB, XVII, pp 387-389 and Dictionary of Scientific Biography, Vol. 2, pp 52-56.

143. Francis, Cement Industry, p. 242.

144. Cole, H. Sir, Fifty Years of Public Works, London, 1884, pp 397-398.

145. On the question of sewage treatment and sanitation see: Wohl, A.S., Endangered Lives: Public Health in Victorian Britain, London, 1984, pp 95-107.

146. Scott, Maj. Gen., 'Clean Drains and Improved Mortars' Royal Institute of British Architects, Sessional Papers 1872, pp 26-29.

147. Ibid, p. 29.

148. Ibid, pp 26-27 and 29-30; Redgrave and Spackman, Calcareous Cements, pp 254-255.

149. Redgrave and Spackman, Calcareous Cements, p. 254.

150. Scott, Royal Institute of British Architects, Sessional Papers 1872, p. 31.

151. Redgrave and Spackman, Calcareous Cements, p. 256.

152. Scott, H.Y.D. Maj. Gen. and Redgrave, G.R., 'The Manufacture and Testing of Portland Cement', MPICE, Vol. 62 (1880), pp 67-86. For notice of the premium award see: Annual Report 1880, MPICE, Vol. 62 (1880), p. 22.

153. See Chapter 5.

154. Innes, W. Capt. 'Notes on the supply, storage and testing of Portland cement', PPNS, Vol. XXI (1873) pp 1-18; Grant, J., 'Further Experiments on the strength of Portland Cement', MPICE, Vol. 32, (1870), pp 319-324.

155. Seddon, H.C., Capt. RE, 'On Present Knowledge of Building Materials And How to Improve It', Royal Institute of British Architects Sessional Papers 1871-72, pp 156-157; also in PPNS, Vol. XXII (1874), pp 35-36.

156. Watson, C.M. History of the Corps of Royal Engineers, Vol. II, Chatham, 1915, p. 159.

157. Watson, Cements and Artificial Stone, p. 53. Skempton, TNS, Vol. 35, pp 138-146; Draffin, Historic American Papers on Concrete, pp 14-17; Francis, The Cement Industry, pp 246-264. The Swiss established national test standards in 1883 followed by the French in 1885. Further German standards came in 1887. The first American 'National' standard was not until 1921. British standards evolved from Grant's tests of the 1860's, Kirkaldy's testing laboratory (1866), Faija's testing works (1875 and D.B. Butler's book of 1899 on test methods), manufacturers' private test laboratories of the 1880's and 1890's, the 1898 Cement Testing Association and the 1901 initiative of the Institution of Civil Engineers in establishing an Engineering Standards Committee. This Committee developed the British Standards Specification 12 for Portland cement (1902-1904).

158. Redgrave and Spackman, Calcareous Cements, p. 275.

159. MPICE, Vol. 62 (1880), p. 185.

160. Ibid, pp 188-189.

161. Ibid, p. 126.

162. Ibid, p. 203.

3. Railway Inspectors and Safe Bridges

1. As explained in Chapter 1, the services of the Royal Engineers could be obtained cheaply. Moreover, the 1840 statute made ineligible for inspection any person who within one year had been a director or held any office in a railway company. This effectively rendered ineligible the great majority of the few British engineers who had railway experience at the time. The regulation was removed in 1844. See: Parris, H., Government and the Railways in Nineteenth Century Britain, London, 1965, pp 30 and 65.

2. Roberts, D., Victorian Origins of the British Welfare State, New Haven, 1960, pp 93-94. Examples of these new departments of central government were the Poor Law Commission (1834), the Factory inspectors (1833), the Prison inspectors (1835), the Mining inspectors (1842 and 1850) and the Merchant Marine Department (1850).

3. Ibid, pp 103 and 118.

4. Ibid, pp 152-159. Examples of engineers or building professionals employed as government inspectors were William Ranger, Robert Rawlinson and Edward Cresy with the General Board of Health. Captain Laffan, a railway inspector, also served on the General Board of Health.

5. Pugsley, A.G., Sir, The Safety of Structures, London, 1966, p. 6.

6. BSP/1880/LXIII/459; BSP/1847/LXIII/266-267.

7. Parris, Government and the Railways, pp 29, 37, 91, 114-115 and 149.

8. Ibid, pp 66, 232 and 129-130.

9. Ibid, pp 140 and 149.

10. Biographical information is not available for all the inspectors but a career profile has been developed for five covering the period 1841 to 1885. Pasley (1841-46) had been a teacher and inventor primarily. His structural knowledge was limited mainly to masonry and timber with very little experience of iron. He had built pontoon and other types of military bridges by way of instruction at the Chatham school and was early interested in suspension bridges and the question of deck stiffening. Coddington (1844-47) served in the Ordnance Survey and Bermuda building fortifications. There is no evidence that he had built bridges. Simmons (1847-50) had been stationed in Canada and was engaged there in construction of fortifications. Once again there is no evidence that he built bridges. Tyler (1853-77) served several years in military engineering works and before his appointment to the inspectorship had apparently specialised in railway work (not specified).

Yolland (1854-85) had first served in Canada then for 15 years with Ordnance Survey and nothing suggests he built bridges. See: for Pasley, DNB, Vol. 15 pp 439-42; *Proceedings of the Royal Society*, Vol. 12, (1863), pp xx-xxv; and Kealy, P.H., Lieut. Col. *Sir Charles William Pasley*, 1780-1861, London, 1930; for Coddington, MPICE, Vol. 14 (1855), pp 165-167; for Simmons, DNB (1901-1911), pp 313 et seq;and Watson, C.M., *History of the Corps of Royal Engineers*, Vol. II, Chatham, 1915, pp 259-266; for Tyler, *The Engineer*, Vol. 15 (1908), p. 146;and *Dictionary of Business Biography*, Vol. 5, pp 591-592; and Yolland, DNB, Vol. XXI, pp 1237-1238.

11. Douglas, Sir Howard, General, *An Essay on the Principles and Construction of Military Bridges and the Passage of Rivers in Military Operations*, 3rd Edition, London, 1853. Sir Howard Douglas (1776-1861) graduated from the Royal Military Academy in 1794 and was commissioned in the Royal Artillery. His book was originally produced in manuscript for senior students at the Royal Military College, High Wycombe,where Douglas had been appointed commandant in 1804. First published in 1816, further editions appeared in 1832 and 1853, the latter considerably revised.

12. Pugsley, *Safety of Structures*, p. 2.

13. On the psychology of public views concerning bridge safety and the response of government and the civil engineering profession in America see: Petroski, H., 'On 19th-Century Perceptions of Iron Bridge Failures, *Technology and Culture*, Vol. 24, No. 4, 1983, pp 655-659.

14. Parris, *Government and the Railways*, p. 91.

15. Rolt, L.T.C., *Isambard Kingdom Brunel*, Harmondsworth, 1980, p. 283; Pugsley, A.(Editor), *The Works of Isambard Kingdom Brunel*, London, 1976, p. 22.

16. MPICE, Vol. IX (1849-50), pp 257 and 271.

17. Ibid, p. 287.

18. Smith, D., 'Structural Model Testing in the Design of British Railway Bridges in the Nineteenth Century', TNS, Vol. 48, p. 82.

19. Simmons, J. (Editor), *The Men Who Built Railways*, A Reprint of F.R. Conder's, Personal Recollections of English Engineers, London, 1983, pp 153-158. I would like to acknowledge and thank James Sutherland for bringing this book to my attention. For a biography of Conder see: MPICE, Vol. 100, pp 379-383. As Simmons has explained, Conder left no mark on railway engineering but went after a time into the business of contracting, and after returning to engineering later in life concerned himself with things other than railways.

20. Pasley Papers, Add MSS, 41989-41992, British Library. See Also: Parris, H., 'A Civil Servant's Diary, 1841-46', *Public Administration*, Vol. 38 (1960), pp 369-380.

21. Simmons, *The Men Who Built Railways*, pp 156-157.

22. Hawkshaw's biography is in:MPICE, Vol. CVI (1891), pp 321-335.

23. MPICE, Vol. XXI (1862), pp 423-424.

24. MPICE, Vol. XXV (1866), pp 258-259.

25. Ibid, p. 260.

26. MPICE, Vol. XXXV (1872-73), pp 359-360.

27. Porter, W., *History of the Corps of Royal Engineers*, Vol. 2, London, 1889, p. 328.

28. Simmons, J., *The Railway in England and Wales 1830-1914*, Leicester, 1978, p. 238.

29. Booth, L.G., 'The Development of Laminated Timber Arch Structures in Bavaria, France, And England in the Early Nineteenth Century', *Journal of the Institute of Wood Science*, Vol. 29, 1972, pp 3-15; Booth, L.G., 'Laminated Timber Arch Railway Bridges in England and Scotland', TNS, Vol. XLIV (1971-72), pp 1-21.

30. Jee, A.S., 'Description of the Dinting Vale Viaduct, on the line of the Sheffield and Manchester Railway', MPICE, Vol. V (1846), p. 217.

31. Pasley Papers, Add MSS 41991, p. 4., British Library.

32. JEE, MPICE, Vol. V (1846), p. 219.

33. Ibid, p. 219.

34. Quoted in Booth, TNS, Vol. XLIV (1971-72), p. 8.

35. BSP/1849/XXVII, Report of the Commissioners of Railways, Appendix 12, North-Western Railway: Capt. George Wynne, Report on Viaduct of River Lune, 13 June 1848, p. 311.

36. Ibid, p. 311.

37. BSP/1850/XXXI, Report of the Commissioners of Railways, Appendix 22, Dundee, Perth and Aberdeen Railway, J.L.S. Simmons, 17 February 1849, p. 46.

38. Booth, TNS, Vol. XLIV, p. 13.

39. Ibid, p. 7.

40. Puglsey, A.G., 'Concepts of Safety in Structural Engineering', *Journal of the Institution of Civil Engineers*, Vol. 36, December 1951, p. 7.

41. Sutherland, R.J.M., 'The Introduction of Structural Wrought Iron', TNS, Vol. 36 (1963-64), pp 72-73.

42. Pasley Papers, Add MSS 41992, British Library, pp 51 and 76.

43. CEAJ, Vol. X (1847), pp 204-205.

44. Simmons, The Men Who Built Railways, p. 157.

45. CEAJ, Vol. X (1847), pp 204-205. John Rennie had expressed a somewhat similar opinion a month before the disaster and the report of the Royal Commission on Iron in Railway Structures was to make this observation two years later. See: MPICE, Vol. VI (1847), p. 222 and BSP/1849/XXIX, Report of the Commissioners Appointed to Inquire into the Application of Iron to Railway Structures, p. xvii.

46. Ibid, p. 205.

47. Ibid, p. 205. Stephenson told a meeting of the Institution of Civil Engineers that the cracked girder was due to improperly placed tension rods but remarked to railway inspector Simmons that the crack probably occurred because of a defect in the casting. See, MPICE, Vol. VI (1847), p. 220 and BSP/1847/LXIII, p. 259.

48. Ibid, 205.

49. Rolt, L.T.C., George and Robert Stephenson, Harmondsworth, 1978, p. 302.

50. Fairbairn, W., 'On some defects in the Principle of Construction of Fireproof Buildings', MPICE, Vol. VI (1847), pp 216, 220, 221 and 223. Fairbairn had written a report on the Oldham disaster of 31 October 1844 and diagnosed the cause as the poor design of a simple cast iron beam. The coroner's jury accepted his report unanimously. See: Report of Mr. W. Fairbairn and Mr. D. Bellhouse on the cause of the Falling of Messrs. Radcliffe's Mill at Oldham, Liverpool, 1844, and Pole, W. (Editor), The Life of Sir William Fairbairn, 1877, David and Charles Reprints, Newton Abbot, 1970, p. 186. Fairbairn was later to undertake experiments to prove his personal misgivings about trussed girders and published these in his On the Application of Cast and Wrought Iron to Building Purposes, 2nd Edition, London, 1857, pp 37-46.

51. Sutherland, TNS, Vol. 36, pp 74-75.

52. BSP/1847/LXIII/257, Report to the Commissioners of Railways by Mr. Walker and Captain Simmons RE. on the fatal Accident on the 24th day of May 1847, by the falling of the Bridge over the River Dee, on the Chester and Holyhead Railway, pp 257-271; CEAJ, Vol. X (1847), pp 205-206.

53. CEAJ, Vol. X (1847), p. 206.

54. BSP/1847/LXIII/257, . 266; *Parris, Government and the Railways*, p. 105.

55. Lewis, G.G. Col. RE., 'Memoir of Lieutenant Colonel Brandreth', PP, Vol. X (1849), p. 15; BSP/1849/XXIX, p. ix.

56. BSP/1849/XXIX/1, pp ix-x.

57. For biographies of James and Galton see Appendix A.

58. BSP/1849/XXIX/1, pp 250 and xviii.

59. Pugsley, *Safety of Structures*, p. 21; Fairbairn, *Application of Cast and Wrought Iron*, pp 50-53.

60. Fairbairn described tests in 1864 which indicated a 15% variation in the strength of 13 identical cast girders. See: Pugsley, *Safety of Structures*, p. 22.

61. BSP/1849/XXIX/1, p. 259; Timoshenko, *History of Strength of Materials*, pp 165-167.

62. BSP/1849/XXIX/1, p. 262.

63. Ibid, xviii, Pugsley, *Journal of the Institution of Civil Engineers*, Vol. 36, p. 7.

64. BSP/1849/XXIX/1, p. 262.

65. Ibid, p. 181.

66. Charlton, T.M., *A History of Theory of Structures in the Nineteenth Century*, Cambridge, 1982, p. 162.

67. Barlow, P., *A Treatise on the Strength of Materials*, 6th Edition, London, 1867, p. 330.

68. Ibid, p. 386; BSP/1849/XXIX, p. xii-xiii; Timoshenko, *History of Strength of Materials*, pp 173-177; Charlton, *History of Theory of Structures*, p. 163.

69. BSP/1849/XXIX/1, p. xviii.

70. James undertook some very preliminary experiments on reinforced castings. These were cast iron beams 9 feet long with wrought iron ties on the underside fixed at the ends only. James said in the Commissioners' report that time and limited means did not allow him to carry these tests as far as he desired. Ibid, pp 257-258.

71. Ibid, p. xvii.

72. Sutherland, TNS, Vol. 36, p. 67.

73. Sutherland, R.J.M., '1780-1850', in Collins, A.R., (Editor), Structural Engineering: two centuries of British achievement, Chislehurst, 1983, p. 34. Its long term significance lies in the effect the massive theoretical and testing programme had on understanding of the behaviour not only of iron bridges but of all types of structure.

74. Ibid, p. 34.

75. Pasley Papers, Add MSS, 41991, British Library, p. 31; Clark, E., Britannia and Conway Tubular Bridges, Volume 1, London, 1850, p. 65. The two arches were of 350 foot span each, with a clearance of 50 to 55 feet at the springings and 105 feet at the crown.

76. Clark, Britannia and Conway Bridges, p. 29.

77. Pasley Papers, Add MSS, 41991, British Library, p. 31.

78. Clark, Britannia and Conway Bridges, p. 65.

79. Ibid, pp 65-66.

80. James, J.G., 'The Evolution of Wooden Bridge Trusses to 1850', Part 2, Journal of the Institute of Wood Science, No. 52, 1982, pp 175-181.

81. Pasley Papers, Add MSS, 41990, British Library, p. 49.

82. MPICE, Vol. III (1844), p. 64.

83. James, J.G., 'The Evolution of Iron Bridge Trusses to 1850', TNS, Vol. 52 (1980-81), p. 81.

84. Moorsom won a prize from the Prussian government in 1850 for a proposed lattice bridge in wrought iron of 1,380 feet with maximum span of 600 feet to cross the Rhine at Cologne. He also claimed he was the first to build wooden lattice or trellis railway bridges in England (1837), MPICE, Vol. iii (1844), p. 64; MPICE, Vol. XIV (1854-55), p. 487.

85. Sutherland, TNS, Vol. 36, p. 77. MacNeill designed a 267 foot span wrought iron lattice bridge in 1855 which Captain Wynne inspected in March of that year. Wynne undertook repeated load tests and reported it perfectly satisfactory. See: Barton, S., 'On the Economic Distribution of Material in the Sides or Vertical Position of Wrought Iron Beams', MPICE, Vol. XIV (1854-55), p. 453. The Royal Commission on Iron in Railway Structures was to recommend against the use of the lattice design. See: BSP/1849/XXIX/1, p. xvii.

86. Clark, Britannia and Conway Bridges, p. 29.

87. BSP/1849/XXIX/1, p. 340.

88. Clark, Britannia and Conway Bridges, p. 29; Kemp, E.L., 'Samuel Brown: Britain's Pioneer Suspension Bridge Builder', History of Technology, 2nd Annual Volume, 1977, pp 27-28.

89. Brown's Montrose Bridge (1829) suffered serious damage in 1830 and again in 1838. Pasley urged members of the Institution of Civil Engineers to pursue the question of stiffening and offered his own explanation for the causes of failure of the Montrose Bridge. He claimed his explanation concurred with that of James Rendel who was repairing the bridge and that he had arrived at his insights independently. Pasley demonstrated that he was very familiar with the major suspension spans then extant and the principles of their construction, including Telford's bridge at Menai which had also suffered damage because of insufficient stiffness. Pasley, C.W., 'Description of the State of the Suspension Bridge at Montrose etc.', Transactions of the Institution of Civil Engineers, Vol. 3 (Part 3) (1839), pp 219-227.

90. Ibid, p. 219.

91. Clark, Britannia and Conway Bridges, p. 30.

92. Fairbairn, W., An Account of the Construction of the Britannia and Conway Tubular Bridges, London, 1849, pp 50-53.

93. Clark, Britannia and Conway Bridges, pp 32 and 67-68.

94. Ibid, pp 495-510.

95. BSP/1851/XXX/61, Report of the Commissioners of Railway, Appendix 4, Chester and Holyhead Railway, Report of J.L.A. Simmons, 18 March, p. 61.

96. Ibid, p. 62.

97. Ibid, p. 62.

98. Fairbairn, W. 'On Tubular Girder Bridges', MPICE, Vol. IX (1849-50), p. 241.

99. BSP/1850/XXXI/46, Report of the Commissioners of Railways, Appendix 51, Manchester, Sheffield and Lincolnshire Railway, Report of J.L.A. Simmons, 24 December 1849, p. 100.

100. Ibid, p. 109.

101. Ibid, p. 110.

102. Ibid, p. 111.

103. Fairbairn, MPICE, Vol. IX, p. 274; BSP/1850/XXXl, p. 100.

104. Fairbairn, MPICE, Vol. IX, pp 241-242.

105. Ibid, p. 268.

106. Ibid, pp 268-269.

107. BSP/1850/XXXI/46, p. 113; Pugsley, Safety of Structures, p. 35; Parris, Government and the Railways, pp 118 and 182-183.

108. Fairbairn, MPICE, Vol. IX, p. 257.

109. Ibid, pp 282-287.

110. BSP/1850/XXXI/61, p. 117.

111. Ibid, p. 115.

112. Dictionary of Business Biography, Vol. 2, pp 412-413.

113. Jee, A.S., 'Description of an Iron Viaduct, erected at Manchester on the joint station of the London and North Western, and the Manchester, Sheffield and Lincolnshire Railways', MPICE, Vol. XI (1851-52), pp 224-225 and 237-238.

114. BSP/1864/LIII/749, Report by Mr. Fairbairn to the Board of Trade of his Experiments for ascertaining the strength of Iron Structures, p. 749.

115. Parris, Government and the Railways, p. 170.

116. BSP/1864/LIII/749, p. 759.

117. Pugsley, A.G. 'The History of Structural Testing', The Structural Engineer, Vol. 22, December 1944, p. 498.

118. Gale, W.K.V., 'The Rolling of Iron', TNS, Vol. XXXVII (1964-65), pp 37-38; Smith, D. 'David Kirkaldy (1820-1897) and Engineering Materials Testing', TNS, Vol. 52 (1980-81), p. 57.

119. MPICE, Vol. XXV (1866), p. 259; MPICE, Vol. LXIX (1881-82), PT3, p. 44.

120. Engineering, Vol. XI (June-January 1871), p. 51; MPICE; Vol. XXV (1866) pp 261-262.

121. Engineering, Vol. XI, p. 51.

122. Pugsley, The Structural Engineer, Vol. 22, p. 495; Engineering, Vol. XI, pp 51-52.

123. Engineering, Vol. XI, pp 51-52.

124. Smith, TNS, Vol. 52, p. 58.

125. Parris, Government and the Railways, p. 118.

126. Barlow, W.H., 'Presidential Address', MPICE, Vol. LX 1879-80), pp 15-16.

127. BSP/1877/LXXIII/265, Report of the Committee Appointed by the Board of Trade to consider the practicability of assigning a safe coefficient for the use of steel in railway structures, pp 268-271.

128. Ibid, p. 272.

129. Gies, J., *Bridges and Men*, London, 1964, p. 146.

130. Rolt, L.T.C., *Victorian Engineering*, Harmondsworth, 1977, pp 190 and 192.

131. MPICE, Vol. LXIX (1881-82), PT3, p. 47. Indeed, mild steel produced by the Bessemer process caused problems for the shipbuilding and marine engineering industry from its introduction and it was the open-hearth process which provided the sound basis for the adoption of the new material. See: Clarke, J.F. and Storr, F., 'The Introduction of the Use of Mild Steel into the Shipbuilding and Marine Engine Industries', *Occasional Papers in the History of Science and Technology*, No. 1, Newcastle upon Tyne Polytechnic, n.d.

132. MPICE, Vol. LXIX, PT3, p. 48.

133. Ibid, p. 48. Conservatism with steel was long lasting in Britain. The London County Council produced its first regulation for steel in construction in 1909 - 7½ tons per square inch. See Pugsley, *Safety of Structures*, p. 35.

134. BSP/1880/XXXIX/357, Reports from the Commissioners, Inspectors and Others on the Tay Bridge Disaster, p. 430; Gies, *Bridges and Men*, pp 136-137.

135. BSP/1880/XXXIX/357, p. 432.

136. Stoney, B.B., *Theory of Strains in Girders and Similar Structures*, London, 1873, quoted in Pugsley, *Safety of Structures*, p. 60.

137. Gies, *Bridges and Men*, pp 143-144.

138. BSP/1880/XXXIX/357, p. 373.

139. BSP/1881/LXXXI/331, Report of the Committee Appointed to Consider the Question of Wind Pressure on Railway Structures, p. 335.

140. Pugsley, *Safety of Structures*, p. 136.

141. Gies, *Bridges and Men*, p. 136.

4. Pioneering Works in the Naval Dockyards

1. Coad, J.G., Historic Architecture of the Royal Navy, London, 1983, pp 21-39, 79, 80 and 106; for biographies of Bentham, Bunce, Holl and Taylor see respectively: DNB, Vol. II pp 281-284; Colvin, Biographical Dictionary of British Architects, p. 157; Ibid, p. 423; Ibid, pp 812-813.

2. Lewis, G.G. Col. RE, 'Memoir of Lieut-Col. Brandreth', PP, Vol. X (1849) p. 7.

3. The original postings were: Captain Montgomery Williams (Pembroke), Captain Burgmann (Devonport), Captain William Denison (Woolwich and Deptford), Captain Thomas Mould (Chatham and Sheerness), Captain Roger Stewart Beatson (Portsmouth) and Captain Hope (Bermuda). See: James, H. Capt., 'Description of the Steam Basin, Docks and Factory and Other Works Recently Executed in Portsmouth Dockyard', PPNS, Vol. III (1853), p. 77.

4. Lewis, PP, Vol. X, p. 7.

5. Ibid, p. 7.

6. James, PPNS, Vol. III, p. 77.

7. The navy got its first steam assisted frigate in 1842 and in 1846 the HMS Ajax became the first steam assisted ship of the line. Coad, J., 'Historic Architecture of H.M. Naval Base Portsmouth 1700-1850', Mariner's Mirror, Vol. 67, No. 1, February 1981, pp 27 and 30; James, PPNS, Vol. III, p. 77.

8. BSP/1850/XXV/351, Amount Expended for Establishment, Repair and Improvement of Dockyards, 1828-1849, p. 352.

9. H.R. Brandreth, RE (1838-46); Archibald Irvine, BE (retired) (1846-49); G.T. Greene, BE (retired) (1850-64); Sir Andrew Clarke, RE (1864-73); Charles Pasley, RE (1873-82); Percy Guillemand Llewellin Smith, RE (1882-92).

10. William Denison (Woolwich/Deptford 1837-45 and Portsmouth 1845-46); Roger Stewart Beatson (Portsmouth 1839-45 and Woolwich 1845-48); Henry James (Portsmouth 1846-50); Thomas Mould (Chatham/Sheerness 1838-50 and Portsmouth 1850-53); Montgomery Williams (Pembroke and later Devonport 1838-50); Captain Burgmann (Devonport and Keyham 1838-50); Charles Pasley (Chatham 1865-73); Percy Guillemand Llewellin Smith (Portsmouth 1879-82).

11. See: Navy Estimates: BSP/1837-38/XXXVII/185; BSP/1840/XXX/259; BSP/1847/XXV/125; BSP/1847-48/XL/130; BSP/1854/XL/149; BSP/1854-55/XXX/165;

BSP/1857-58/XXXV/341; BSP/1859/XIV/609. Originally all civilian engineers were given the title Clerk of the Works but Bernays led a protest against this classification in the late 1850's which resulted in the Admiralty creating the grade of Civil Engineer in the Works Department. See: MPICE, Vol. 91 (1887), p. 408. For biographies of Scamp, Bernays and Wood, see respectively: MPICE, Vol. 36 (1872), pp 273-78; MPICE, Vol. 91 (1887), pp 408-11; and MPICE, Vol. 90 (1886), pp 436-439.

12. See Admiralty Digest of Letters, PRO, ADM/12 as well as BSP/1861/XXXVI/1, Report of the Commissioners Appointed to Inquire into the Control and Management of Her Majesty's Naval Yards.

13. BSP/1861/XXVI/1, pp 199-200.

14. Ibid, p. 208.

15. BSP/1859/Sess.2/XVIII/1, Report of the Committee on Dockyard Economy, p. 205.

16. Mechanic's Magazine, New Series, Vol. 2 (1859), p. 114.

17. Ibid, pp 114 and 146.

18. MPICE, Vol. 36 (1872), pp 270-273. Murray was a member of the Institution of Civil Engineers from 1838. He had apprenticed under William Fairbairn in Manchester (1832) and later was a partner and managing director of Fairbairn's works at Millwall until 1843 when he was appointed Assistant Chief Engineer at Woolwich naval dockyard.

19. Coad, Historic Architecture of the Royal Navy, p. 39.

20. Bentham, S., Statement of Service, Part 2, London, 1827, quoted in Davis, H.W., Hatch, E.M. and Wright, D.G., 'Alexander Parris, Innovator in Naval Facility Architecture', IA, The Journal of the Society for Industrial Archeology, Vol. 2, No. 1, 1976, p. 21, Note 53.

21. See: Skempton, A.W. and Johnson, H.R., 'The First Iron Frames', Architectural Review, March 1961, pp 175-186.

22. Coad, Historic Architecture of the Royal Navy, pp 39, 72, 80, and 106.

23. Lewis, PP, Vol. X, p. 8.

24. The roof over Slip No. 3 (1841) at Pembroke, built of wood to the design of Sir Robert Seppings (1767-1840), Surveyor of the Navy, was 100 feet clear span, while the first iron slip roofs, Slip Nos. 8 and 9 at Pembroke, constructed in 1844, were 80 feet 7 5/8 inches clear span. See: Williams, M. Capt.

'Description of Wrought Iron Roofs erected over two Building Slips in the Royal Dockyard at Pembroke, South Wales, PP, Vol. IX (1847), pp 51 and 52. Greene's iron roof for Slip No. 7 (1852-54) at Chatham was only 82 feet clear span. See: PRO, ADM/140/66. None of the iron slip roofs exceeded 85 feet clear span. See Appendix F.

25. PRO, ADM/12/460/41-10.

26. PRO, ADM/12/444/41-10.

27. Denison, W., 'Detail of some Experiments carried on in Her Majesty's Dockyard, Woolwich, for the purpose of ascertaining the Resistance of Brickwork under various conditions', PP, Vol. VI (1843), pp 219-220. The 'Mr. Fox' was probably Sir Charles Fox of Fox, Henderson Company, the distinguished engineering contractors who did a great deal of work in the naval dockyards. On the other hand, it may have been Dr. Fox of Messrs. Fox and Barrett who patented (1844) a new system of fireproof floor using concrete on iron beams, but Denison was unlikely to have called him 'Mr.' in that case.

28. Denison, W. Capt., ' Observations on Barracks, and on the Moral Condition of the Soldier', CP, p. 261; B, Vol. 5 (1847), p. 7.

29. PRO, ADM/12/604/41-10.

30. Skempton, A.W., 'The Boat Store, Sheerness (1858-60) and its Place in Structural History', TNS, Vol. XXXII (1959-60), p. 58.

31. Hamilton, S.B., 'The Use of Cast Iron in Building', TNS, Vol. 21 (1940-41), p. 153.

32. Coad, Historic Architecture of the Railway Navy, p. 82.

33. The only evidence found was an article commissioned by Denison, editor of the Royal Engineer Professional Papers, while he was serving at Woolwich in 1843. See: Turnbull, W., 'Practical Essay on the Strength of Cast Iron Beams, Girders and Columns; in which the principles of calculation are exhibited in plain and popular manner', PP, Vol. VI (1843), pp 77-148. William Turnbull's calculations were based on Thomas Tredgold's Practical Essay on Cast Iron, (1822, 2nd edition 1824, 3rd 1831 and subsequent editions to 1860-61). In 1832 Turnbull found it worthwhile to publish a greatly simplified version of Tredgold's book which he entitled, A Treatise on the strength, flexure and stiffness of cast iron beams and columns. In the preface to Turnbull's article in the Professional Papers, Denison acknowledged Eaton Hodgkinson's recent experiments. This work was first published in 1830 by the Manchester Literary and

Philosophical Society and entitled, Theoretical and Experimental Researches to Ascertain the Strength and Best Forms of Iron Beams; later experiments at Fairbairn's works were published in the British Association's Report 1837-38. Denison said: "I have not lost sight of the experiments made by Mr. Hodgkinson, which appear conclusive in favour of increasing the width of the bottom flange on cast iron beams; but as I am not aware that the results of these experiments have as yet been embodied into a form susceptable of calculation, I have thought it better not to delay the publication of the present Tables." See: Turnbull, PP, Vol. VI (1843), p. 78. It is not known to what extent the Royal Engineers used Tredgold but if they did follow his advice they were working with a dangerously low safety factor. See: Sutherland, R.J.M., 'Thomas Tredgold (1788-1829) Some Aspects of his Work, Part 3: Cast Iron', TNS, Vol. 51 (1979-80), p. 76. The Royal Engineers probably had adopted Hodgkinson's more advanced principles for the design of a cast iron beam by the time he published his Experimental Researches on the Strength and Properties of Cast Iron, London, 1846, a quite accessible work.

34. PRO, ADM/12/476/41-10.

35. PRO, ADM/12/411/41-10; PRO, ADM/140/548.

36. PRO, ADM/12/444/41-10; PRO, ADM/12/460/41-10; PRO, ADM/12/476/41-10; Riley, R.C., 'Portsmouth Dockyard: An Industrial Archeological Overview', Industrial Archaeology Review, Vol. VIII, No. 2, Spring 1986, p. 186.

37. Boase, Vol. 3, p. 270. In his connection with the Thames Iron Works, Rolt took part in the construction of the 'Warrior', Britain's first ironclad warship (1860).

38. James, PPNS, Vol. 3 (1853), p. 2.

39. PRO, ADM/140/539.

40. PRO, ADM/12/619/41-10; PRO, ADM/140/1062.

41. Riley, Industrial Archeology Review, Vol. VIII, No. 2, p. 186.

42. Ibid, p. 186.

43. Sutherland, Building Early America, p. 108.

44. In 1824 J. Rastrick designed a 41 foot cast iron beam for Sydney Smirke's British Museum. Many engineers considered 30-40 feet was the practical limit for cast iron beams but a few were willing to consider spans up to 60 feet. Ibid, p. 101.

45. Boase, Vol. IV, p. 327.

46. PRO, ADM/12/397/41-10. Nevertheless, it does not appear in the Navy Estimates 1843/44. See: BSP/1843-44/XXVII/309.

47. PRO, ADM/12/411/41-10.

48. PRO, ADM/12/428/41-10.

49. Drawings, all signed by Beatson, are dated 7 January, 15 January and 24 January 1845. I am indebted to James Sutherland who kindly brought copies of the drawings to my attention. Originals are held by the Property Services Agency.

50. Ibid.

51. PRO, ADM/12/460/41-10. This was presumably John Rigby of the Hawarden Ironworks, Flintshire who had submitted an unsuccessful tender proposal for iron slip roofs at Portsmouth in December 1844. See: PRO, ADM/140/625.

52. PRO, ADM/12/492/41-10.

53. Ibid. This was Henry Grissell (1817-83) whose Regents Canal Ironworks did a lot of business in the dockyards, especially with Greene in the 1850's.

54. Ibid.

55. BSP/1847/LXIII/257.

56. Fairbairn, W., 'On some defects in the Principle of Construction of Fireproof Buildings', MPICE, Vol. VI (1847), p. 216.

57. See Chapter 3.

58. Fairbairn, MPICE, Vol. VI, p. 216; Fairbairn, W. *On the application of cast and wrought iron to building purposes*, 2nd edition, London, 1857, Appendix 2. Report on the Causes of the Fall of the Cotton Mill at Oldham in October, 1844, p. 275.

59. Riley, *Industrial Archaeology Review*, Vol. VIII, No. 2, p. 188; *Proceedings of the Institution of Mechanical Engineers*, 1892, p. 375.

60. Sutherland, *Building Early America*, p. 104.

61. PRO, ADM/12/397/41-10.

62. PRO, ADM/12/411/41-10.

63. Sutherland, *Building Early America*, pp 104 and 117, note 27. Sutherland's speculation in 1976 that the tie rods were an afterthought was absolutely correct. I would like to acknowledge his insightful comment and suggestion that more research be undertaken to reveal the truth of the matter.

64. Fowler, C., 'Metal Roof at Hungerford Market', Transactions of the Institute of British Architects, Vol. 1, Part 1 (1835-36), pp 44-46; Taylor, J., 'Charles Fowler: Master of Markets', Architectural Review, March 1964, pp 179-180

65. James, PPNS, Vol III (1853), p. 93.

66. Ibid, p. 93.

67. Ibid.

68. PRO, ADM/12/540/41-10; PRO, ADM/12/556/41-10; Riley, Industrial Archaeology Review, Vol. vIII, No. 2, p. 188.

69. ADM/12/540/41-10.

70. Ibid.

71. Ibid.

72. PRO, ADM/556/41-10.

73. ADM/12/540/41-10.

74. Proceedings of the Institution of Mechanical Engineers, 1892, pp 373-374. One might question this claim since Mould had taken steps to dispose of used materials from the temporary smithery which would have been available. On the other hand, the castings may not have been of the required size. James' cast iron windows were similar to those for the permanent building and these may have been re-used.

75. Riley, Industrial Archaeology Review, Vol. VIII, No. 2, p. 188.

76. Wrought iron took over when production and jointing techniques had advanced in order to compete with cast iron in price and quantity available. The two essential rolled sections were plates and angles. Rolled angles and tees date from 1800-1820 in Britain. Sutherland, TNS, Vol. XXVI (1963-64), pp 67-84; Sutherland, Building Early America, pp 104-112.

77. Sutherland, Building Early America, pp 108-109.

78. Diestelkamp, E.J., 'Richard Turner and the Palm House at Kew Gardens', TNS, Vol. 54 (1982-83), pp 1-26.

79. Denison, Capt., 'Description of some Iron Roofs erected in different places within the last few years', PP, Vol. VI (1843), pp 212-215. Denison gave the examples of a 62 foot span at Crawshay's works near Newbridge in Glamorganshire, a 64 foot span for a depot at Gloucester for the Gloucester and Birmingham Railway, and a 60 foot span for Cowlairs Station, Glasgow, on the Edinburgh and Glasgow Railway.

80. Ibid, p. 212.

81. PRO, ADM/12/397/41-10.

82. PRO, ADM/12/411/41-10.

83. Denison, W., 'Account of an Experiment on the strength of the Principals of a Wrought Iron Roof of 62 feet 4 inches span', PP. Vol. VII (1845), p.225.

84. Ibid, Plate XLVI.

85. Ibid, Plate XLVI. The drawing is signed by Bernays. Peter Rolt (1798-1882) was originally a timber merchant at Deptford, but later was associated with the Thames Iron Works. He was contractor for most of the Portsmouth Naval Dockyard extension works 1846-50. See Note 37 and James, PPNS, Vol. 3 (1853). p. 2.

86. Lime Street Station had a clear span of 153 feet 6 inches. See: Turner, R. 'Description of the Iron Roof over the Railway Station, Lime Street, Liverpool', MPICE, Vol. IX (1849-50), p. 205.

87. Important exceptions are James Sutherland and Jonathan Coad. See: Sutherland, Building Early America, p. 110; Coad, Historic Architecture of the Royal Navy, p. 46; Coad, J., 'Historic Architecture of the Chatham Dockyard, 1700-1850', Mariner's Mirror, Vol. 68, No. 2 (May 1982) p. 182; Coad, Mariner's Mirror, Vol. 67, No. 1 (February 1981) p. 32.

88. See Appendix F.

89. Thorne, R., 'Crystal Exemplar', Architectural Review, Vol. 1049, July 1984, p. 52.

90. Mechanic's Magazine, Vol. 51 (1849), pp 344-345.

91. Williams, PP, Vol. IX (1847), pp 50-51, Coad, Historic Architecture of the Royal Navy, p. 42; Mariner's Mirror, Vol. 68, No. 2, pp 180-181. For a biography of Seppings see: DNB, XVII, pp 1187-1189.

92. Williams, PP, Vol. IX (1847) p. 51.

93. Ibid, p. 51.

94. PRO, ADM/397/41-10; BSP/1841/XIV/290, Navy Estimates 1841-42.

95. MPICE, Vol. 8 (1848), p. 13.

96. Williams, PP, Vol. IX (1847), pp 50-57.

97. PRO, ADM/460/41-10.

98. Williams, PP, Vol. IX (1847), p. 51.

99. Ibid, p. 51.

100. See his obituary: MPICE, Vol. 39 (1874), pp 264-266. It is interesting that Fox said he preferred spans of 50 or 60 feet to any other dimensions for iron roofs because he considered this size was the most economical. This was well below the over 80 foot span slip roofs. See: MPICE, Vol. XIV (1854-55), p. 265. Fox is perhaps best known to architectural historians for his collaboration with Paxton on the Crystal Palace.

101 Phillips, J., 'Description of the Iron Roof, in one span, over the Joint Railway Station, New Street, Birmingham', MPICE, Vol. XIV (1854-55), pp 251-261 and 264. Major responsibility for the design of the New Street station roof has been attributed to Edward Alfred Cowper (1819-93) who was in the employ of Fox, Henderson, engineering contractors. The strut was made of four curved wrought iron angle members with cast iron spacers. It had similarities of form in some respects to the main strut or gib used in the roofs of Slip Nos. 8 and 9 at Pembroke. Cowper may have been involved in the design of Slip No. 4 roof at Woolwich since he described it at a meeting of the Institution of Civil Engineers in 1854. See: Ibid, p. 264.

102. PRO, ADM/140/625.

103. Cumberland, F.W., 'Iron Roofs over Building Slips, Nos. 3 and 4, in Her Majesty's Dockyard, Portsmouth', PP, Vol. IX (1847), p. 59. PRO, ADM/140/633. Unfortunately, nothing is known of Messrs. Bakers' firm except that Admiralty records indicate that it did an enormous amount of work in the naval dockyards.

104. Ibid, pp 60-62; PRO, ADM/140/633; PRO, ADM/140/630.

105. Cumberland, PP, Vol. IX (1847), p. 59 and Plate XVI.

106. Ibid, pp 62-64. In 1850 Messrs. Baker and Sons submitted a proposal for strengthening the roofs using 'Fielder's Patent Purlins'. Henry Fielder's patent of 1847 was for building up sections by rivetting angle flanges on to plate webs. Baker's drawings for the proposal were sent by James to Greene but it is not known if the proposal was accepted and executed. PRO, ADM/12/524/41-10; PRO, ADM/140/633; Hamilton, TNS, Vol. 21 (1940-41), p. 153.

107. Turner, MPICE, Vol. IX (1849-50), p. 212.

108. PRO, ADM/12/476/41-10. Turner had taken out his patent in 1846 following his experience in constructing the Palm House at Kew Gardens. Shortly after, he designed several railway station roofs and industrial buildings utilizing the wrought iron deck

beam as arched principal which in most cases was tied and strutted with other iron members. See Diestelkamp, TNS, Vol. 54 (1982-83), pp 16 and 24.

109. PRO, ADM/476/41-10; PRO, ADM/508/41-10.

110. In addition to Slip Nos. 8 and 9, the firm had built an iron roof for Slip No. 7 (1846-47). See: PRO, ADM/12/476/41-10.

111. See: Appendix F and PRO, ADM/12/476/41-10.

112. Messrs. Baker and Sons' roofs for Slip Nos. 3 and 4, Portsmouth, cost a total of £14,292.15s, whereas Fox, Henderson's roofs for Slip Nos. 8 and 9, Pembroke, cost a total of £15,480. Considering that these contracts were awarded only a year apart, and that the Pembroke roofs were larger overall, the firms appear to have been very competitive on price. See: Cumberland, PP, Vol. IX (1847), p. 65; and Williams, PP, Vol. IX (1847), p. 51.

113. PRO, ADM/140/66.

114. PRO, ADM/12/556/41-10. Grissell also got the contract for extending the roof in 1856. See: PRO, ADM/12/619/41-10.

115. BSP/1854/XL/184-185, Navy Estimates 1854-55.

116. PRO, ADM/140/66.

117. Phillips, MPICE, Vol. XIV (1854-55), p. 252.

118. Skempton, A.W., 'The Boat Store, Sheerness (1858-60) and its Place in Structural History', TNS, Vol. XXXII (1959-60), pp 65-66.

119. PRO, ADM/476/41-10.

120. PRO, ADM/12/492/41-10.

121. PRO, ADM/12/604/41-10; PRO, ADM/12/619/41-10; PRO, ADM/12/668/41-10; PRO, ADM/12/652/41-10.

122. Herbert, G., Pioneers of Prefabrication: The British Contribution in the Nineteenth Century, Baltimore, 1978, p. 32.

123. Ibid, pp. 33-35; Dickinson, H.W., 'A Study of Galvanized and Corrugated Sheet Metal', TNS, Vol. 24 (1943), pp 27-28.

124. Evill, W., 'Description of the Iron Shed at the London Terminus of the Eastern Counties Railway', MPICE, Vol. III (1844), pp 288-290.

125. Dickinson, TNS, Vol. 24 (1943), p. 28.

126. Herbert, *Pioneers of Prefabrication*, p. 37.

127. PRO, ADM/12/428/41-10.

128. PRO, ADM/12/411/41-10. Charles Fowler had used zinc for roof covering in his Hungerford Market building of 1835. See: Fowler, *Transactions of the Institute of British Architects*, Vol. 1, Part 1, 1835-36, p. 44.

129. MPICE, Vol. XIV (1854-55), p. 266.

130. Ibid, pp 267-272.

131. Ibid, pp 272 and 265.

132. PRO, ADM/12/540/41-10.

133. Ibid, Tupper and Carr, Galvanized (Patent) Iron Company were located at Mansion House Place, London and had been in business since 1845. After 1858 the firm was known as Charles William Tupper and Company of London and (from 1864) Birmingham. See: Herbert, *Pioneers of Prefabrication*, p. 45.

134. Herbert, *Pioneers of Prefabrication*, p. 45.

135. Morewood and Rogers, Small Smithery, Chatham, 1847 and Metal Mills Scales, Chatham, 1851; Richard Walker, Coke Store, Chatham, 1851; John Porter, roof over Steam Hammer Boiler, Woolwich, 1847; Malins and Rawlinson, covering for roof of Slip Nos. 1 and 2, Woolwich, 1846. See: PRO, ADM/12/476/41-10; PRO, ADM/12/540/41-10; PRO, ADM/12/492/41-10; and PRO, ADM/12/460/41-10.

136. Condit, C.W., 'The Wind Bracing of Buildings', *Scientific American*, February 1974, pp 92-95; Skempton, TNS, Vol. XXXII (1959-60), pp 72-73; Wyatt, M.D., 'On the Construction of the Building for the Exhibition of the Works of Industry of all Nations in 1851', MPICE, Vol. 10 (1850-51), pp 144-145, 157-159, 180, 188; Kilstedt, F.T., 'The Crystal Palace', *Scientific American*, October 1984, pp 135-136.

137. Skempton, TNS, Vol. XXXII (1959-60), pp 57-78; Skempton, A.W., 'Evolution of the Steel Frame Building', *The Guilds Engineer*, Vol. 10 (1959), pp 37-51; Condit, *Scientific American*, February 1974, pp 92-105; Sutherland, R.J.M., '1850-1890', in Collins, A.R., (Editor), *Structural Engineering: Two Centuries of British Achievement*, Chislehurst, 1983, pp 56-58.

138. Skempton, TNS, Vol. XXXII (1959-60), pp 58-61 and 72-74; PRO, ADM/140/1331, 1332, 1333, 1340 and 1341; BSP/1861/XXVI/389.

139. Skempton, TNS, Vol. XXXII, p. 63; Vibart, *Addiscombe*, p. 667; BSP/1862/XXXIII/592.

140. In 1846 Captain Henry Goodwyn reported in a letter to Greene, who was then Secretary to the Military Board, about model experiments which Goodwyn had undertaken at the Iron Bridge Department, Fort William to prove the strength of the novel Dredge taper chain wrought iron suspension bridge. From the nature of the letter it appears that Greene was considered knowledgeable about the technical details and not simply a government official to whom Goodwyn was required to report. See: Goodwyn, Capt., 'The Taper Chain Tension Bridge at Ballee Khâl, near Calcutta, in its renewed Form, after failure in June, 1845', PP, Vol. IX (1847), pp 130-136.

141. PRO, ADM/12/540/41-10; PRO, ADM/12/556/41-10; PRO, ADM/12/619/41-10; PRO, ADM/140/60; PRO, ADM/140/1062; Skempton, TNS, Vol. XXXII, p. 65.

142. Skempton, TNS, Vol. XXXII, p. 65. Evidence of Grissell's work as contractor may be found in: PRO, ADM/12/652/41-10 and ADM/12/668/41-10.

143. Skempton, TNS, Vol. XXXII, p. 64.

144. PRO, ADM/12/652/41-10.

145. Colvin, Biographical Dictionary of British Architects, pp 721-722; MPICE, Vol. 36 (1872), pp 273-278; PRO, ADM/12/460/41-10; PRO, ADM/12/556/41-10.

146. BSP/1861/XXVI/1, Report of the Commission Appointed to Inquire into the Control and Management of Her Majesty's Naval Yards, p. 383.

147. MPICE, Vol. 36 (1872), p. 276.

148. Sutherland, Structural Engineering, p. 58.

149. BSP/1861/XXVI/389.

150. Ibid, p. 390.

151. Ibid, p. 390.

152. Ibid, pp 384 and 534.

153. Ibid, p. 390.

154. Taylor, G.L., 'An Account of the Methods used in Underpinning the long Storehouse at His Majesty's Dock Yard, Chatham,in the year 1834', Transactions of the Institute of British Architects, Vol. 1, Part 1, 1836, pp 40-43.

155. Scott, H. Capt., 'On Concrete as a Substitute for Brick and Stone Masonry in Works of Fortification', PPNS, Vol. XI 1862), p. 224.

156. BSP/1845/XVl/1, Report of the Commissioners on Harbours of Refuge; BSP/1847/XVl/1, Report on the Harbour of Refuge to be constructed in Dover Bay. Formed in April 1844 and active until its final report in January 1846, the ten member Commission included two Royal Engineers - Brandreth, Director of the Admiralty Works Department, and Colonel R. Alderson. Other engineer officers who presented evidence were Captain J. Vetch, Lieutenant Colonel Jones and Colonel Charles W. Pasley

157. Denison, Lieut., 'Notes on Concrete', PP, Vol. II (1838), pp 263-266, and CEAJ, Vol. 1 (1837-38). BSP/1847/XVI/19. Denison used concrete in the foundations for a 210 foot chimney at Woolwich, for example.

158. BSP/1847/XVI/17 and 107.

159. Ibid, p. 18.

160. Ibid, pp 17-18.

161. As early as 1841 concrete blocks of 360 cu. ft. and 22 tons each had been used in parts of the 'Mole of Algiers'. The concrete was made of fat lime and artificial pozzulana. Similar blocks were used in the early 1840's at Marseilles, Rochefort and Cherbourg in marine works. Blocks had been used in exposed situations and had experienced failure (Vicat thought the cause was seawater's magnesia content acting injuriously on the lime). See: MPICE, Vol. 16 (1857), pp 438-440 and Gillmore, Q.A., *Practical Treatise on Limes, Hydraulic Cements and Mortars*, New York, 1874, p. 264.

162. These included James Meadows Rendel, William Cubitt, Jesse Hartley, George Godwin and Robert Smirke. See: B, Vol. 5 (1847), pp 442-443.

163. Ibid, p. 443.

164. Ibid, p. 443.

165. BSP/1847/XVI/7, 103 and 8-9.

166. MPICE, Vol. 16 (1857), p. 439.

167. Colson, C., 'Portsmouth Dockyard Extension Works', MPICE, Vol. 64 (1880-81), pp 118-119; *Engineering*, Vol. X (July-December 1870) pp 181-182, MPICE, Vol. 83 (1885), p. 435.

168. Watson, *History of the Corps of Royal Engineers*, pp 299-304; DNB (1901-11), pp 362-65; Vetch, R.H. Col., *The Life of Lieutenant-General the Hon. Sir Andrew Clarke*, London, 1905, pp 10-87.

169. Skempton, TNS, Vol. 35 (1962-63), p. 125; MPICE, Vol. 16 (1857), p. 445. Portland cement was mixed in various proportions with Medina cement and used in concrete blocks in exposed locations at Cherbourg 1846-53. Blocks were 700 cu. ft. and 45 tons each and about 2,000 blocks or 40,000 cu. m. were used.

170. MPICE, Vol. 16 (1857), pp 439, 440, 445. Walker and Burges used Portland cement concrete blocks of 6 to 10 tons each in the Dover Harbour of Refuge (1850) but as hearting only. In a discussion of Portland cement at a meeting of the Institution of Civil Engineers in 1857, there was concern over the quality of concrete blocks made from the material but some prominent civil engineers attributed it to poor manufacture, not the product itself (Walker and Burnell). Manufacturer G.F. White said the works at Dover used nearly a half million cubic feet of concrete blocks annually and the breakage rate scarcely exceeded one percent. White further remarked that the example at Cherbourg proved the durability of concrete blocks in seawater even to the extent of using the blocks in external walls, without the protection of stone casing. Ibid, pp 439-445.

171. Colson, MPICE, Vol. 64 (1880-81) Part 2, pp 119 and 225; MPICE, Vol. 52 (1877), p. 287; MPICE, Vol. 83 (1885) p. 435.

172. MPICE, Vol. 62 (1879-1880) Part 4, p. 229.

173. Colson, MPICE, Vol. 64 (1880-81) Part 2, pp 124-125, 127-137.

174. Ibid, pp 121 and 223.

175. MPICE, Vol. 62 (1879-1880) Part 4, p. 227.

176. Colson, MPICE, Vol. 64 (1880-81) Part 2, p. 222.

177. Ibid, p. 222-223.

178. Ibid, p. 217; Carey, A.E., 'The Selection, Testing and Employment of Cement', PPOS, Vol. XXIV (1898), p.3.

179. Bernays, E.A., 'Portland Cement Concrete and Some of its Applications', MPICE, Vol. 62 (1880), p. 87, MPICE, Vol. 91 (1887), pp 408-409.

180. DNB, Vol. 15, pp 437-439; Australian Dictionary of Biography, Vol. 5, pp 409-411.

181. Bernays, MPICE, Vol. 62 (1880), pp 88-96, MPICE, Vol. 91 (1887) p. 410.

182. MPICE, Vol. 62 (1879-1880) Part 4, p. 229.

183. Ibid, p. 215.

184. MPICE, Vol. 91 (1887), p. 410.

185. At least one prominent civil engineer, Harrison Hayter, stated that the use of Portland cement at Portsmouth and Chatham had induced him to use the material in dock walls exposed up to low water mark and with stone above. Hayter had spent a year on the Dover harbour works as resident engineer for Walker and Burges (1850) and after 1856 was chief assistant to John Hawkshaw and later a partner in Hawkshaw's firm. Under Hawkshaw he was responsible for numerous dock projects and was also involved in foundations for the Spithead Forts for the War Office, working under the Royal Engineers. See: Colson, MPICE, Vol. 64 (1880-81) Part 2, p. 212; MPICE, Vol. 134, pp 391-394.

186. J.T. Leather and E.P. Smith. See: MPICE, Vol. 83 (1885), pp 433-443; MPICE, Vol. 52 (1877), pp 2851287.

5. New Technology and Fortifications

1. Greenough, J.J., The Halifax Citadel, 1825-60: A Narrative and Structural History, Part 1, Volume 1, Manuscript Report No. 154, Parks Canada, September, 1974, p. 17.

2. Porter, History of the Corps of Royal Engineers, Vol. 2, p. 200.

3. Hughes, Q., A Chronology of Events in Fortification from 1800 to 1914 and An illusrated English glossary of terms used in military architecture, Fortress Study Group, Liverpool, 1980, pp 23-26; Coad, Mariner's Mirror, Vol. 67, No. 1, February 1981, p. 30; Coad, Historic Architecture of the Royal Navy, p. 33

4. Hughes, Chronology of Events in Fortifications, pp 28-35.

5. Yule, P. Major-General, 'On Batteries for Defence of Coasts, and the Adaptation of Gun Carriages to Them', PPNS, Vol. V (1857), p. 83.

6. Greenough, Halifax Citadel, p. 297, quoted from: Tyler, H. 'Remarks on Fortification; with Especial Reference to Rifled Weapons', PPNS, Vol. 9 (1860), p. 95.

7. Porter, History of the Corps of Royal Engineers, Vol. 2, pp 406-433; DNB, Vol. 3, pp 342-344. Burgoyne had an especially close professional friendship with Charles Blacker Vignoles whom he advised on railway embankments and excavation methods by explosion of powder, for works in Ireland. Vignoles in turn advised Burgoyne on plans for building forts at Portsmouth. See: Vignoles, K.H., Charles Blacker Vignoles, romantic engineer, Cambridge, 1982, pp 50, 58 and 151. Burgoyne had correspondence with Belgian engineer Brialmont and Russian Todleben as well as Joseph Totten of the U.S. Corps of Engineers, an expert on materials testing for works of fortification. See: Porter, History of the Corps of Royal Engineers, Vol. 2, p. 431.

8. BSP/1868-69/XII/433, Report of the Committee Appointed to Enquire into the Construction, Condition and Cost of Fortification Erected or Under Construction, p. 438; Smith, V. 'The Later Nineteenth Century Land Defences of Chatham', Post-Medieval Archaeology, Vol. 10, 1976, pp 107-110; Hogg, I.V., Coast Defences of England and Wales 1856-1956, Newton Abbot, 1974, pp 22-26.

9. BSP/1867/XLV/491, Report with reference to the Progress Made in the Construction of Fortifications for the Defence of Dockyards and Naval Arsenals of the United Kingdom, pp 497-498.

10. BSP/1868-69/XII/441.

11. Porter, History of the Corps of Royal Engineers, Vol. 2, pp 222-223; DNB, Vol. XXII, pp 912-915.

12. Hogg, Coast Defences, pp 47-48; Smith, Post-Medieval Archaeology, Vol. 10, 1976, pp 110-111; Powter, A., Conservation of Concrete in Fortifications and Gun Batteries, Unpublished Thesis, Diploma in Conservation Studies, Institute of Advanced Architectural Studies, University of York, 1979, pp 40 and 43-46.

13. Harding, G.J. 'Description of a Concrete Bomb-Proof erected at Woolwich with Detailed Experiments as to the Effect Produced on it by the Fire of Artillery', PP, Vol. 1 (1837), pp 33, 35-36, and 37-38.

14. Ibid, p. 33.

15. Ibid, p. 34.

16. See Chapter 2.

17. Boase, Vol. 1, p. 1326.

18. Collins, Concrete, pp 27-28.

19. BSP/1856/XXXVI/Part III/413 Reports on the Paris Universal Exhibition, On Civil Construction by Capt. Fowke, RE, p. 656.

20. Ibid, p. 657.

21. Scott, PPNS, Vol. XI (1862), pp 236-239. Unfortunately Fowke's paper seems not to have survived but Scott gives a rather good account of its salient points.

22. Ibid, p. 226.

23. Survey of London, The Museum Area of South Kensington and Westminster, Vol. XXXVIII, London, 1975, p. 99.

24. Fox and Barrett's system was patented in 1844. At a discussion at the Institution of Civil Engineers five years later, Barrett credited the invention to Dr. Fox of Bristol and referred to the recent use of the system in the extension of Middlesex Hospital. See: MPICE, Vol. VIII (1849), p. 157; and MPICE, Vol. XII (1853) pp 244-265. Fowke rejected the conventional method of fireproof floor construction using parralel iron girders carrying brick barrel vaults tied with wrought iron rods because of the weakness of exposed iron in fire conditions. Fowke also eliminated from consideration Fox and Barrett's system which used wrought iron I beams with wood ceiling laths coated with mortar and covered over with concrete. He thought that with the wide span of the storehouse a large surface of the main girders would be exposed to a fire and the concrete may fail under intense heat. Fowke's

design was an adaptation of the traditional brick jack arch fireproof floor system. He proposed a groin vault of brick springing from stone capped brick piers which supported cast iron beams of ⊥ section. The vault was 9 inches thick with brickwork bonded in Portland cement. Concrete was used only as a filler over the arches to level the floor. See: Fowke, Capt. F., 'On a proposed method of constructing fireproof brick arch floors, devoid of any lateral thrust, and without the use of tie rods, capable of carrying the heaviest weights, with suggestions for the application of the same system to the roofing of magazines, bomb-proofs, and casemated construction generally', PPNS, Vol. X (1861), pp 8-10.

25. B, Vol. 25 (1867), p. 253.

26. Scott, PPNS, Vol. XI (1862), pp 220-239.

27. Ibid, p. 239.

28. Vincent, E. *Military Construction Techniques in the Use of Building Materials in British North America, 1820-1870*, Parks Canada, Microfiche Report Series, 156, 1985, p. 144.

29. Graham, Lieut. Col., 'Experiments on Limes and Cements', PPNS, Vol. XIV (1865), pp 155-161; Ardagh, Lieut., 'Report Upon Concrete Revetments Built at Newhaven', PPNS, Vol. XV (1866), p. 161.

30. DNB, Vol. XXII, pp 759-763.

31. Watson, *History of the Corps of Royal Engineers*, pp 380-387; DNB, (1901-11), pp 50-53.

32. Hamilton-Baillie, *Concrete*, Vol. 14, 1980, p. 15.

33. Powter, *Conservation of Concrete*, p. 41.

34. Ardagh, PPNS, Vol. XV (1866), p. 162.

35. Ibid, p. 161.

36. Ibid, pp 161-162.

37. Hamilton-Baillie, *Concrete*, Vol. 14, 1980, p. 16.

38. Ardagh, PPNS, Vol. XV (1866), pp 165-166.

39. Hamilton-Baillie, *Concrete*, Vol. 14, 1980, p. 16.

40. Ibid, p. 16. Brigadier, J.R.E. Hamilton-Baillie (Retd.) MC MA CEng MICE is Vice-President of the Institution of Royal Engineers, Chairman of the Fortress Study Group and a member of the Historic Working Party of The Concrete Society.

41. Powter has rightly made this point but attributes the motivation for the experiment to Parliamentary cuts in the Commission Forts programme which is not accurate. Appropriations for the fort building programme had increased from 1860-65 as shown earlier. See Powter, Conservation of Concrete, p. 43.

42. BSP/1867/XLV/498.

43. Ardagh, PPNS, Vol. XV (1866), p. 163.

44. Powter, Conservation of Concrete, p. 40.

45. The Engineer, Vol. 18 (1864), p. 163.

46. Ibid.

47. Ibid.

48. Ibid; MPICE, Vol. 83 (1885), p. 435.

49. MPICE, Vol. 43 (1875-76), pp 312-317; Innes, Capt. W., 'Notes on the supply, storage and testing of Portland Cement', PPNS, Vol. XXI (1873), pp 1-18.

50. Innes, PPNS, Vol. XXI (1873), pp 7-18; Maquay, Maj., 'Notes on Portland Cement Concrete', PPNS, Vol. XXII (1874), pp 149-153.

51. Maquay, PPNS, Vol. XXII (1874), p. 150.

52. Ibid, p. 154 and Plate XXXIV.

53. Powter, Conservation of Concrete, p. 46.

54. Hughes, Chronology of Events in Fortification, p. 46; Totten, Joseph G., Brevet Brigadier-General, Col. and Chief Engineer U.S. Army, 'Extracts From a Report on the Effects of Firing Heavy Ordnance From Casemate Embrasures, And Also the Effects of Firing Against the Same Embrasures With Various Kinds of Missiles in the Years 1852, 53, 54 and 55 at West Point in the State of New York', PPNS, Vol. VIII (1859), pp 1-33.

55. Powter, Conservation of Concrete, p. 46.

56. Gillmore, Practical Treatise on Limes, p. 246.

57. Ibid, p. 322.

58. Hughes, Chronology of Events in Fortification, p. 42.

59. Fowler built a 75 foot span mass concrete access bridge over the Metropolitan and District Railway line in 1867 but this was an isolated event. See: TNS, Vol. XLII (1969-70), p. 159. In civil architecture, mass concrete was used in workers' cottages, houses and industrial buildings from the

late 1860's, especially by a few London contractors (Joseph Tall, Charles Drake, etc.). A few well known architects dabbled with it (Blomfield, Street and Shaw). However, the use of mass concrete was by no means ubiquitous in British architecture of the late nineteenth century. See: Collins, Concrete, pp 40-51.

60. Collins, Concrete, p. 52.

61. Chabrier, E. 'The Application of Asphalt', Translated by W.H. Delano, MPICE, Vol. XLIII (1876), pp 276-277.

62. Pasley, Observations, 1838, Appendix CXXVII, p. 103.

63. Chabrier, MPICE, Vol. XLIII (1876), p. 278.

64. Sims, F.W., 'Asphaltic Mastic', MPICE, Vol. 1 (1838), p. 6.

65. Pasley, Observations, 1838, Appendix CXXVII, pp 104-105.

66. Vincent, Military Construction Techniques, p. 222.

67. Sims, MPICE, Vol. 1 (1838), p. 6.

68. Ibid.

69. Pasley, Observations, 1838, Appendix CXXVII, p. 105.

70. Ibid.

71. Ibid.

72. Laffan, Lieut. (Translator), 'Instructions of the Minister of War concerning the Model-towers approved of by Napoleon, PP, Vol. III (1839), p. 107.

73. BSP/1844/XXVIII/129, Report of the Surveyor-General of Prisons on the Construction, Ventilation and Details of Pentonville Prison, pp 147-148.

74. Vincent, Military Construction Techniques, pp 223-224, and 244.

75. Oldfield, Col. J. 'Memorandum on the Use of Asphalte, 24 May 1848', PPNS, Vol. III (1853), p. 132.

76. He had also served at Fort George in Scotland (1809-14), in Holland at the end of the Napoleonic Wars, and in the West Indies (1823), Ireland (1824-30) and Jersey (1835-39). See: DNB, Vol. XIV, pp 994-996.

77. Oldfield, PPNS, Vol. III (1853), p. 132; CEAJ, Vol. XII (1849), p. 352.

78. Oldfield, PPNS, Vol. III (1853), p. 132.

79. CEAJ, Vol. XII (1849), p. 352.

80. Vincent, *Military Construction Techniques*, p. 231; Oldfield, PPNS, Vol. III (1853), pp 132-148.

81. Oldfield, PPNS, Vol. III (1853), p. 132.

82. Ibid, p. 133.

83. BSP/1868-69/XII/433, Appendix No. IV: Memorandum on the Condition of Magazines and Other Buildings covered with earth, in Respect to Dampness. On the Probable Causes, and on the Means of Prevention by Improved Ventilation, 8 January 1868, by Lieut. J.C. Ardagh, pp 548-550.

84. Ibid; Home, Lieut., 'Notes on the Construction of Magazines', PPNS, Vol. XII (1863), pp 40-41; Innes, Lieut., 'On Damp in Powder Magazines as Affected by Ventilation', PPNS, Vol. XVI (1868), pp 67-69; BSP/1868-69/XII/548-550

85. Innes, PPNS, Vol. XVI (1868), pp 67-69.

86. Home, PPNS, Vol. XII (1863), pp 40-41.

87. BSP/1868-69/XII/550.

88. Collinson, Lieut. Col., 'Iron Casemates', PPNS, Vol. XIV (1865), p. 70; Inglis, Lieut. Col., 'Casemate and Shield Experiments', PPNS, Vol. XVIII (1870), pp 275-276.

89. Inglis, Capt., 'On the Application of Iron to Defensive Works', PPNS, Vol. XI (1862), p. 185.

90. BSP/1862/XXXIII/531-533; PRO, WO/33/12, Transactions and Report of the Special Committee on Iron, 1862, pp viii-ix; Connolly, T.W.J., Capt. RE, *Roll of Officers of the Corps of Royal Engineers 1660-1898*, Chatham, 1898

91. Porter, *History of the Corps of Royal Engineers*, Vol. II, p. 223.

92. *The Engineer*, Vol. 51 (1881), p. 326.

93. Inglis, PPNS, Vol. XI (1862), pp 189-190.

94. Totten, PPNS, Vol. VIII (1859) pp 20-23; Inglis, PPNS, Vol. XI (1862), pp 190-191.

95. PRO, WO/33/12/Appendix D, p. 32.

96. Yule, PPNS, Vol. V (1857), p. 87 and Plate 2.

97. Inglis, PPNS, Vol. XI (1862), p. 191.

98. Ibid, pp 191-209; PRO, WO/33/12/viii. The target, designed with rolled iron bars, tongued and grooved in horizontal layers was a collaborative effort between Captain G. Wrottesley of the Royal Engineers and Messrs. Thorneycroft of Wolverhampton.

99. PRO, WO/33/12/vii.

100. Inglis, PPNS, XI (1862), p. 213.

101. Ibid, pp 213-214.

102. Ibid, p. 218.

103. Du Cane, E.F., Capt., 'Fortification in Iron', PPNS, Vol. XII (1863), pp 16-17.

104. The Engineer, Vol. 18 (1864), p. 163.

105. Ibid, p. 209.

106. DNB, Vol. 22, pp 301-302; Dictionary of Business Biography, Vol. 1, pp 475-477.

107. Collinson, PPNS, Vol. XIV (1865), pp 69-127.

108. Ibid, p. 124.

109. Inglis, PPNS, Vol. XVIII (1870), pp 193-266; The Engineer, Vol. 25 (1868), pp 464-465.

110. The Engineer, Vol 25 (1868), p. 464.

111. Inglis, Lieut. Col., 'Iron Shield Experiments', PPNS, Vol. XIX (1871), pp 93-95. The contract for the shields specified that the materials and workmanship should conform to the specifications for the ironwork of Fort Cunningham, Bermuda, which was then in hand.

112. Hughes, Q., Military Architecture,London, 1974, p 188.

113. Jervois, Col. RE, 'Coast defences and the application of iron to fortification', Journal of the Royal United Services Institution, Vol. XII (1869), p. 566.

114. Schaw, Capt. H. 'The Present State of the Question of Fortification', Journal of the Royal United Services Institution, Vol. X (1866), p. 460.

115. Jervois, Journal of the Royal United Services Institution, Vol. XII (1869), p. 569; Schaw, Journal of the Royal United Services Institution, p. 460.

116. The Engineer, Vol. 51 (1881), p. 326.

117. Ibid.

118. Burnell, The Annual Retrospect of Engineering and Architecture, p. 276.

6. *Designing Healthy Prisons, Barracks and Hospitals*

1. Dixon, R. and Muthesius, S., *Victorian Architecture*, London, 1978, p. 109; Wohl, A.S., *Endangered Lives: Public Health in Victorian Britain*, London, 1984, pp 6-328; Spiers, *The Army and Society*, pp 55-58; Skelley, *The Victorian Army at Home*, pp 27-51.

2. Tomlinson, M.H., *Victorian Prisons: Administration and Architecture 1835-1877*, Unpublished PhD Dissertation, University of London, Bedford College, 1975, p. 2.

3. Evans, R., *The fabrication of virtue: English prison architecture 1750-1840*, Cambridge, 1982, pp 5-6.

4. Ibid, pp 8 and 394.

5. Dixon and Muthesius, *Victorian Architecture*, p. 109.

6. Wohl, *Endangered Lives*, p. 285.

7. Reid, D.B., *Illustrations of the Theory and Practice of Ventilation*, London, 1844, p. x.

8. Skelley, *The Victorian Army at Home*, p. 19.

9. Ibid, pp 21-27.

10. Wohl, *Endangered Lives*, pp 287-328

11. King, A.D., *Buildings and society: Essays on the social development of the built environment*, London, 1980, p. 17.

12. Tomlinson, *Victorian Prisons*, pp 231-277.

13. Forty, A., 'The modern hospital in England and France: the social and medical uses of architecture', in King, *Buildings and Society*, p. 79.

14. Cook, E., *The Life of Florence Nightingale*, Volume I, London, 1913, pp 388, 417 and 420; Smith, F.B., *Florence Nightingale: Reputation and Power*, London, 1982, pp 91 and 96.

15. Galton, D., *Observations on the Construction of Healthy Dwellings, Namely Houses, Hospitals, Barracks, Asylums, etc.*, Oxford, 1880, p. v.

16. Ibid, p. 156.

17. Bruegmann, R., 'Central Heating and Forced Ventilation: Origins and Effects on Architectural Design', *Journal of the Society of Architectural Historians*, Vol. 37 (1978), pp 143-160.

18. Tomlinson, *Victorian Prisons*, pp 2, 11-14, 332; Tomlinson, H., 'Design and reform: the 'separate system' in the nineteenth-century English prison' in King, *Buildings and Society*, p. 94; Evans, *Fabrication of Virtue*, pp 326-398.

19. Evans, *Fabrication of Virtue*, pp 221 and 320-326; Tomlinson, *Buildings and Society*, p. 113.

20. Jebb, Major, RE, 'On the Construction and Ventilation of Prisons', PP, Vol. VII (1845), p. 14.

21. Evans, *Fabrication of Virtue*, pp 338 and 342-343; On Haviland see: Colvin, *Dictionary of British Architects*, p. 400. English penal reformers had compared the two methods of imprisonment used in the United States in the 1830's - the separate system and the silent system (Auburn) - and chose the former, which was represented well in Cherry Hill.

22. Tomlinson, *Victorian Prisons*, pp 266-277; DNB, Vol. X, pp 698-699.

23. DNB, Vol. X, pp 698-699; PP, Vol. 1 (1837), p. 74.

24. BSP/1844/XXVIII/129, Report of the Surveyor-General of Prisons on the Construction, Ventilation and Details of Pentonville Prison, p. 129; Evans, *Fabrication of Virtue*, p. 331.

25. BSP/1844/XXVIII/131-132.

26. Evans, *Fabrication of Virtue*, pp 367-370.

27. Ibid, p. 384.

28. Ibid, pp 388 and 391.

29. DNB, Vol. 22, pp 834-836; *Australian Dictionary of Biography*, Vol. 4, pp 376-377; Tomlinson, *Victorian Prisons*, p. 311

30. DNB (1901-11), pp 528-529.

31. Mayhew, H. and Binney, J., *The Criminal Prisons of London*, Reprint, London, 1971, p. 116; Colvin, H., *The history of the King's works*, Volume 6: 1782-1851, London, 1973, pp 630-631; BSP/1844/XXVIII/148.

32. Jebb, PP, Vol. VII (1845), p. 19.

33. Both the radial and polygonal plans were first used by William Blackburn, the notable prison architect (radial at the National Penitentiary in 1782, and the polygonal at Northleach in 1784). George Blyfield revived and improved the radial in 1802. See: Evans, *Fabrication of Virtue*, pp 284-286.

34. Ibid, p. 295.

35. Jebb, PP, Vol. VII (1845), p. 11.

36. Ibid, p. 12.

37. Ibid, pp 12-13.

38. BSP/1844/XXVIII/146.

39. Jebb, PP, Vol. VII (1845), pp 19-20.

40. BSP/1844/XXVIII/135.

41. Reid, *Theory and Practice of Ventilation*; Hood, C., 'On Warming and Ventilation of Public Buildings and Apartments, with an account of the methods which have been most successfully employed for ensuring a healthy state of the Atmosphere', MPICE, Vol. I (1839(, pp 72-75; Spencer, Mr., 'On the System of combining Mechanical Ventilation with Warming by Steam Heat, as adapted to Public Buildings', PP, Vol. VI (1843), pp 166-177; Tomlinson, C., *A Rudimentary Treatise on Warming and Ventilation*, London, 1850; Ferguson, E.S., 'An Historical Sketch of Central Heating: 1800-1860', in Peterson, C. (Editor), *Building Early America*, Radnor, Pennsylvania, 1976, pp 165-185; Bruegmann, *Journal of the Society of Architectural Historians*, Vol. 37 (1978), p. 148, Note 20; Richardson, C.J., *A Popular Treatise on the Ventilation and Warming of Buildings*, 3rd Edition, London, 1856.

42. Tomlinson, *Victorian Prisons*, p. 114.

43. Reid, *Theory and Practice of Ventilation*, pp 337-338.

44. Ibid, pp 112-113.

45. Ibid, p. 273-276; Bruegmann, *Journal of the Society of Architectural Historians*, Vol. 37 (1978), pp 150-153.

46. Richardson, *Popular Treatise on Ventilation and Warming*, pp 24 and 115. The first edition of Richardson's book was in 1837; Tomlinson, *Victorian Prisons*, p. 114.

47. Richardson, *Popular Treatise on Ventilation and Warming*, p. 24.

48. Ferguson, *Building Early America*, p. 171.

49. Tomlinson, *Victorian Prisons*, p. 114.

50. BSP/1844/XXVIII/135.

51. Ibid, p. 135.

52. Ibid.

53. MPICE, Vol. 16 (1857), pp 124-127.

54. BSP/1847/XXIX/1, Second Report of the Surveyor-General of Prisons, p. 10.

55. BSP/1844/XXVIII/137.

56. Ibid, p. 138.

57. BSP/1847/XXIX/10-11.

58. BSP/1844/XXVIII/135-136.

59. Jebb, PP, Vol. VII (1845), p. 25, Mechanic's Magazine, Vol. 49 (1848), p. 28.

60. Tomlinson, Rudimentary Treatise on Warming and Ventilation, p. 243.

61. Ibid.

62. For another commentary on the debate which refers to advocates of each system see: Spencer, PP, Vol. VI (1843), pp 170-171. Spencer quite decidedly preferred the 'ascending' system.

63. Mechanic's Magazine, Vol. 42 (1845), p. 156.

64. Mechanic's Magazine, Vol. 49 (1848), p. 28; BSP/1847/XXIX/9.

65. Galton, D., Observations on the Construction of Healthy Dwellings Namely Houses, Hospitals, Barracks, Asylums etc., Oxford, 1880, p. 156. Galton was married to the eldest daughter of Joseph Strutt of Derby. It is interesting to speculate that Jebb may have studied the Sylvester-Strutt system either first hand, especially since he was born and raised in Derbyshire, or in Charles Sylvester's, The Philosophy of Domestic Economy (1819), a book which was widely distributed.

66. Tomlinson, Victorian Prisons, p. 116. In the 1830's Charles Sylvester worked in partnership with John Sylvester, but Tomlinson does not indicate which of them undertook experiments at Pentonville nor does she give the date.

67. Jebb, PP, Vol. VII (1845), p. 28.

68. Ibid.

69. Ibid.

70. BSP/1854-55/XXXII/163.

71. Ibid.

72. B, Vol. 2 (1844), p. 596.

73. Mechanic's Magazine, Vol. 42 (1845), p. 154.

74. B, Vol. 3 (1845), p. 70.

75. Mechanic's Magazine, Vol. 42 (1845), p. 155

76. Ibid, p. 156.

77. Tomlinson, Buildings and Society, p. 104.

78. This concern was explicitly expressed by Jebb, William Denison and Douglas Galton (and other members of the Army Sanitary Commission). See: Jebb, PP, VII (1845), p. 25; Denison, Capt. W., 'Observations on Barracks, and on the Moral Condition of the Soldier; CP, (1849-50), p. 259; BSP/1861/XVI/1, General Report of the Commission Appointed for Improving the Sanitary Condition of Barracks and Hospitals, p. 80.

79. Evans, Fabrication of Virtue, pp 339-341; Tomlinson, Buildings and Society, pp 102.

80. Evans, Fabrication of Virtue, p. 339.

81. In 1840 there were only two projects in England of the same scale or degree of sophistication in building servicing: the Reform Club (1837) and the Houses of Parliament, Westminster, both by Sir Charles Barry. See: Evans, Fabrication of Virtue, p. 367; Tomlinson, Buildings and Society, p. 102.

82. BSP/1861/XVI/68.

83. BSP/1850/XXIX/151, Report on the Discipline and Construction of Portland Prison, pp 174, 286-287 and 290-293; B, Vol. 6 (1848), p. 605; Tomlinson, Victorian Prisons, pp 313-329. The first group of convicts was moved into Portland Prison 24 November 1848. It was designed by Jebb but works were executed under his architectural assistant, James Ottey.

84. BSP/1854-55/XXXII/162.

85. Ibid, p. 162.

86. Ibid.

87. Ibid.

88. BSP/1861/XVI/76 and 136.

89. BSP/1854-55/XXXII/162-163.

90. Ibid, p. 165.

91. Ibid, p. 161

92. Tomlinson, Buildings and Society, p. 100

93. Evans, Fabrication of Virtue, pp 335-337; Tomlinson, Buildings and Society, pp 99-100.

94. BSP/1844/XXVIII/147-148.

95. Ibid.

96. Du Cane, Major-General, Sir E.F., 'The Prison At Wormwood Scrubs With An Account Of The Circumstances Attending Its Erection', The Royal Engineers Journal, Thursday, May 1890, p. 99. See also: Curl, J.S., Victorian Architecture: Its Practical Aspects, Newton Abbot, 1973, p. 82.

97. Ibid, p. 101.

98. Dixon and Muthesius, Victorian Architecture, p. 114.

99. Evans, Fabrication of Virtue.

100. Watson, History of the Corps of Royal Engineers, pp 148-151.

101. For example, Anthony Salvin worked with George Arnold RE on the Officers Barracks at Dover Castle in 1856. See: BSP/1862/XXXIII/701-702.

102. BSP/1861/XVI/1, General Report of the Commission Appointed for Improving the Sanitary Condition of Barracks and Hospitals, pp 13-80.

103. Skelley, Victorian Army at Home, p. 27.

104. Spiers, The Army and Society, p. 56.

105. Ibid, p. 57.

106. Cook, Florence Nightingale, Vol. II, p.6.

107. DNB, Vol. XXII, pp 691-694.

108. DNB, Vol. XIX, pp 178-179.

109. Smith, Nightingale, pp 100-101.

110. Skelley, The Army and Society, p. 37.

111. B, Vol. 5 (1847), p. 7.

112. Ibid; Denison, CP, p. 261. The building also had advanced plumbing with cast iron with coated whiteware basins. The toilets flushed by stopping up the drain. This cleansed the privies by scouring.

113. Denison, CP, pp 259-260.

114. Bernan W., On the History and Art of Warming and Ventilating Rooms, London, 1845, pp 88-89. Deacon's system drew air from an underground tunnel or from a cellar by means of a fan, and forced it through small iron or earthenware tubes placed in boiling water into rooms. Vitiated air was conducted into a tube or channel at the ceiling, which was usually carried above the roof where it exited into external atmosphere. Occasionally, Deacon used iron plates parallel to each other, leaving a space of about 1 1/2 inches between them. These were placed in boiling water and the air rose in the space between the hot plates. In warm weather Deacon's system could be used to cool rooms by immersing the pipes or plates in cold water and using the fan to force the cooled air between them into the rooms. For large rooms Deacon used fans powered by manual labour but more commonly he used the power of an unbending spring or falling of a weight. Deacon's so called 'Eolian' apparatus was used in some public buildings but apparently without much success and failed to bring the merited reward to the inventor. Dr. Reid was critical of winding weights for powering fans because they were apt to be neglected. See: Reid, Illustrations of Ventilation, p. 112.

115. Porter, History of the Royal Engineers, Vol. II, p. 494; DNB, Vol. 7, p. 519.

116. BSP/1861/XVI/18.

117. The Commissioners were nevertheless much more critical of other barracks. Their list of condemnations included unhealthy aspects of plan both in the arrangement of blocks (eg. courtyard plans) and of rooms in interior (eg. back-to-back rooms), and poor adaptation of buildings not originally erected as barracks (eg. a linen hall, a prison, a castle and a factory). See: BSP/1861/XVI/13-28. On the matter of planning, the Army Sanitary Commission appears to have been more concerned with describing the faults of existing barracks than with specifying a plan type as they did for hospitals (ie. pavilion plan) but perhaps this was because their main task was to recommend improvements to existing structures. Interesting, however, are their comments on hut barracks. These included prefabricated huts which had been provided by a variety of manufacturers during and after the Crimean War and erected at Aldershot, Colchester, Shorncliffe, Pembroke dockyard and elsewhere. Huts had been shipped to the Crimea from 1854, especially the so called 'Gloucester Huts'. The huts were becoming an important part of barrack accommodation in 1861. There were four types: wooden huts with single walls; wooden huts with double walls; corrugated iron huts; and brick

huts. The Commission thought the wooden huts with overlapping boards were the best for ventilation, but found various faults in the others in this respect and criticised all huts for poor drainage under the floors, inadequate ventilating louvres in the roof ridge, iron stoves used as heating and overcrowding. Despite this, the Commissioners concluded: "Notwithstanding several obvious sanitary defects in all the huts we have seen, the principle of subdividing men into a number of separate houses renders this kind of barrack accommodation as a rule, more healthy than the great majority of barrack rooms." The primacy of the principle of separation was as close as the Commission came to articulating a design specification for barracks. See: BSP/1861/XVI/28-30.

118. BSP/1857/Sess.2/XLI/309, Report to the General Board of Health by the Commissioners Appointed to Inquire into the Warming and Ventilation of Dwellings, p. 410. William Fairbairn (1789-1874) is well known to students of engineering history. James Glashier (1809-1903) was an astonomer and meteorologist, and Charles Wheatstone (1802-1875) was a man of science, an inventor, and professor of experimental physics at King's College, London (1834).

119. Ibid, pp 405-412.

120. Galton, D., An Address on the General Principles Which Should Be Observed in the Construction of Hospitals, London, 1869, p. 82.

121. BSP/1861/XVI/65-77.

122. Ibid, p. 67.

123. Ibid, p. 72.

124. Ibid, p. 80.

125. DNB, Vol. XXII (1899), pp 693-694. Arthur-Jules Morin was author of Studies sur la ventilation, Paris, 1863.

126. Galton, D. Sir, 'Hospital Construction', PPOS, Vol. XXIV (1898), p. 53.

127. BSP/1862/XXXIII/656.

128. Galton, Observations on Healthy Dwellings, p. 124.

129. Galton, Address on Hospitals, p. 84.

130. BSP/1857/Sess.2/XLI/405.

131. Galton, D. Report on the Herbert Hospital at Woolwich, London, 1865, p. 3.

132. Ibid.

133. Ibid, p. 9.

134. Ibid, pp 9-10.

135. Ibid, Drawings 23 to 32.

136. Ibid, p. 15. B, Vol. 23 (1865), p. 185.

137. Forty, Buildings and Society, pp 78 and 81-82.

138. Skelley, Victorian Army at Home, p. 32.

139. A number of individuals, in addition to Nightingale, had been involved in the linking of bad air and soil to disease. One of the chief proponents of the miasmic theory was Dr. George Corfe who had twenty-five years experience at Middlesex Hospital. See: King, A. 'Hospital Planning: Revised Thoughts on the Origin of the Pavilion Principle in England', Medical History, Vol. 10, No. 4, 1966, p. 365

140. Galton, Observations on Healthy Dwellings, p. 3.

141. Ibid, p. 48.

142. Smith, Nightingale, p. 99.

143. Ibid; Galton, PPOS, XXIV (1898), p. 37.

144. Thompson, J.D. and Goldin, G., The Hospital: A Social and Architectural History, London, 1975, pp 188-196.

145. King, Medical History, Vol. 10, No. 4, 1966, pp 360-373.

146. B, Vol. 16 (1858), p. 473; Smith, Nightingale, pp 93-94.

147. Galton, Report on Herbert Hospital, p. 4.

148. Ibid, p. 5. It is interesting that Galton made no mention of the fact that the layout concept of the pavilion plan was adopted by I.K. Brunel in his famous prefabricated British Hospital at Renkioi in 1855 during the Crimean War. These timber hut ward units were arranged on either side of a connecting corridor. The W.C.s and bath facilities were at the end of the ward segregated by a wall, and the structure was well drained. Ventilation was by a forced air mechanical system using a rotary air pump, manually powered, supplemented by windows running along the eaves and in the gables. See: Toppin, D. 'The British Hospital at Renkioi 1855', The ARUP Journal, Vol. 16, No. 2, July 1981, pp 3-18.

149. BSP/1857-58/XXXVII/101, Report of a Board of Medical Officers ordered to assemble by the Director-General of the Army Medical Department in 1856, to Report upon the Plans of a Proposed Hospital for Aldershot, pp 101-102. The proposal was for isolated three storey blocks, with windows on each side ensuring ventilation. Apparently, Nightingale wrote to Stent saying: "I consider the ground plan as the most perfect example of the block system I have seen... " (See: B, Vol. 15 (1857), p. 467). Stent suggested a natural ventilation system. The construction of the pavilion floors was to be perforated hollow bricks of glazed earthenware. These were to be divided horizontally into two compartments, the under half receiving vitiated air from the lower ward and the upper half supplying the ward with pure cool air from the ward above. External air was introduced by way of flues and a series of perforated plates of zinc running around the base of the skirting board and up the centre of the floor. The vitiated air was extracted by flues connected with a fireplace at the end of the building which was to be kept constantly burning to extract foul air. Stent felt that mechanical ventilation was neither necessary nor desirable. See: B. Vol. 15 (1857), p. 467 and BSP/1857-58/XXVII/101-102.

150. King, Medical History, Vol. 10, No. 4, 1966, pp 366-367. Another important pavilion plan hospital under construction after 1861 was the Leeds General Infirmary (1863-67) by George Gilbert Scott. Pavilion principles were also used before 1865 in the construction of small regimental hospitals at Hounslow, York, Fleetwood and Hilsea. See: Galton, Report on the Herbert Hospital, p. 23.

151. Galton, Report on the Herbert Hospital, p. 23.

152. BSP/1862/XXXIII/594.

153. Dixon and Muthesius, Victorian Architecture, p. 112.

154. BSP/1862/XXXIII/652.

155. Galton, Report on Herbert Hospital, p. 23.

156. Cook, Nightingale, Vol. I, p. 420.

157. Galton, Report on Herbert Hospital, p. 23.

158. BSP/1864/XXVIII/463, Sixth Report of the Medical Officer of the Privy Council, 1863, App. No. 15 Report by Dr. John Syer Bristowe and Mr. Timothy Holmes on the Hospitals of the United Kingdom. Bristowe (physician) and Holmes (surgeon) were respected, well experienced members of the British medical community. In their investigations they visited 102 hospitals in England, Scotland and Ireland, 1860-62. This provides a reasonably good

cross section of what was going on about the time Galton was designing the Herbert Hospital.

159. B, Vol. 16 (1858), pp 577-578.

160. Galton, Report on Herbert Hospital, p. 3.

161. B, Vol. 23 (1865), p. 183.

162. Ibid, p. 99; Galton, Report on Herbert Hospital, p. 9.

163. Galton, Observations on Healthy Dwellings, pp 17-18.

164. B, Vol. 16 (1858), pp 609-610.

165. B, Vol. 23 (1865), p. 99.

166. Galton, Report on Herbert Hospital, p. 7.

167. Galton, Observations on Healthy Dwellings, p. 168.

168. BSP/1864/XXVIII/508.

169. Galton, Report on Herbert Hospital, p. 11.

170. Currey, H., 'St. Thomas's Hospital, London', Royal Institute of British Architects, Sessional Papers, 1870-71, pp 62-63.

171. Thompson and Goldin, The Hospital, p. 147.

172. Galton, Report on Herbert Hospital, p. 17 and Drawing No. 9.

173. B, Vol. 16 (1858), p. 643. Roberton's and Godwin's ward measured 128 feet long and 30 feet wide.

174. Galton, Report on Herbert Hospital, pp 15, 16 and 18; BSP/1864/XXVIII/503-504.

175. Galton, Report on Herbert Hospital, pp 15-16; Galton, Address on Hospitals, p. 27; Galton, Observations on Healthy Dwellings, pp 130-132.

176. Galton, Observations on Healthy Dwellings, pp 134-135.

177. B, Vol. 23 (1865), p. 184.

178. MPICE, Vol. 55 (1879), p. 166.

179. Galton, Report on Herbert Hospital, pp 17 and 19; Galton, Observations on Healthy Dwellings, p. 153.

180. BSP/1864/XXVIII/490.

181. King, Medical History, Vol. 10, No. 4, 1966, p. 362; BSP/1864/XXVIII/490.

182. BSP/1864/XXVIII/490.

183. King, Medical History, Vol. 10, No. 4, 1966, pp 364 and 368.

184. In St. Thomas's Hospital (1868-71), London, one of the major new pavilion hospitals of the early period, Currey employed Haden and Son of Trowbridge to design the heating and ventilation system. Ventilating stoves were used in each ward which were similar to a patent stove by Gurney rather than Galton's design. These had vertical flues instead of Galton's horizontal type under the floor and Currey pointed out that this design was much easier to repair should something go wrong. This system was supplemented, as in Herbert Hospital, by ventilating hot water coils. Nevertheless, the principle foul air extraction method was by way of a heat-aided system where multiple shafts from each ward connected with a stairwell main shaft in which was placed the smoke flue from the main boiler in the basement. See: Currey, H., Royal Institute of British Architects, Sessional Papers, 1870-71, pp 69-70.

185. Skelley, Victorian Army at Home, p. 51.

186. Galton, Address on Hospitals, p. 17.

187. Galton, PPOS, Vol. XXIV, p. 37.

188. DNB, Vol. XXII, p. 694.

189. Galton, Capt. D., 'On Sanitary Progress in India', Journal of the Society of Arts, Vol. XXIV (1875-76), p. 533.

190. DNB, Vol. XXII, pp 693-694.

191. Smith, Nightingale, p. 171. Smith has revealed that Nightingale obtained secret intelligence from Galton, in the period 1865-67, by way of documents from the Poor Law Office, which detailed frightful overcrowding, privation, cruelty and filth in London workhouses.

192. Forty, Buildings and Society, p. 82. Chorlton Union Infirmary, designed by architect Thomas Worthington, was the first Poor Law workhouse infirmary to be built on the pavilion principle. Nightingale described it as the best pavilion plan in the country when the design proposal was illustrated in The Builder in June 1865. See: Dickens, A., 'The Architect and the Workhouse', Architectural Review, Vol. CLX, No. 958, December 1976, p. 351.

193. Proceedings of the Institution of Mechanical Engineers, 1899, p. 132.

194. Galton, Address on Hospitals, pp 6-7.

7. Innovative Technology and Victorian Taste in Works of Monumental Public Architecture

1. See especially: Survey of London, The Museums Area of South Kensington and Westminster, Vol. XXXVIII, London, 1975; and Physick, J., The Victoria and Albert Museum: The history of its building, Oxford, 1982. On the use of terracotta at South Kensington see: Stratton, M.S., The Manufacture and Utilization of Architectural Terracotta and Faience, unpublished PhD Thesis, University of Aston, Birmingham, 1983. On the matter of architectural style see: Physick, J. 'The South Kensington Museum', in Macready, S. and Thompson, F.H., Influences in Victorian Art and Literature, London, 1985, pp 73-80.

2. Survey of London, Museums of South Kensington, p. 97; Physick, Victoria and Albert Museum, p. 12.

3. DNB, Vol. 7, p. 519; PPNS, Vol. XV (1866), p ix; Cole, H., Sir, Fifty Years of Public Works, Vol. 2, London, 1884, p. 349.

4. Cole, Fifty Years of Public Works, Vol. 2, p. 350.

5. BSP/1856/XXXVI/Part 1/1; BSP/1856/XXXVI/Part 3/413.

6. B, Vol. 15 (1857), p. 90.

7. Survey of London, Museums of South Kensington, p. 100.

8. DNB, Vol. 7, p. 519.

9. Cole, Fifty Years of Public Works, p. 351; Survey of London, Museums of South Kensington, p. 99; Herbert, G., Pioneers of Prefabrication: The British Contribution in the Nineteenth Century, Baltimore, 1978, pp 164-165.

10. BSP/1862/XXXIII/585-586.

11. MPICE, Vol. 30 (1865), p. 469.

12. In a paper describing his cement experiments, Scott referred to his concern about the quick decomposition of shale under an escarp wall for Jumper's Battery at Gibraltar which he presumably constructed or repaired. See: Scott, PPNS, Vol. VI (1857), p. 143.

13. Survey of London, Museums of South Kensington, pp 66-67 and 93.

14. BSP/1866/XXV/337, 13th Report of the Science and Art Department, p. 350.

15. DNB, Vol. 17, p. 965; MPICE, Vol. 75 (1883), p. 321.

16. Survey of London, Museums of South Kensington, pp 88-89.

17. MPICE, Vol. CXII (1892-1893) Pt. 2, pp 347-349.

18. Physick, Victoria and Albert Museum, p. 47.

19. Cole, Fifty Years of Public Works, Vol. 1, p. 330.

20. Survey of London, Museums of South Kensington, p. 90.

21. BSP/1866/XXV/349.

22. Cole, Fifty Years of Public Works, Vol. 2, p. 355.

23. Survey of London, South Kensington Museums, p. 90.

24. Ibid, p. 144.

25. Ibid, p. 94.

26. Ibid, p. 93; Cole, Fifty Years of Public Works, Vol. 1, p. 33.

27. Survey of London, South Kensington Museums, p. 93.

28. Cole, Fifty Years of Public Works, Vol. 1, pp 335-336.

29. Son of artist Charles W. Wild and a pupil of G. Basevi, Wild had been a church architect in the late 1830's and 1840's. In 1849-50 he designed St. Martin's in the Fields Northern District School, London, which was one of the first secular Victorian designs in an Italian Gothic style and won the praise of Ruskin. The school served as a model for commercial buildings in the High Victorian Gothic style. Wild was therefore a senior architect when he joined Scott in 1865 and was firmly grounded in the principles of the High Victorian Movement in architecture. See: Dixon and Muthesius, Victorian Architecture, pp 269, 238 and 131; and Muthesius, S., The High Victorian Movement in Architecture 1850-1870, London, 1972, p. 189.

30. Survey of London, South Kensington Museums, pp 88-89; The Times, Tuesday 17 June 1941, p. 9.

31. Survey of London, South Kensington Museums, p. 93.

32. The Times, Tuesday 17 June 1941, p. 9.

33. BSP/1866/XXV/526-527; BSP/1868-69/XXIII/621, Report of the Commission on the Heating, Lighting, and Ventilation of the South Kensington Museum, p. 626.

34. Survey of London, South Kensington Museums, p. 78.

35. Cole, Fifty Years of Public Works, Vol. 2, p. 349.

36. Survey of London, South Kensington Museums, p. 94.

37. Cole, Fifty Years of Public Works, Vol. 2, p. 297.

38. Ibid, p. 326. Cole's eldest son, H.H. Cole (1843-1916) was a Royal Engineer. He served mostly in India but designed the National Training School for Music (1874-75) at South Kensington in collaboration with Science and Art Department staff and in consultation with his father. See: Survey of London, South Kensington Museums, pp 271-273.

39. Cole, Fifty Years of Public Works, Vol. 1, p. 337.

40. The design process for the buildings at South Kensington was described by the Science and Art Department in December 1867. It outlined how the Director of New Buildings (Scott) drew up preliminary plans and block models after discussion on required accommodation with the General Superintendent of the Museum. Modellers and artists to be employed on decoration were consulted at an early stage but the block model, structural plans and working drawings were first completed without architectural and decorative details. To obtain these, structural plans with sketches were sent to the artists' studios. Importantly, decorative design was the result of consultation between artists and the Director of New Buildings, but the latter remained soley responsible. The Director also supervised the making of models of architectural details in the artists' studios. Architectural models of the building were then made incorporating the decorative details accompanied by drawings and perspectives, and the whole subjected to extensive criticism within the Department before the design was finalized. See: BSP/1867-68/XXVII/419, 15th Report of the Science and Art Department, p. 642.

41. Ibid, p. 642.

42. Physick, Victoria and Albert Museum, p. 9; Survey of London, South Kensington Museums, pp 90-91; Stratton, Manufacture and Utilization of Architectural Terracotta, p. 69.

43. Cole, Fifty Years of Public Works, Vol. 1, p. 33.

44. Olsen, D.J., The City as a Work of Art, London, 1986, pp 296-297.

45. Survey of London, South Kensington Museums, p. 90.

46. Stratton, Manufacture and Utilization of Architectural Terracotta, p. 81.

47. Survey of London, South Kensington Museums, p. 77.

48. Physick, Influences in Victorian Art, pp 78-80.

49. The *Building News*, in commenting on Fowke's design for the Royal Horticultural Society conservatory in 1861, explained that Fowke had adopted the "Italian" style and that he had studied examples of the style in Italy and evidently learned his lessons well: "... he has shown himself fully competent to realize the impressions produced on his own mind by his studies." BN, Vol. 7 (1861), p. 437.

50. *Journal of the Society of Arts*, Vol. XIV (1866), p. 60.

51. BN, Vol. 7 (1861), p. 437.

52. B, Vol. 23 (1865), p. 882.

53. B, Vol. 22 (1864), pp 394-395.

54. BSP/1863/XVI/21, 10th Report of the Science and Art Department, p. 281.

55. Bradford, B., 'The Brick Palace of 1862', *Architectural Review*, Vol. 132, July 1962, pp 15-21.

56. B, Vol. 20 (1862), p. 22.

57. *Art Journal*, New Series, Vol. 1 (1862), p. 47.

58. Ibid.

59. Ibid.

60. Ibid.

61. B, Vol. 20 (1862), p. 22; Phillpotts, Capt. W. RE, 'The Building for the International Exhibition of 1862', *Journal of the Society of Arts*, Vol. X (1861), p. 57.

62. Phillpotts, *Journal of the Society of Arts*, Vol. X (1861), pp 55-56.

63. Ibid, p. 53.

64. CEAJ, Vol. XXV (1862), p. 8.

65. Bradford, *Architectural Review*, Vol. 132, July 1962, p. 20.

66. Phillpotts, *Journal of the Society of Arts*, Vol. X (1861), pp 54-55.

67. Survey of London, *Museums of South Kensington*, p. 87 Street, A.E., *Memoir of George Edmund Street R.A., 1824-1881*, London, 1888, p. 267.

68. Street, *Memoir of Street*, pp 267-268.

69. Jenkins, F., Architect and Patron, London, 1961, pp 194-195; Wilton-Ely, J., 'The Rise of the Professional Architect in England', in Kostof, S. (Editor), The Architect: Chapters in the History of the Profession, New York, p. 197. In an address to the Royal Institute of British Architects in 1872, Captain Henry C. Seddon of the Royal Engineers called for greater co-operation between architects and engineers for their mutual benefit and that of society, arguing that art and science, beauty and utility could be better united. See: Seddon, Capt. RE, 'Our Present Knowledge of Building Materials And How to Improve It', Royal Institute of British Architects Sessional Papers, 1871/72, pp 143-157.

70. Scott, Major-General, 'On the Construction of the Albert Hall', Royal Institute of British Architects, Sessional Papers, 1872, p. 83.

71. Ibid.

72. Survey of London, Museums of South Kensington, p. 93.

73. Scott, Royal Institute of British Architects, Sessional Papers, 1872, p. 95.

74. Survey of London, Museums of South Kensington, p. 97.

75. Ibid, p. 99.

76. The museum also accommodated and supplemented a collection of prints and drawings formerly shown by the Department at its Marlborough House location as well as the casts and models of architectural antiquities belonging to the former Architectural Museum which had been established as a private institution in Cannon Row, London, in 1851, and which had served as a centre for teaching stone carving, and architectural drawing. These collections, however, had little to do with advanced building technology. See: Cole, Fifty Years of Public Works, Vol. 2, p. 292.

77. BSP/1856/XXXVI/Part 3/660-663; B, Vol. 16 (1858), p. 137; Survey of London, Museums of South Kensington, p. 101.

78. BSP/1856/XXXVI/Part 3/666. On this he was not quite right. Herbert Minton began production of encaustic tiles in the 1830's and Chamberlain and Co. of Worcester in the 1840's. Maw's started in 1850 and took over the remains of Chamberlains, and two years later moved to Benthall near Ironbridge. See: Herbert, A.T., 'Jackfield Decorative Tiles in Use', Industrial Archaeology Review, Vol. 3, No. 2, Spring 1979, p. 146.

79. BSP/1856/XXXVI/Part 3/606.

80. Ibid, pp 669-670; Hamilton, S.B., 'The History of Hollow Bricks', Transactions, British Ceramic Society, Vol. 58, No. 2, February 1959, p. 47.

81. BSP/1856/XXXVI/Part 3/673.

82. BSP/1856/XXXVI/Part 1/402.

83. Ibid, pp 403-410; BSP/1856/XXXVI/Part 3/690.

84. BSP/1863/XVI/218-219.

85. BSP/1859/XXI/Sess.1/Part 2/433, 6th Report of the Science and Art Department, p. 465.

86. BSP/1862/XXI/321, 9th Report of the Science and Art Department, p. 463; BSP/1856/XXXVI/Part 3/663-664.

87. BSP/1864/XIX/Part 1/1, 11th Report of the Science and Art Department, pp 203-204.

88. Ibid, p. 204.

89. BSP/1865/XVI/301, 12th Report of the Science and Art Department, p. 548.

90. Ibid, p. 549.

91. BSP/1861/XXXII/1, 8th Report of the Science and Art Department, p. 140.

92. Ibid.

93. BSP/1863/XVI/219.

94. BSP/1865/XVI/549.

95. Stratton, Manufacture and Utilization of Architectural Terracotta, p. 96.

96. BSP/1865/XVI/549. Terracotta was later promoted outside the museum. A copy of a terracotta arcade and one bay from new buildings at South Kensington were displayed at the Paris Universal Exhibition, 1867, and on its close were re-erected in the Conservatoire des Arts et Metiers, Paris. See: BSP/1867-68/XXVII/419, 15th Report of the Science and Art Department, pp 643-644.

97. BSP/1861/XXXII/139.

98. BSP/1859/XXI/Sess.1/Part 2/465.

99. BSP/1865/XVI/550.

100. BSP/1859/XXI/Sess.1/Part 2/465.

101. BSP/1861/XXXII/140

102. Ibid, p. 139.

103. BSP/1859/XXI/Sess.1/Part 2/465-466.

104. BSP/1861/XXXII/140.

105. Ibid, p. 141.

106. BSP/1862/XXI/464.

107. BSP/1863/XVI/219.

108. BSP/1866/XXV/587.

109. BSP/1882/XXVI/1, 29th Report of the Science and Art Department, p. 13. The committee consisted of three civilians and one Royal Engineer: Charles Hutton Gregory, George Edmund Street, James Abernathy and Major Henry C. Seddon.

110. BSP/1862/XXI/463.

111. Physick, *Victoria and Albert Museum*, p. 11.

112. BSP/1862/XXI/463.

113. Ibid.

114. BSP/1860/XXIV/77, 7th Report of the Science and Art Department, p. 225.

115. Ibid.

116. BSP/1864/XIX/Part 1/205; BSP/1865/XVI/550.

117. BSP/1860/XXIV/225.

118. BSP/1862/XXI/464; BSP/1864/XIX/Part 1/205.

119. BSP/1862/XXI/464. These experiments were continued from 1862 to 1864. See: BSP/1863/XVI/218; BSP/1864/XIX/Part 1/205; and BSP/1865/XVI/550.

120. BSP/1864/XIX/Part 1/205.

121. Redgrave, G.R., 'The Semicircular Timber Roof-Truss Designed by the late Captain Fowke, R.E.', MPICE, Vol. LXXXII (1884-1885), Pt. IV, p. 302; James, J.G., 'The Evolution of Wooden Bridge Trusses to 1850', *Journal of the Institute of Wood Science*, No. 51 (June 1982), pp 129-130; Booth, L.G., 'The Development of Laminated Timber Arch Structures in Bavaria, France and England in the Early Nineteenth Century', *Journal of the Institute of Wood Science*, Vol. 29 (July 1971), p. 3. The technique was published by de l'Orme in his *Inventions pour bien bastir et a petits fraiz* (1561),

and was republished in most subsequent building treatises. Two German works devoted to the de l'Orme system were published at the end of the eighteenth century and a few bridges were built with such ribs in the early nineteenth century. Vertically laminated arches, however, were primarily used for roofs. De l'Orme's system did not see much use until it was adopted in 1783 for the original timber roof of the Halle aux Ble in Paris.

122. Booth, Journal of the Institute of Wood Science, Vol. 29 (July 1971), pp 8-11. Emy first employed his method in a 20 m wide hangar at Marac and the next year for a new riding school at the Libourne barracks. Emy published a book on his new system in 1828 in which he confidently recommended his method for projects with spans of 40 m and 100 m.

123. Ibid, pp 13-14.

124. Cole, Fifty Years of Public Works, Vol. 2, p. 352; Phillpotts, Journal of the Society of Arts, Vol. X (1861), p. 51.

125. Phillpotts, Journal of the Society of Arts, Vol. X (1861), pp 41-51.

126. Dixon and Muthesius, Victorian Architecture, p. 108.

127. CEAJ, Vol. 25 (1862), p. 8.

128. Phillpotts, Journal of the Society of Arts, Vol. X (1861), pp 46-47.

129. Bradford, Architectural Review, Vol. 132 (July 1962), pp 19-20.

130. Phillpotts, Journal of the Society of Arts, Vol. X (1861), p. 46.

131. MPICE, Vol. 87 (1886), pp 451-455.

132. Phillpotts, Journal of the Society of Arts, Vol. X (1861), p. 51.

133. Ibid, pp 44-45.

134. B, Vol. 20 (1862), pp 840-841; BSP/1862/XVI/321; McWilliam, C. (Editor), Edinburgh: The Buildings of Scotland, 1984, p. 187.

135. Engineering, Vol. XXV (1883), p. 414. See also: Redgrave, MPICE, Vol. 82 (1884-1885), Pt. 4, p. 303. The buildings cost about £25,000.

136. Phillpotts, Journal of Society of Arts, Vol. X (1861), p. 51.

137. Redgrave, MPICE, Vol. 82 (1884-85), Pt. 4, p. 304.

138. Survey of London, Museums of South Kensington, p. 93.

139. Physick, Victoria and Albert Museum, p. 40.

140. Survey of London, Museums of South Kensington, p. 102.

141. BN, Vol. 12 (1865), p. 130.

142. MPICE, Vol. XXXII (1871), pp 310-311; Cole, Fifty Years of Public Works, Vol. 1, p. 266.

143. MPICE, Vol. XXXII (1871), p. 311.

144. Scott, Royal Institute of British Architects Sessional Papers, 1872, pp 90-91.

145. Survey of London, Museums of South Kensington, pp 235-237.

146. B, Vol. 29 (1871), p. 689.

147. Stratton, Manufacture and Utilization of Architectural Terracotta, pp 1-3 and 70; Barry, C. 'Some Descriptive Memoranda on the Works Executed in Terra Cotta at New Alleyn's College, Dulwich', Royal Institute of British Architects Sessional Papers, 1868, pp 261-264; Olley, J. and Wilson, C., 'The Natural History Museum', Architect's Journal, Vol. 181, No. 13, 27 March 1985, p. 40.

148. Stratton, Manufacture and Utilization of Architectural Terracotta, p. 69.

149. Girouard, M., Alfred Waterhouse and the Natural History Museum, London, 1981, pp 53-56.

150. Stratton, Manufacture and Utilization of Architectural Terracotta, p. 143.

151. Barry, Royal Institute of British Architects Sessional Papers, 1868, pp 270-271. Kirkaldy did not test full size columns amongst his experiments, only solid column specimens 15 inches high maximum; but his methods and comparative data on other samples and materials were more convincing. Notwithstanding the limitations of Fowke's contribution to establishing scientifically the strength advantage of terracotta, it reflected his reliance and confidence in an earlier practical tradition of strength testing by trials of a facsimile of the real thing. He did not have much choice in this matter. Unlike Barry, he did not have the opportunity of seeking Kirkaldy's help - Kirkaldy's testing works were not established in The Grove, Southwark, until 1865, the year of Fowke's death.

152. BSP/1864/XIX/Part 1/171.

153. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 97.

154. Ibid, p. 100.

155. Stratton, Manufacture and Utilization of Architectural Terracotta, p. 118.

156. Barry, Royal Institute of British Architects Sessional Papers, pp 267-268.

157. Girouard, Alfred Waterhouse and Natural History Museum, p. 56.

158. BSP/1865/XVI/553.

159. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 90.

160. Survey of London, Museums of South Kensington, p. 101, Physick, Influences in Victorian Art, p. 74; BSP/1857-58/XXIV/219, 5th Report of the Science and Art Department, pp 274-279; B, Vol. 16 (1858) pp 137-139.

161. Survey of London, Museums of South Kensington, p. 107.

162. BSP/1864/Part 1/170.

163. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 93; Survey of London, Museums of South Kensington, pp 189-190.

164. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 93.

165. Ibid.

166. BN, Vol. 7 (1861), p. 437.

167. Ibid.

168. B, Vol. 19 (1861), p. 497.

169. Stratton, Manufacture and Utilization of Architectural Terracotta, pp 100 and 350-351.

170. B, Vol. 23 (1865), p. 882.

171. BN, Vol. 7 (1861), 497.

172. BN, Vol. 30 (1876), p. 162.

173. B, Vol. 29 (1871), p. 689.

174. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 92.

175. Ibid, p. 92.

176. Ibid.

177. Ibid.

178. Barry, Royal Institute of British Architects Sessional Papers, 1868, pp 268-272.

179. Stratton, Manufacture and Utilization of Architectural Terracotta, p. 387.

180. Ibid, pp 386-387.

181. Muthesius, S., 'The Iron Problem in the 1850's', Architectural History, Vol. 13, 1970, pp 58-63.

182. See for example. Aitcheson, 'On the Progressive Use of Iron in Building', Royal Institute of British Architects Sessional Papers, 1871-1872, pp 81-85.

183. Hix, J., The Glass House, London, 1974, p. 105.

184. Diestelkamp, TNS, Vol. 54 (1982-83), p. 2.

185. Higgs, M., 'The Exported Iron Buildings of Andrew Handyside and Co. of Derby', Journal of the Society of Architectural Historians Vol. XXIV, May 1970, pp 175-180.

186. Matheson, E., Works in Iron: Bridge and Roof Structures, London, 1873, pp 251-254.

187. Survey of London, Museums of South Kensington, p. 126.

188. B, Vol. 19 (1861), p. 496; MPICE, Vol. CXII (1892-93) Pt. 2, p. 347.

189. Survey of London, Museums of South Kensington, p. 126; Hix, Glass House, p. 144.

190. PPNS, Vol. XV (1866), p. xii.

191. MPICE, Vol. CXII (1892-93) Pt. 2, p. 347.

192. Matheson, Works in Iron, p. 254.

193. The conservatory used 157 tons of cast iron costing £14 per ton and 70 tons of wrought iron at £26 per ton. See: Matheson, Works in Iron, p. 254. The Builder said the entire cost of the conservatory project, including the interior, was £16,000. See: B, Vol. 19 (1861), p. 496.

194. BSP/1863/XVI/164; Physick, Victoria and Albert Museum, p. 47.

195. BSP/1863/XVI/164-165.

196. Quoted in: Survey of London, Museums of South Kensington, p. 104.

197. BN, Vol. 12 (1865), pp 130-131; BSP/1863/XVI/166; Physick, Victoria and Albert Museum, p. 53.

198. Phillpotts, Journal of the Society of Arts, Vol. X (1861), pp 48-50; Fowke, F. Capt. RE, Some Account of the Buildings for the International Exhibition of 1862, London, 1861, p. 13.

199. Fowke, Account of Buildings for Exhibition of 1862, p. 13.

200. Survey of London, Museums of South Kensington, p. 143.

201. B, Vol. 20 (1862), p. 816.

202. Ibid.

203. Art Journal, New Series Volume 1 (1862), p. 108.

204. CEAJ, Vol. 25 (1862), p. 8.

205. Phillpotts, Journal of the Society of Arts, Vol. X (1861), pp 47-48.

206. B, Vol. 28 (1870), pp 977-978; Engineering, 20 August 1869, pp 117-118; Scott, Royal Institute of British Architects Sessional Papers, 1872, pp 89 and 97.

207. Scott, Royal Institute of British Architects Sessional Papers, 1872, pp 88-89.

208. The Engineer, Vol. 62 (1886, pp 232-233.

209. Ibid, p. 233.

210. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 90.

211. B, Vol. 28 (1870), p. 977.

212. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 99.

213. Ibid.

214. B, Vol. 28 (1870), p. 978.

215. Ibid.

216. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 85.

217. Quoted in: Survey of London, Museums of South Kensington, p. 188.

218. In 1874 a controversy erupted in the Building News on the attribution of the design for the Albert Hall. Frank Fowke, who had worked in his father's office, protested at Scott being given all the credit and John Liddell spoke for Fowke and his own share in Fowke's work. Gilbert Redgrave made a more convincing defence of Scott's primacy and so did Scott himself in a paper delivered to the Royal Institute of British Architects in 1872. See: BN, 6, 13, 20, 27 February and 6, 27 March 1874, pp 162, 189, 216, 244, 271, 353; Scott, Royal Institute of British Architects Sessional Papers, 1872, pp 83-85.

219. B, Vol. 15 (1857), p. 689.

220. BSP/1857-58/XXIV274-275 and 280.

221. Ibid, p. 279.

222. Ibid, p. 280.

223. Ibid, p. 280.

224. B. Vol. 15 (1857), p. 690.

225. Ibid.

226. BSP/1857-58/XXIV/280 and 282.

227. Fowke, Buildings for Exhibition of 1862, pp 11-12; Phillpotts, Journal of Society of Arts, Vol. X (1861), pp 43-44 and 45.

228. Cole, Fifty Years of Public Works, Vol. 1, p. 325.

229. Ibid, p. 326.

230. B, Vol. 16 (1858), p. 139. Fish tail burners had been invented about 1820 by James Neilson and James Milne of Glasgow. They worked on the principal that two jets of gas of equal size be allowed to impinge upon each other at a certain angle thus producing a flat flame with increased light. See: Chandler, D., Outline of History of Lighting by Gas, London, 1936, p. 87.

231. B, Vol. 16 (1858), p. 139; BSP/1863/XVI/166.

232. PPNS, Vol. XV (1866), p. xii.

233. BSP/1860/XXIV/77, 7th Report of the Science and Art Department, Appendix P, Report of the Commission appointed to consider the Subject of Lighting Picture Galleries by Gas, p. 201. The Commissioners were Professors Faraday, Hofmann and Tyndall, Mr. Richard Redgrave, and Captain Fowke.

234. Ibid.

235. BSP/1868-69/XXIII/621, Report of the Commission on the Heating, Lighting, and Ventilation of the South Kensington Museum, p. 264. The Commissioners were John Tyndall, John Percy, E. Frankland, Henry Scott RE, and J.F.D. Donnelly RE.

236. Fowke, Buildings for the Exhibition of 1862, pp 11-12.

237. Phillpotts, Journal of the Society of Arts, Vol. X (1861), p. 44.

238. B, Vol. 15 (1857), p. 690.

239. Ibid.

240. These are the views of Mr. Imray expressed at a meeting of the Institution of Civil Engineers in 1878. Imray had been associated from the 1840's with Dr. David Boswell Reid in a great number of projects including St. George's Hall, Liverpool and the Houses of Parliament. See: MPICE, Vol. 55 (1879), pp 156-158.

241. B, Vol. 16 (1858), pp 137-139. The description of the Gurney Stove is based on an analysis of an apparatus like it installed in St. Thomas's Hospital (1868-71), London by Henry Currey. See: Currey, Royal Institute of British Architects Sessional Papers, 1870-71, pp 69-70.

242. BSP/1868-69/XXIII/717.

243. Ibid, pp 717-718.

244. BSP/1863/XVI/165-166.

245. BSP/1864/XIX/Part 1/169; BSP/1863/XVI/167; BSP/1868-69/XXIII/718.

246. BSP/1863/XVI/165.

247. BSP/1868-69/XXIII/625-626.

248. B, Vol. 29 (1871), p. 80.

249. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 91.

250. MPICE, Vol. 108 (1892), pp 406-408.

251. B, Vol. 29 (1871), pp 80-81.

252. Ibid, p. 81.

253. Scott, Royal Institute of British Architects Sessional Papers, 1872, p. 91

254. Survey of London, Museums of South Kensington, p. 191.

255. Phipson, W.W., 'On the Heating and Ventilation Apparatus of the Glasgow University', MPICE, Vol. 55 (1859), p. 70. Phipson was an ardent advocate of mechanical forced air central heating and ventilation well into the 1870's. He later abandoned this method and adopted low pressure steam on the gravity or open circulation system which provided better control. See: MPICE, Vol. 108 (1892), p. 408.

8. Colonial Connections and Global Building Experience

1. Books by Nilsson and Davies have underlined the importance of military engineers in the development of British architecture in India from the mid-eighteenth to the twentieth century. Nilsson provides the best discussion of building technology, but neither author looks in any detail at the role of the military engineers as agents in the diffusion of technology through imperial expansion. See: Nilsson, S., European Architecture in India 1750-1850, London 1968; and Davies, P., Splendours of the Raj: British Architecture in India 1660-1947, London, 1985 Lewcock's book on early colonial architecture in South Africa acknowledges the contributions of Royal Engineers, but provides scant information about them in discussions of technology transfer. See: Lewcock, R., Early Nineteenth Century Architecture in South Africa: A Study of the Interaction of Two Cultures 1795-1837, Cape Town, 1963. McNicoll's study of the Royal Engineers in Australia provides little in the way of critical assessment of the Corps' buildings or the technology used by engineer officers. See: McNicoll, R., The Royal Australian Engineers 1835 to 1902: The Colonial Engineers, Canberra, 1977. By far the best study of the Royal Engineers and building technology transfer is Elizabeth Vincent's, Military Construction Techniques in the Use of Building Materials in British North America, 1820-1870, Parks Canada, Microfiche Report Series 156, 1985. The only work which examines the global role of British engineers in the diffusion of technology through imperial expansion is a recent article by R.A. Buchanan, 'The Diaspora of British Engineering' in Technology and Culture, Volume 27, No. 3, July 1986, pp 501-524. Buchanan's primary focus, however, is on railways, ports, waterworks, urban services and mechanical engineering, and little mention is made of structures and no mention of architecture. He acknowledges that the Royal Engineers were part of the diaspora of British engineering and that they were off the mark earlier than civil engineers who remained isolated until 1830. Nevertheless, he fails to give the Corps its due credit, mentioning only its construction of the Rideau Canal (1827-1832) and contribution to the development of the Grand Trunk Railway in Canada (late 1840's), and its role in irrigation works in India from the 1820's. Buchanan has also discussed the Corps in a recent article on the British contribution to Australian engineering. While acknowledging the Royal Engineers' role in both military and public works at certain critical points in the development of the individual colonies, he sees their influence as essentially short lived and their role declining in importance after 1860 by which time civil engineers dominated. See: Buchanan, R.A., 'The British Contribution to Australian Engineering:

The Australian Dictionary of Biography Entries', in Historical Studies (Australia and New Zealand), Vol. 20, April 1983, pp 401-419. E.W.C. Sandes, The Military Engineer in India, Vol. 2, 1935, devotes little space to architecture and is not very helpful on building technology except for a few points on bridges.

2. Headrick, D.R., 'The Tools of Imperialism: Technology and the Expansion of European Colonial Empires in the Nineteenth Century', The Journal of Modern History, Vol. 51, 1979, p. 234.

3. Headrick, D.R., The Tools of Empire: Technology and European Imperialism in the Nineteenth Century, Oxford, 1981, p. 206.

4. India provides perhaps the best example. Both Nilsson and Davies have demonstrated the role of British military engineers in the construction of forts, cantonments and a wide variety of public buildings which were a practical reality and a highly visible symbol of imperial power and dominance. Civil engineering works by military engineers were also a critical aspect of the use of building technology in the service of imperial expansion. Irrigation canals and other works in India provide an excellent example. See: Nilsson, European Architecture in India; Davies, Splendours of the Raj; and Brown, J.M. 'Contributions of the British to Irrigation Engineering in Upper India in the Nineteenth Century', TNS, Vol. 55 (1983-1984), pp 85-112.

5. Buchanan, Technology and Culture, Vol. 27, No. 3, July 1986, pp 505, 511, 516 and 522-523.

6. Nilsson, European Architecture in India, p. 156; Davies, Splendours of the Raj, pp 14-15 and 12-13; Buisseret, D., Historic Architecture of the Caribbean, London, 1980, p. 61; Shipley, Charles, Sir (1755-1815), DNB, XVIII, pp 109-110; Noppen, L. and Grignon, M., L'Art de l'architecte: trois siècles de dessin d'architecture à Québec, Québec, 1983, p. 69; Connolly, T.W.J., History of the Royal Sappers and Miners, Vol. 1, London, 1857, pp 253-287; Maitland, L., Neoclassical Architecture in Canada, Parks Canada, 1984, p. 40; McNicoll, Royal Australian Engineers, pp 5, 118 and 106-107.

7. Nelson, R.J., Lieut., 'Engineer Details: For the most part Collected at Bermuda between April 1829 and May 1833', PP, Vol. IV (1840), p. 136.

8. Denison et al, 'Remarks and Experiments on Various Woods, both Foreign and Domestic', PP, Vol. V (1842), p. 174.

9. Headrick has explained how Western peoples, whether Europeans or descendents of Europeans settled on other continents, were intensely interested in events elsewhere, technological and otherwise. Thus, what seemed to work in one place was quickly known and applied in other places. In every part of the world, Europeans were more knowledgeable about events on other continents than indigenous peoples were about their neighbours. See: Headrick, Tools of Empire, p. 208.

10. CEAJ, Vol. 1 (1837-1838), p. 3.

11. DNB, Vol. XVIII, pp 498-499.

12. Vicat, L.J., (Translation, Smith, J.T.), A Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural, London, 1837, pp xii, x-xi, 12, 59.

13. Pasley, Observations, 1838, p. 28.

14. Newbold, Lieut, 'Magnesian Cement', Mechanic's Magazine, Vol. 36 (1842), p. 336.

15. Ibid.

16. Ibid, Parker's cement was a form of Roman cement made from pulverized cement stones. See Chapter 2.

17. Ibid; Cotton, A.T. Capt., 'Magnesia Cement', Professional Papers of the Madras Engineers, Vol. 1 (1845), 3rd Edition, 1859, p. 28; Vicat, Treatise on Calcareous Mortars and Cements, p. 147.

18. Cotton, Professional Papers of the Madras Engineers, Vol. I (1845), 3rd Edition, 1859, p. 28.

19. Ibid.

20. Ibid, p. 29.

21. Ibid, p. 30.

22. Vibart, Addiscombe, pp 345-350.

23. Ibid, p. 347.

24. This topic is beyond the scope of the present thesis. A good introduction to the subject may be found in Brown, TNS, Vol. 55 (1983-84), pp 85-112.

25. Vicat, Treatise on Calcareous Mortars and Cements, p. 11.

26. Ibid, p. 148. Military engineers in India, from the eighteenth century, had adopted lime from limestone brought from the Morungs to Calcutta and lime produced from burning sea shells from the Coromandel and Malabar coasts. Shell lime was also the initial

source of lime in South Africa and in Australia for European settlers. Lime from sea shells was used to make a white plaster called 'chunam' which was used to render brick, the predomenant structural material used by military engineers in India during the nineteenth century. The entirely white building was a product of the marble cult of neoclassicism and rendered brick an adaptation of Regency fashion in England. The violent monsoons scaled off the chunam and it had to be replaced each rainy season but it was a very effective sun radiator during the hot season. Madras chunam stucco was laid in 3 coats - the first a common mixture of shell lime and sand tempered with jaghery water (a coarse sugar disolved in water to which quicklime was mixed) and about 1/2 inch thick, the second made of sifted shell lime and white fine sand also sifted and applied finer than the first, and the third which received a polish made of the purest and whitest shell lime and white sand of the finest quality ground to a uniform paste with the appearance of white cream and to each bushel was added a dozen eggs and half a pound of clarified butter (ghee) as well as a quart of fresh sour curd (tyre) and powdered soapstone (balapong) at from 1/4 to 1/2 lb. By the late 1860's Madras chunam was regarded by British architects as one of the materials of India which could be described as really excellent of its kind, but it was so expensive that it was not often employed. See: Nilsson, European Architecture in India, p. 169; Vicat, Treatise on Calcareous Mortars and Cements, p. 176; Smith, T. Roger, 'On Buildings for European Occupation in Tropical Climates, Especially India', Royal Institute of British Architects, Sessional Papers, 1866-67, pp 204-205.

27. Smith, Royal Institute of British Architects, Sessional Papers, 1866-67, pp 204-205.

28. Vincent, Military Construction Techniques, pp 109-111 and 116.

29. Gordon, Alexander, Lieut. RE, 'Experiments tried at Quebec as to the properties and adhesive qualities of the following cements by order of Col. Nicolls, Commanding Royal Engineer, dated 17th November 1834, PP, Vol. III (1839), pp 184-185.

30. Pasley, Observations, 1838, p. 171; Vincent, Military Construction Techniques, pp 109-111.

31. Vincent, Military Construction Techniques, p. 111.

32. Ibid, p. 116; Skempton, TNS, Vol. 35 (1962-63), pp 126-129; Halstead, TNS, Vol. 34 (1961-62), p. 44; Weiler, J., 'The Industrial Archaeology of Building Materials', Ontario Society for Industrial Archaeology Bulletin, Vol. 2, No. 4, Winter 1983-84, p.1.

33. In India pisé construction was used in the Madras Presidency from the early nineteenth century and its use extended to Upper India by the 1860's where the military engineers in the Public Works Department used it extensively in the construction of jails. See: Professional Papers on Indian Engineering, Series 2, Vol. 2, pp 409-410. A form of pisé work called 'tapia' was used by the Royal Engineers at Gibraltar in the late 1850's. See: Stehelin, Col. CRE, 'Notes Upon the Construction of Buildings at Gibraltar with Tapia', PPNS, Vol. X (1861), pp 25-27. As Collins has pointed out, the importance of pisé in the development of concrete construction lay in the technique employed, which consisted of ramming packed earth between moveable timber formwork. The formwork consisted of parallel sets of tongue and groove boarding, which slid between vertical timber posts and were maintained the correct distance apart by short wooden props and twisted thongs. Once a layer of earth had been tamped into position, the boarding was raised and the process repeated, until finally all that remained to be done was to fill in the holes through which the thongs had passed. See: Collins, Concrete, p. 21.

34. Vincent, Military Construction Techniques, pp 111-113.

35. Ibid, p. 144.

36. Ibid, p. 113.

37. Fox, H.C. Lieut., 'Memorandum on Some Examples of Walls and Arch Buildings in Cement Concrete', Professional Papers on Indian Engineering, Series 2, Vol. 1 (1872), pp 547-548.

38. Ibid, pp 548-549.

39. Ibid, p. 549.

40. Sutherland, R.J.M., 'The birth of stress: a historical review in the art and practice of structural design, 75th Anniversary International Conference, 11-13 July 1984, Imperial College, London, Institution of Structural Engineers, London, July, 1984, p. 6.

41. Timoshenko, History of Strength of Materials, pp 99-100.

42. Davis, R., The Industrial Revolution and British Overseas Trade, Atlantic Highlands, New Jersey, 1979, p. 48.

43. Lower, A.R.M., Great Britain's Woodyard: British America and the Timber Trade 1763-1867, Montreal, 1973, pp 45-56, 67 and 122.

44. Davis, Industrial Revolution and British Overseas Trade, p. 49.

45. Lower, Great Britain's Woodyard, pp 30-31 and 173.

46. DNB, Vol. V, pp 805-807; MPICE, Vol. XXXIII (1871), pp 251-259.

47. Lower, Great Britain's Woodyard, p. 63. Colonel By had taken an interest in the timber trade by urging Lieutenant-Governor Colbourne to support the building of a timber slide at Ottawa in 1829. A timber slide was a structure over which rafts of square timber were floated to avoid rapids or falls on the river route to the shipping centre at Quebec.

48. Denison, W. Lieut. RE, FRS, AICE, 'A Series of Experiments on different kinds of American Timber', Transactions of the Institution of Civil Engineers, Vol. II (1838), p. 15.

49. Ibid.

50. Barlow, P., A Treatise on the Strength of Materials, 6th Edition, London, 1867, pp 5-7 and 66.

51. Ibid, p. 66.

52. Ibid.

53. Denison, Transactions of the Institution of Civil Engineers, Vol. II (1838) p. 16.

54. Ibid, pp 15-16; Denison et al, PP, Vol. V (1842, pp 127-139.

55. Denison, Transactions of the Institution of Civil Engineers, Vol. II (1838), p. 16.

56. Burt, H.P., 'On the Nature and Properties of Timber, with descriptive particulars of several methods now in use, for its Preservation from Decay', MPICE, Vol. XXII (1852-53), pp 206-243.

57. Alderson, R.C. Capt. 'On Mr. Kyan's Process for the Preservation of Timber from Dry Rot, with a Description of the Tank erected for that purpose in the Royal Arsenal, Woolwich, PP, Vol. I (1837), pp 131-150. Captain Alderson, who had served in Canada, advocated the substitution of 'Kyanized' timber for masonry in the coping of walls in military works such as retaining walls and boundary walls for barracks and magazines. He got the idea from observation of the practice in Canada of coping common rubble walls with wood.

58. MPICE, Vol. I (1837-41), p. 8. Denison won a silver medal. The Telford Medal or Premium was awarded for meritorious communications and was furnished from Telford's bequest to the Institution. It was first awarded in 1837 and there were gold, silver and bronze medals presented. See: Institution of Civil Engineers, A Brief History of the Institution of Civil Engineers, London, June 1928, p. 46.

59. MPICE, Vol. I (1837-41), p. 8.

60. Webster, T., 'On experiments on the strength of materials', MPICE, Vol. I (1837-41), p. 28.

61. Denison et al, PP, Vol. V (1842), p. 90.

62. Ibid.

63. Ibid, pp 99-113; Nelson, PP, Vol. IV (1840), pp 136-197; Nelson, R.J., 'Report on Beaufort Bridge', PP, Vol. III (1839), pp 121-129; Nelson, R.J. 'On the mode of Bending Timber adopted in Prussia', PP, Vol. III (1839), pp 139-143; DNB, Vol. XIV, pp 209-210.

64. Denison et al, PP, Vol. V (1842) pp 91-101. The Colonel who sent test results on sneezewood to Nelson was either John Lewis or G.G. Lewis, both of whom were stationed at Cape Town in the 1830's and 40's and constructed important buildings in the colony. See: Lewcock, *Early Nineteenth Century Architecture in South Africa*, pp 277 and 353.

65. Denison et al, PP, Vol. V (1842), p. 113.

66. Ibid.

67. Ibid, p. 117.

68. Ibid, p. 117.

69. Best, S. Capt. 'Abstract of Some Experiments on the Strength of Woods Tried at Guntoor in 1840 and at Singapore in 1843', *Professional Papers of the Madras Engineers*, Vol. II, 2nd Edition, 1859, p. 191.

70. Ibid, p. 192.

71. Ibid, p. 192.

72. Du Cane, Capt. E.F., 'Notes on the Jarrah Timber of Western Australia', PPNS, Vol. XIII (1864), p. 67.

73. Kerr, J.S., *Design for Convicts: An Account of design for convict establishment in the Australian Colonies during the transportation era*, Sydney, 1984, p. 167.

74. Du Cane, PPNS, Vol. XIII (1864), p. 67.

75. Ibid, pp 68-69.

76. Ibid, p. 71.

77. Ibid, p. 68. The Royal Engineers arrived in Western Australia in 1850.

78. Vincent, *Military Construction Techniques*, p. 231

79. Ibid, p. 228.

80. Ibid, p. 235; PRO, W.O./55/885, pp 410.

81. Vincent, Military Construction Techniques, p. 236.

82. Ibid, p. 238.

83. Savage, Col. H. and Parsons, Lieut., 'Remarks on the Use of Asphalte in Cold Climates', PPNS, Vol. IV, p. 85.

84. Ibid, p. 85.

85. Ibid, p. 86.

86. Ibid, p. 86.

87. Vincent, Military Construction Techniques, p. 241.

88. Greenough, J.J., The Halifax Citadel, Vol. 1, p. 211.

89. Vincent, Military Construction Techniques, p. 244.

90. Greenough, J.J., The Halifax Citadel, Vol. 1, pp 193-211; Vincent, Military Construction Techniques, p. 244.

91. Denison, W., Lieut. 'Description of a Series of Bridges erected across the river Ottawa, connecting the province of Upper Canada and Lower Canada, and especially of a wooden arch of 212 feet span which crossed the main branch of the river', PP, Vol. III (1839), pp 158-163; Allodi, M., Printmaking in Canada: The Earliest Views and Portraits, Royal Ontario Museum, Toronto, 1980, pp 91-92.

92. James, Journal of the Institute of Wood Science, No. 52, 1982, pp 175 and 191-192, note 127; Douglas, Military Bridges, pp 311-312

93. Douglas, Military Bridges, p. 312.

94. Denison, PP, Vol. III (1839), p. 161.

95. Denison, W., 'Description of a Wooden Swing Bridge erected over the Grenville Canal, Canada', PP, Vol. VI (1843), p. 163.

96. Passfield, R.W., 'Swing Bridges on the Rideau Canal', IA, The Journal of the Society for Industrial Archeology, Vol. 2, No. 1, 1976, p. 61

97. Douglas, Military Bridges, p. 365.

98. Ibid. This material was made by people of low caste called "Whalliaw'. They collected green husks of coconuts, steeped them in water for six months and afterwards placed them on a stone and beat them with

a stick to produce a fibre or coir which was then twisted into a yarn in the way ordinary rope is formed.

99. Ibid, p. 366. Apparently, rope suspension bridges continued to be built into the 1850's since Douglas commented that with the advent of improved suspension bridges in England, which had been found particularly serviceable in India, iron chains or rods should be used instead of ropes. He had recently received a drawing of an experimental bridge in India of 250 foot span using tarred coir rope of only 3 1/2 or 4 1/2 inch circumference.

100. Smith, D., 'The Use of Models in Nineteenth Century British Suspension Bridge Design', History of Technology, 2nd Annual Volume, 1977, pp 180-187. In 1841, while the debate grew over Dredge's system, he built five modest footbridges in Regent's Park. Captain Denison published an article on one of them in 1845 in the Professional Papers. He included drawings and a description of this 67 foot 10 inch span which was completed in the summer of 1842, but was concerned with the sliding forward of one of the piers and bank failure and the solution to this problem. Denison did not enter the debate over the uniform versus the taper chain system. See: Denison, Capt. RE., 'Description of a Suspension Bridge erected over the Canal in the Regent's Park, upon Mr. Dredge's principle'. PP, Vol. VII (1845) pp 58-60.

101. Goodwyn, Capt. E.I.C., 'The Taper Chain Tension Bridge at Ballee Khâl, near Calcutta, in its renewed Form, after Failure in June, 1845', PP, Vol. IX (1847), p. 83; Mechanic's Magazine, No. 1106, 19 October 1844, pp 258-261

102. CEAJ, Vol. VIII (1845), p. 307.

103. Smith, History of Technology, pp 211-212.

104. CEAJ, Vol. VII (1845), pp 304-307; Mechanic's Magazine, No. 1106, 19 October 1844, pp 258-61.

105. Goodwyn, PP Vol. IX (1847), p. 97. The committee included Lieut. Col. Garstin, Lieut. Col. W.N. Forbes and Lieut. Col. A. Irvine. It is interesting to observe that the last officer was later appointed Director of Works for the Admiralty (1846-49) to succeed Brandreth. Irvine served during the pioneering period of wide span iron slip roof construction.

106. Ibid, pp 117-118.

107. Abbot, F. Major, 'An Inquiry into the Principle of Mr. Dredge's Tension Bridge', CP, p. 24.

108. Ibid.

109. CEAJ, Vol. VIII (1845), p. 306.

110. Goodwyn, PP, Vol. IX (1847), p. 128.

111. Ibid.

112. Ibid, p. 129.

113. Ibid, p. 121.

114. Ibid, p. 125.

115. Ibid, p. 86.

116. Ibid, p. 130.

117. Davies, Splendours of the Raj, pp 149 and 151.

118. Goodwyn, PP, Vol. IX (1847), p. 130.

119. Ibid, p. 134.

120. Ibid, p. 144.

121. Smith, History of Technology, p. 192.

122. Ibid, p. 194. It was explained in Chapter 2 that model testing was a distinctive aspect of British engineering in the early nineteenth century and that Sir Charles Pasley had used models for experiments at the Royal Engineer Establishment.

123. Goodwyn, PP, Vol. IX (1847), p. 138.

124. Mechanic's Magazine, Vol. 46 (1847), p. 62.

125. Ibid.

126. Goodwyn, PP, Vol. IX (1847), p. 138.

127. Goodwyn, Henry Maj., Bengal Eng., 'A Resultant System for the Construction of Iron Tension Bridges', PP, Vol. X (1849), p. 197.

128. Ibid, pp 208-215.

129. Ibid, p. 220.

130. Ibid, p. 207.

131. Vibart, Addiscombe, p. 637; Watson, History of the Royal Engineers, p. 375; Innes, J.J. Macleod, The Life and Times of General Sir James Browne, London, 1905, pp 23, 115 and 117; Sandes, Military Engineer in India, p. 68.

132. Vibart, Addiscombe, p. 639; Innes, Sir James Browne, p. 123.

133. Smith, *History of Technology*, pp 196-197 and 205-207.

134. Sandes, *Military Engineer in India*, pp 143-151.

135. Scott-Moncrieff, G.K., 'The Frontier Railways of India', PPOS, Vol. XI (1885), p. 247.

136. Vibart, *Addiscombe*, p. 639.

137. Herbert, *Pioneers of Prefabrication*, p. 2; Higgs, *Journal of the Society of Architectural Historians*, Vol. XXIV (1970), p. 175.

138. There is no mention of it in G. Herbert's seminal work *Pioneers of Prefabrication*.

139. W.D.B., 'Iron Bridge Over the Goomtee-Lucknow', *Professional Papers on Indian Engineering*, Vol. 3 (1866), p. 329.

140. Herbert, *Pioneers of Prefabrication*, pp 30-32.

141. Nilsson, *European Architecture in India*, p. 169; Lewcock, *Early Nineteenth Century Architecture in South Africa*, p. 389. Cast iron did not reach Australia until the 1840's. See: Freeland, J.M., *Architecture in Australia: a history*, Melbourne, 1968, p. 108.

142. Skempton and Johnson, *Architectural Review*, March 1961, p. 186.

143. Fitzgerald, R.S., 'Technological Aspects of Early English Iron Architecture', ICOMOS, *The Role of Iron in Historic Architecture in the First Half of the 19th Century*, 1979, p. 275.

144. Coad, *Historic Architecture of the Royal Navy*, pp 39, 72 and 80.

145. Ibid, p. 32.

146. Buisseret, D. *Historic Architecture of the Caribbean*, London, 1980, p. 71 and Plates pp 131-132.

147. Coad, *Historic Architecture of the Royal Navy*, p. 106.

148. Bannister, T., 'The first iron-framed buildings', *Architectural Review*, April 1950, p. 244.

149. DNB, Vol. XVIII, pp 429-432.

150. Brandreth, Captain, 'Memorandum relative to a system of Barracks for the West Indies recommended by Colonel Sir C.F. Smith, C.B. RE., and approved by the Master General and Board of Ordnance', PP, Vol. II (1838), p. 239.

151. Captain John Harper (commissioned 1806, d. 1837) specified cast iron columns for the verandah of a hospital at Up Park Camp, Kingston, Jamaica in 1818. See: PRO, MPH/477.

152. For example, in October 1824 the Inspector General of Fortifications sent to the Board of Ordnance a proposal for a Barracks at Fort Nassau, New Providence, Bahamas. The drawings were by S.B. Howlett, R.M. Surveyor. This two storey structure (178 feet x 47 feet) had a main building of stone with encircling verandah on both floors. It had cast iron columns and girders for the galleries but hardwood beams anchored in stone walls for internal floors. The cast iron connections were bolted and wrought iron tie bars were used for bracing. A wrought iron tie bar was also employed as a king post in the roof truss but was connected to a hardwood transverse beam. Much the same thing was being proposed for Bermuda at this time. In drawings for a proposed military hospital at St. George, Bermuda, by Major Thomas Blanshard (commissioned 1807, d. 1859), dated May 1823, sections show a main building of stone with encircling galleries. It had iron columns and girders in the gallery on one side, timber on the other and timber floor beams and roof truss. There were no iron ties through the building. See: PRO, WO/78/886; PRO, MPH/524.

153. PRO, MPH/192.

154. PRO, WO/55/945.

155. PRO, MPH/192.

156. PRO, WO/55/945.

157. Brandreth, PP, Vol. II (1838), p. 243.

158. Ibid.

159. PRO, MPH/192.

160. Brandreth, PP, Vol. II (1838), p. 239 and Plates 1-5.

161. PRO, WO/55/945.

162. Ibid.

163. Ibid.

164. PRO, WO/55/926.

165. Ibid.

166. Ibid.

167. Ibid.

168. Ibid.

169. Ibid.

170. PRO, WO/55/945.

171. Ibid.

172. Ibid.

173. Smyth, PP, Vol. II (1838), p. 238.

174. Buisseret, Historic Architecture of the Caribbean, p. 70.

175. Smyth, PP, Vol. II (1838), p. 238.

176. Ibid.

177. PRO, WO/55/927.

178. Ibid.

179. Ibid.

180. Buisseret, Historic Architecture of the Caribbean, pp 3-4. As Buisseret has explained, on Guadeloupe (French) which is near Antigua (British), there are many houses of two storeys with iron verandahs similar in concept to Smith's but with ironwork deliberately decorative in contrast to the Corps' plain, utilitarian castings. The connection, if any, between the two is not known.

181. Bowle, J., The Imperial Achievement: The Rise and Transformation of the British Empire, London, 1974, p. 228.

182. Renborn, E.T., 'Seasoning Fluxes and Fevers of Acclimatization. An Introduction to the History of Tropical Adaptation', Journal of Tropical Medicine and Hygiene, Vol. 66, No. 8, August 1963, pp 193-203.

183. Smyth, PP, Vol. II (1838), p. 233.

184. Ibid.

185. Edwards, J.D., 'The Evolution of Vernacular Architecture in the Western Caribbean', Wilkeson, S.J.K. (Editor), Cultural Traditions and Caribbean Identity: The Question of Patrimony, Gainsville, Florida, 1980, p. 319. Orientation with prospect to the prevailing wind direction was also adopted by the Corps from earlier planter cottages.

186. Examples include: a new hospital (1818) for Up Park Camp, Kingston, Jamaica by Captain John Harper, a single storey on raised basement stone and timber structure with cast iron columns for the encircling verandah; a proposed military hospital (1823) by Major Thomas Blanshard, a two storey stone and timber

structure with cast iron gallery on one side and a timber one on the other; and Smith's prefabricated iron barrack frameworks with two storey encircling gallery. See: PRO, MPH/477; PRO, MPH/524.

187. Examples include Captain Barney's hospital (1824) for Park Camp Barracks, Jamaica and Captain John Smyth's barracks at Demerara. See: PRO, MPHH/70; Smyth, PP, Vol. II (1838), p. 237.

188. Denison, Lieut. W., 'Description of Barracks at Lucea, in Jamaica', PP, Vol. II (1838), pp 246-247.

189. Edwards, Cultural Traditions and Caribbean Identity, p. 319.

190. For example, this was used in the soldiers' barracks and hospital designed by Captain Barney for Park Camp Barracks, Kingston, Jamaica in 1824. See: PRO, MPHH/70.

191. For example, this was used in Captain W.D. Smith's proposed hospital for Pigeon Island, St. Lucia in 1821, in Major Blanshard's proposed hospital at St. George, Bermuda in 1823 and in Colonel Smith's prefabricated cast iron barrack frameworks. See: PRO, MPH/772 and PRO, MPH/524.

192. Cuming, Mr., 'Memorandum with reference to the accompanying sketches of the Officer's Barracks erected at George Town, Demerara', PP, Vol. II (1838), p. 250.

193. PRO, WO/55/924.

194. PRO, MPH/772; PRO, MPH/477; PRO, MPHH/70.

195. Lewis, G.G. Col., 'Memoir of Lieut-Colonel Brandreth', PP, Vol. X (1849), p. 3.

196. Brandreth, PP, Vol. II (1838), p. 245.

197. Lewis, PP, Vol. X (1849), p. 3.

198. Smyth, PP, Vol. II (1838), p. 236.

199. Ibid, p. 238.

200. Brandreth, PP, Vol. II (1838), p. 246.

201. Smyth, PP, Vol. II (1838), p. 238.

202. Ibid, p. 235.

203. Ibid, p. 237.

204. Ibid, p. 236. Smyth had removed some of these trooly sheds occupied by negroe workmen in Demerara and replaced them, because of cost of repair in like materials, with board and shingled houses. Such a change in Guiana had caused mortality to greatly increase among the natives. Smyth found that his new houses did not compare favourably at all with a large trooly shed, occupied by the black and military labourers attached to the quartermaster general and engineer department, in Demerara, with respect to freedom from damp and uniform moderate temperature.

205. King, A.D., *The Bungalow: The production of a global culture*, London, 1984, pp 28-30.

206. Ibid, p. 38.

207. Smith, *Royal Institute of British Architects Sessional Papers*, 1866-67, p. 206.

208. King, *The Bungalow*, p. 34.

209. Davies, *Splendours of the Raj*, p. 100.

210. Ibid, p. 72.

211. During the 39 years 1817 to 1855 the annual mortality rate in India was 70 per 1,000. The annual mortality rate of officers and men serving at home and abroad in the years 1839 to 1853 was 17 for officers and 33 for non-commissioned officers and men respectively. See: BSP/1863/XIX/1, Report of the Commission on the Sanitary State of the Army in India, pp 17-18.

212. Ibid, pp 97-102.

213. Ibid, p. 105.

214. Ibid, p. 137.

215. Ibid, p. 108.

216. Ibid, p. 108.

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219. Ibid, pp 130-132.

220. Vincent, *Military Construction Techniques*, p. 10.

221. PRO, WO/55/927.

222. Ibid.

223. Ibid.

224. Kerr, Design for Convicts, pp 164-167.

9. Conclusions

1. See especially: Pasley, Outline of A Course in Practical Architecture, pp 2-3; and PPNS, Vol. XX (1872), p. xx.

2. Davies has explained that feelings between civil architects practising in India and the Royal Engineers in the Public Works Department were strained throughout the Raj and that this was exacerbated by social condescension on the part of the military. See: Davies, Splendours of the Raj, pp 171-172. T. Roger Smith in his address to the Royal Institute of British Architects on the construction of buildings for Europeans in India cautioned his colleagues that they would have to abide by the dictates of the military engineers in the Public Works Department when tendering for and carrying out the design and execution of public buildings. He reflected some resentment that architects had to work under such conditions. See: Smith, Royal Institute of British Architects, Sessional Papers, 1866-67, pp 205-207.

3. Hobsbawm, E.J., Industry and Empire, The Pelican Economic History of Britain, Vol. 3, Harmondsworth, 1979, p. 20.

4. Headrick, Tools of Empire; Buchanan, Technology and Culture, Vol. 27, No. 3, July 1986, pp 505-523.

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