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THE INFLUENCE OF SEMI-RIGID CONNECTIONS ON THE PERFORMANCE OF STEEL FRAMED STRUCTURES IN FIRE

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SUMMARY

Observation of fire damaged structures and recent fire tests at the Cardington LBTF have suggested that even nominally 'simple' connections are capable of providing significant restraint at elevated-temperatures. As most frames are designed assuming pinned response at ambient-temperature, with no account being taken of the reduction in mid-span moments, this is an aspect of connectivity which may be utilised in the assessment of the fire resistance of steel framed buildings, without necessitating changes in the approach adopted in ambient-temperature design or construction. To date the assessment of the influence of connection response on frame behaviour has been limited by the quantity of available test data, although initial studies based on postulated moment-rotation-temperature characteristics concluded that the failure temperatures for beams are increased due to the rigidity of 'simple' connections.

Moment-rotation relationships have been measured for a flush end-plate connection, both as bare-steel and as composite with a concrete slab across a range of temperatures. To define accurately the full moment-rotation-temperature response a series of tests have been conducted for each arrangement, where specimens were subject to varying constant levels of load and increasing temperatures. Observed failure mechanisms have been compared with those for a nominally identical specimen tested at ambient-temperature, and initial recommendations presented for the degradation of ambient-temperature connection characteristics. A mathematical expression is proposed in order to represent the test data at a number of temperatures.

It is clearly unrealistic to expect that many such tests can be anticipated in the future, and as such a spring-stiffness model has been presented for both bare-steel and composite flush end-plate connections. The use of a spring-stiffness model compares favourably with other forms of modelling due to the combination of efficient solution and the ability to follow accurately the full non-linear range of connection response, based on an understanding of the response of the component parts. A multi-linear representation of response has been adopted, where the stiffness of the connection is revised as elements enter the plastic range of response. Comparison has been made between the response predicted and that recorded experimentally.

Experimentally derived connection characteristics have been incorporated within analysis of typical sub-frames, with parameters including connection stiffness, capacity and temperature being varied. Further studies are presented considering the sensitivity of overall frame behaviour to inaccuracies in the representation of connection response and the use of simplified models to generate elevated-temperature connection characteristics. Based on postulated elevated-temperature moment-rotation characteristics for the connections contained within the Cardington test frame, predictions have been presented for the response of the structure subject to a series of full scale fire tests, with semi-rigid behaviour being compared with the common assumptions of pinned and rigid characteristics.

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NOTATION

(Only the general notations used during this thesis are presented here. Symbols which have only been used once and are of a more specific nature have been clearly explained where they arise in the text).

ϕ_l	Rotation at which beam lower flange bears against support (flexible end-plate).
ρ_c	Density of concrete.
ϕ_c	Connection rotation.
η_{lt}	Modification factor for the tensile strength of lightweight concrete.
α_s	Coefficient of thermal expansion for steel.
δ_T	Thermal Expansion of Steel.
A, A_1, A_2	Terms relating to connection initial-stiffness in Ramberg-Osgood expression.
B, B_1, B_2	Terms relating to connection capacity in Ramberg-Osgood expression.
C_s	Specific heat of steel.
f_c	Concrete cylinder compressive strength.
f_{cb}	Tensile splitting strength of concrete.
f_{ct}	Direct tensile strength of concrete.
f_{cu}	Concrete cube compressive strength.
f_u	Ultimate capacity of steel.
f_y	Yield capacity of steel.
l	Original length of steel specimen.
M_l	Moment at which beam lower flange bears against support (flexible end-plate).
M_c	Connection moment capacity.
M_{cj}	Moment capacity of composite connection.
Mj	Bare-steel connection moment capacity.
M_p	Plastic moment capacity of beam.
n, n_1, n_2	Terms relating to moment-rotation shape in Ramberg-Osgood expression.
S_{cj}	Rotational stiffness of composite connection.
S_j	Rotational stiffness of bare-steel connection.
T	Total potential energy.
U	Strain energy.
V	Potential energy of load.
E	Young's modulus.

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DECLARATION

Except where specific reference has been made to the work of others, this thesis is the result of my own work. No part of it has been submitted to any University for a degree, diploma, or other qualification.

Lee Leston-Jones

1. INTRODUCTION AND LITERATURE REVIEW

Over the centuries fire has consistently caused injury, loss of life and destruction of property, with some of the more notable fires destroying large areas such as the Great Fire of London in 1666, or causing many deaths in the building such as the Manchester Woolworth's fire in 1979. In the United Kingdom alone there are over 8000 casualties of fire each year, including about 1000 fatalities[1]. The cost of fire to UK business is estimated at over £900 million per year[1]. Some of this is from damage to buildings, but an increasingly significant proportion is due to the costs of consequent business interruption.

Structural steel is often the preferred form of construction within the UK due to factors such as speed of erection, reduction in site work, ease of application to demanding situations such as wide spans, and frequently competitive costing over similar concrete structures[2]. However, compared to other materials used in the construction of single and multi-storey structures, steel performs rather poorly under fire conditions, having a high value of thermal conductivity[3]. The temperature of steel therefore increases quickly, resulting in the reduction in strength and stiffness at a far greater rate.

The concept of fire precaution falls into two main categories: fire prevention and fire protection, as illustrated in Fig. 1.1, where these are defined in BS 4422: Part 5[4] as:

fire prevention, 'the concept of preventing the outbreaks of fire, or reducing the risk of fire spreading and of avoiding danger from fire to persons or property'.

fire protection, the 'design features, systems or equipment within a building, structure or other fire risk, to reduce danger to persons and property by detecting, extinguishing or containing fires'.

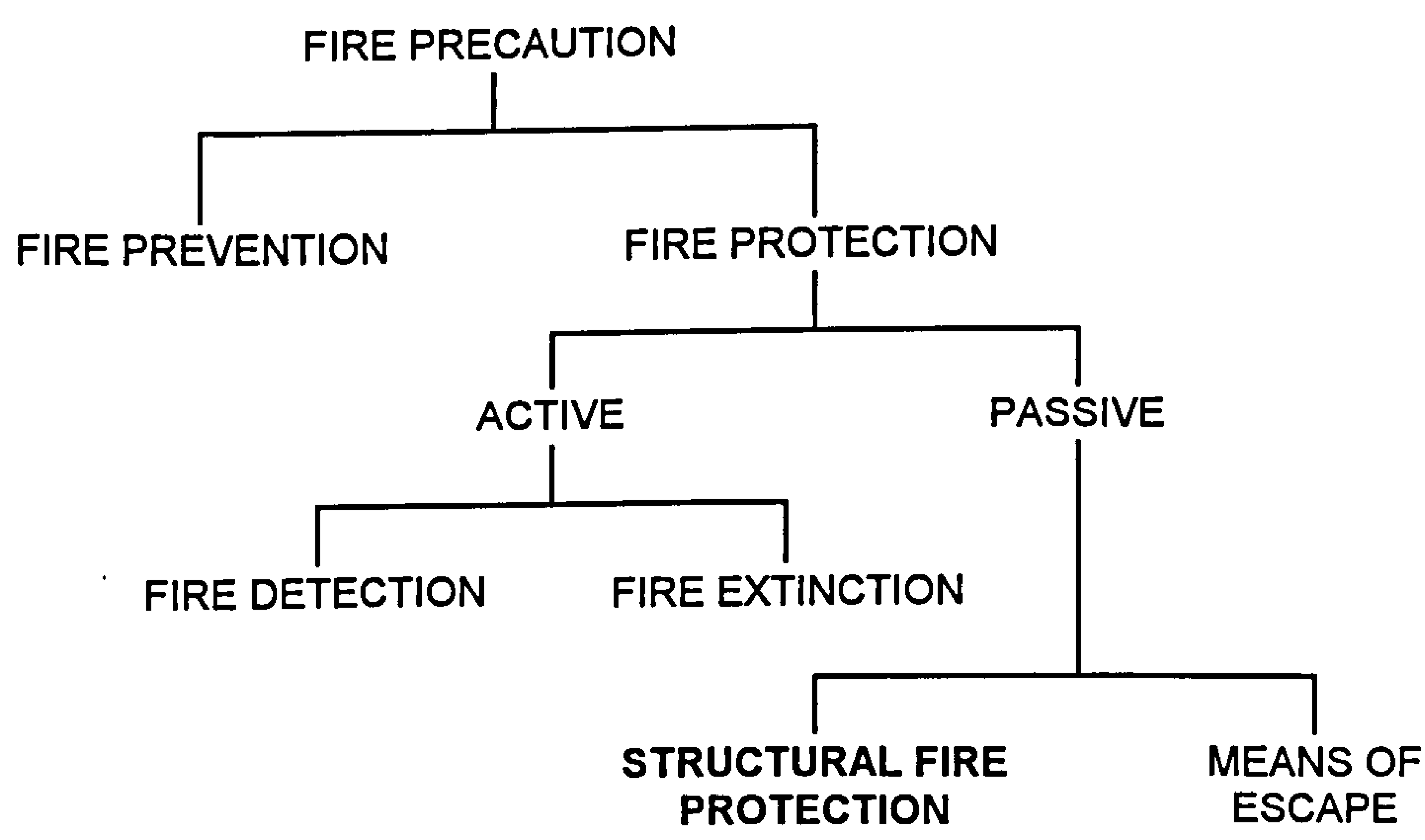


Figure 1.1. Elements of Fire Precaution

In considering fire protection we accept that in some cases efforts of fire prevention will fail, at which point we would wish to expedite the *'active'* processes of fire detection and extinction. From a structural view point we are primarily concerned with *'passive'* aspects of fire protection, which facilitate the safe and efficient *'active'* processes of detection and extinction of the fire, and with the provision of safe means of escape, and minimising the resultant damage to the structure, particularly where this may result in disproportionate collapse, or the spread of fire from the site of ignition.

Structural fire protection is defined as 'those features in the layout and/or construction of a building which are intended to reduce the effects of a fire'[4]

For steel framed structures the most familiar method of providing adequate structural fire protection is to use some form of insulating material, with the aim of limiting the temperature of the steel such that sufficient strength is retained. This has led to the production of a variety of protective materials for coating, spraying or encasing members[5]. Building Regulations[6] require that the structural integrity of the building is maintained for a specified period in the case of a fire. Design codes for the structural fire resistance of steel structures have traditionally adopted a prescriptive approach for determining fire protection requirements[7], although more recent methods[3,8] have been introduced for calculating periods of fire resistance. These generally relate to isolated elements, and are based primarily on the results of experimental studies.

The provision of fire protection is a costly aspect in the construction of steel structures for two reasons. Firstly there is the direct application cost, and secondly there are costs associated with time delays where the process of fire application hinders the progress of construction[9]. The cost of protection to steel structures within the UK is currently estimated at approximately £40 million[10].

It has been known for many years that the performance of both bare-steel steel and composite steel-concrete frames is better in the case of a real fire than indicated by the behaviour of isolated components, with the interaction of beams, columns and floor slabs giving the frame a much higher fire resistance. One aspect of this is the response of beams which are generally assumed to be 'simply' supported, whilst in reality all connections will provide a degree of fixity, resulting in a reduction in moment as shown in Fig. 1.2. The resistance of connections is enhanced with increasing temperatures as the temperature of connections typically increases at a lower rate than the connected beam due to their relative massivity. This form of response has been supported by observations of real fires such as Broadgate[11] and in fire tests at the Building Research Establishment's test facility at Cardington[12,13].

As most frames are designed assuming pinned conditions at ambient-temperature, with no account being taken of the reduction in mid-span moment, this is an aspect of connectivity which may be utilised in the fire protection of steel framed buildings, without resulting in changes to the approach adopted in ambient-temperature design or construction.

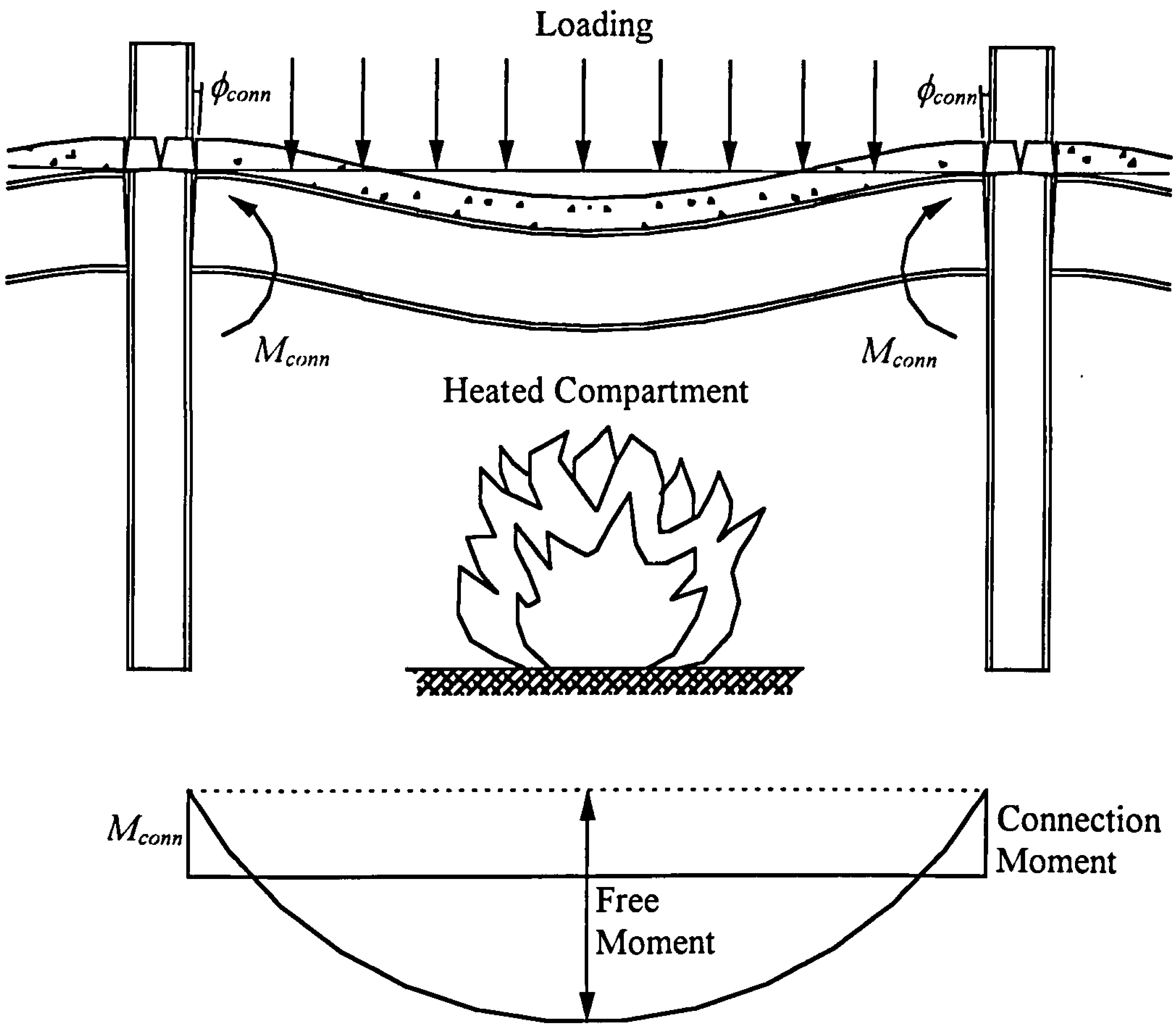


Figure 1.2. Elevated-Temperature Beam Response

1.1. THE PROVISION OF STRUCTURAL FIRE PROTECTION

Current statutory requirements within the UK have evolved over many years. Early attempts were concerned primarily with minimising the possibility of outbreak of fire and its subsequent spread from building to building. The first recorded attempt to legislate the control of fire spread appeared in the London Assize of 1189 by Henry Fitz-Ailwyn, Major of London[1]. This required that houses within the City should be built of stone; thatch roofs were not permitted, and party walls were required to be of a minimum height and thickness. However, there was no means of enforcing these requirements, and in 1212 a disastrous fire in London is said to have taken three thousand lives.

Present day fire resistance requirements for a building are two fold:

1. The primary objective is ensuring life safety for inhabitants, rescue services, and others in the vicinity of the building, and to allow a safe means of escape.
2. The secondary objective is to reduce the economic loss experienced as a consequence of the fire.

The Building Regulations[6] are primarily concerned with the former of these objectives, whilst insurance companies[14] are concerned with both. Fire resistance requirements are stipulated in terms of required resistance periods, where 'failure' is defined in BS476: Part 20[15] as:

- *Insulation* - A fire on one side of a wall or underside of a floor acting as a compartment boundary should not cause combustion of objects on the unexposed side. Limits of temperature rise of 140°C (average) or 180°C (peak) above ambient-temperature are specified.
- *Integrity* - A wall or floor acting as a compartment boundary should not allow passage of smoke or flame from one compartment to another as a result of breaks or cracks in the wall or floor. Both the insulation and integrity criteria also apply to members embedded in walls or floors.
- *Load-carrying capacity* - The members in a structural assembly should resist the applied loads in a fire. Failure criteria for beams and columns are defined in Part 20 as:

Beams:

(a). A limiting deflection of span/20 is reached or,

(b). For deflections greater than span/30, a rate of deflection of $span^2/(9000 \times \text{member depth})$ is exceeded. The units of rate of deflection are mm/min where dimensions are in mm.

Columns:

Failure to support the applied load. In practical terms this corresponds to a rapid rate of increase of vertical deflection (limit undefined) or a maximum lateral deflection of about 120mm.

Fire resistance periods are specified as 1/2, 1, 2, 3 or 4 hours based on the minimum time expected to safely evacuate the building, with the safety of fire fighters, risk of structural collapse and fire spread also being a concern. As such the fire resistance periods specified in the Building Regulations[6] are dependent on:

1. The type of building;
2. The height of the building or compartment;
3. The floor area of the building or compartment;
4. The cubic capacity of the building or compartment.

Active forms of fire protection are primarily concerned with 'life safety', the provision of safe means of escape and the early detection and extinction of the fire. Typical active forms of fire protection include sprinklers and smoke or temperature detectors. The use of active forms of fire protection is attractive as in many cases this results in the successful prevention of the development of the fire, thus minimising the potential loss of both life and property. Passive forms of fire protection are attractive to legislative authorities as these are 'fail safe' methods as compared to active methods.

The fundamental concept behind all methods of assessing structural stability under fire conditions is the fact that construction materials lose strength and stiffness with increasing temperatures[3]. For steel framed structures the most traditional method of passive structural fire protection has been the provision of some form of insulating material. This limits the increase in steel temperature such that sufficient strength and stiffness is retained for the stipulated fire resistance period, where the resistance of insulating systems is verified by testing members in isolation. Traditionally the limiting temperature for steel was chosen as 550°C[16] based on the loss of the design safety margin under fire conditions. However, this approach to design greatly simplifies true structural response, assuming members to be uniformly heated, fully stressed at ambient-temperature, and ignoring the curvilinear form of stress-strain curves at elevated-temperatures.

With the introduction of BS 5950: Part 8[3] and EC3: Part 1.2[8], more rational approaches to the fire resistance of steel structures have followed, with fire engineering methods resulting in fire being treated as one of the basic limit states. Current design methods allow engineers to consider the effects of non-uniform heating where members are partially protected, true load levels and elevated-temperature stress-strain relationships. Fire engineering methods also facilitate the consideration of the actual rate of temperature rise within a section, where this is influenced by its location, thickness and exposed surface area, along with the heating rate and maximum temperature of the compartment. Adopting more rational fire engineering methods generally results in a reduction in the required fire protection, and, in cases where a low fire load exists, the potential to leave steel sections unprotected.

Based on observations of fire damaged structures such as Broadgate[11] and in fire tests at the Building Research Establishment's test facility at Cardington[13], it is known that the fire resistance of whole structures is greater than for isolated elements. As such there is a move towards the refinement of fire engineering methods and constructional forms (slim-floor and composite beam-slab)[17] to utilise the increased capacity of the structure arising from the interaction of connected parts. The consideration of fire resistance incorporating the interaction of members typically requires the use of sophisticated numerical models[18,19,20,21,22], and is therefore not frequently utilised within general design at present.

1.2. THE GROWTH OF A FIRE

In providing fire protection to a structure it is essential to form a knowledge of the growth of a fire such that fire protection principles can be soundly applied. The growth and decay of fires is complex, being controlled by the surrounding environment and fuel load, and as such it is useful to simplify a compartment fire as having three distinct phases:

The growth period - The growth of a fire is controlled by the ignition of materials, usually from a small local source. Local fire growth may develop, with the feedback of generated heat resulting in the possible propagation of the flame. In the ignition phase the fuel itself must raised to a sufficiently high temperature that, given a supply of oxygen, the combustion reactions take place readily and are self sustaining. The point at which the fuel reaches its ignition temperature is commonly termed the 'flash point' or 'ignition temperature', and is found to occur at a temperature of approximately 300°C[23] for most common materials.

Once ignition has been established the development of the fire must involve its spreading from the ignition source, usually via the material first ignited. In the early stages interaction with the compartment will be negligible, and the behaviour will be as a fire in the open. Once the fire becomes well established locally it will continue to grow as long as fuel and oxygen are available. Hot gases from the fire will rise to form a layer under the ceiling, and as the walls warm up they will begin to re-radiate the heat. At this stage the fire may be referred to as a compartment fire, with the progress of the fire being influenced by the geometry and physical properties of the compartment. Ventilation can play a significant part in controlling the rate of growth, and if a door is opened or windows break, the situation may change dramatically. It is now radiated heat from the walls and ceiling which continues to heat the compartment, with fuel remote from the ignition site increasing in temperature. The growth of the fire continues until the fuel within the compartment reaches its ignition temperature, at which point there is a transition from a growing fire to a fully developed fire. This point is referred to as 'flashover'.

Steady state combustion - At this point the fire becomes almost totally ventilation controlled, with the severity of the fire being dependent on the available air supply. Usually it is openings such as windows which control the rate of burning of the fire. As long as fuel is available the fire will continue to burn at this rate until the fire starts to run out of fuel and the decay phase is entered.

Decay - As the fuel supply is depleted the fire will gradually reduce in severity, and eventually die down.

The growth and decay of a natural fire is shown schematically in Fig. 1.3 below.

The definition of fire development for experimental purposes is problematic as no two fires are ever alike, with the rate of growth and decay of fires being influenced significantly by the surrounding environment. As such for the purpose of testing the rate of heating may be assumed to vary with time in accordance with BS 476: Part 8[15] or the European equivalent ISO 834[24], as shown in Fig. 1.3, and described in Eq. 1.1:

$$T = T_o + 345\log_{10}(8t + 1) \qquad \text{Eq. 1.1.}$$

Where T is the furnace temperature (°C);
T_o is the ambient-temperature prior to testing;
t is the time of test (minutes).

As may be seen from Fig. 1.3, the standard fire curve does not accurately follow the phases of a natural fire, and neglects the growth phase prior to flashover. However, the use of a standard curve for testing allows comparison of results between different fire tests.

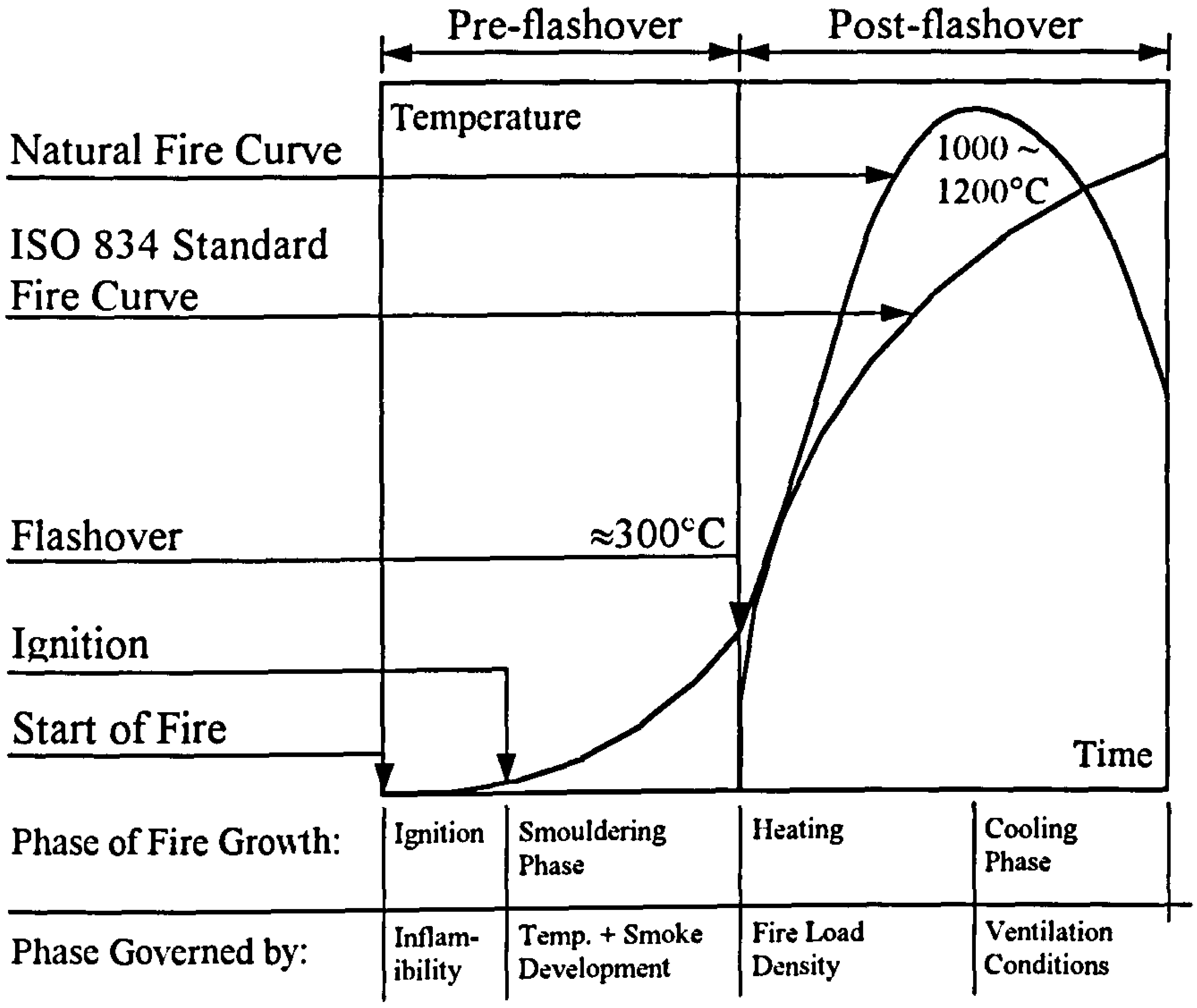


Figure 1.3. The Development of an Uncontrolled Fire and ISO 834 Standard Fire Curve

1.3. MATERIAL PROPERTIES

The mechanical properties of all common building materials decrease with increasing temperatures, and it is this reduction in material properties which controls the fire resistance of both bare-steel and composite structures. Whilst the rates of reduction in properties of steel and concrete are similar[3,25], the thermal conductivity of steel is high compared to that of concrete, and this results in the temperature of steel increasing at a far greater rate. Beyond approximately 400°C the structural properties of steel begin to fall rapidly, and for temperatures in excess of 500°C failure may occur. The influence of increasing temperatures on the mechanical properties of steel, concrete, reinforcing mesh, shear studs and bolts is discussed further in Chapter 2.

1.4. FIRE TESTS

Large scale test were carried out in the mid-eighteenth century following the recognition that fire should be confined to the room of origin rather than the building. These were generally conducted using rather unorthodox methods such as the test of 1776 in which David Hartley occupied the upper floor of a house in Putney Heath, the floor of which had been protected by metal plates, whilst a fire burned below (he remained unharmed)[1]. However, it was not until the end of the nineteenth century that we find the origin of the standard fire test procedures.

To this date assessment of fire resistance of members still relies heavily on the testing of isolated members under standard test procedures[26], as specified in BS476: Part 8[15] and ISO 834[24]. Generally the maximum permissible design stress and the load bearing capacity are assessed under conditions of increasing temperature, where the heating regime adopted is as defined in Eq. 1.1. Members are heated in gas or oil fired furnaces, with the furnace temperature being controlled by thermocouples located 100mm from the face of the section. In column tests the exposed length is typically 3m, whilst in the beam test this is increased to 4m. Standard fire tests are used in both the assessment of unprotected and insulated sections. In testing the performance of any protective system, insulation and ability to adhere are assessed along with structural capacity. In addition to loaded sections, short indicative sections are frequently used to determine the insulating performance of fire protection materials in which failure is deemed to occur when the temperature of the section increases above a limiting value (typically 550°C).

Results from standard fire tests along with a knowledge of the degradation of typical construction materials with increasing temperatures have been instrumental in the development of recent codes such as BS5950: Part 8[3] and EC3: Part 1.2[8]. However, these codes are limited in that they consider isolated member design only.

An increasing understanding of the response of steel structures under fire conditions has led to a realisation that frame response is better than indicated by standard fire tests. A number of tests have therefore recently been conducted by the Building Research Establishment and British Steel at the Cardington LBTF to investigate the influence of fire on full-frame behaviour[12,13].

1.5. THE INFLUENCE OF 'SEMI-RIGID' CONNECTIONS

In the design of steel framed structures at ambient-temperature it is normally assumed that beam-to-column connections are either 'pinned' (providing no moment resistance) or 'rigid' (providing full moment resistance equal to that of the connected beam). However, in reality both of these characteristics are merely extreme examples of the true flexural behaviour of connections, with much experimental work demonstrating that practical connections possess rigidity between these two limits. Thus it seems reasonable to regard most connections as 'semi-rigid'.

When connections are designed as semi-rigid, as opposed to simply supported, allowances are made for the transfer of moments from the beams to the columns, resulting in a reduction in the mid-span bending moment of the beam. In the situation of multi-bay frames this allows the reduction of beam section, with little consequence for the rest of the frame, except in cases where the beam frames into an external column. An additional benefit of considering connection stiffness is the restraint this provides against column buckling[27,28,29]. The relationship between connection characteristics and resultant moment-rotation response for a beam is shown in Fig. 1.4.

Steel framed buildings are generally designed as being simply supported at ambient-temperature, with lateral forces being resisted by bracing, due to the complexities associated with semi-rigid design, and difficulties in defining accurately the moment-rotation response for connections without resorting to testing[30].

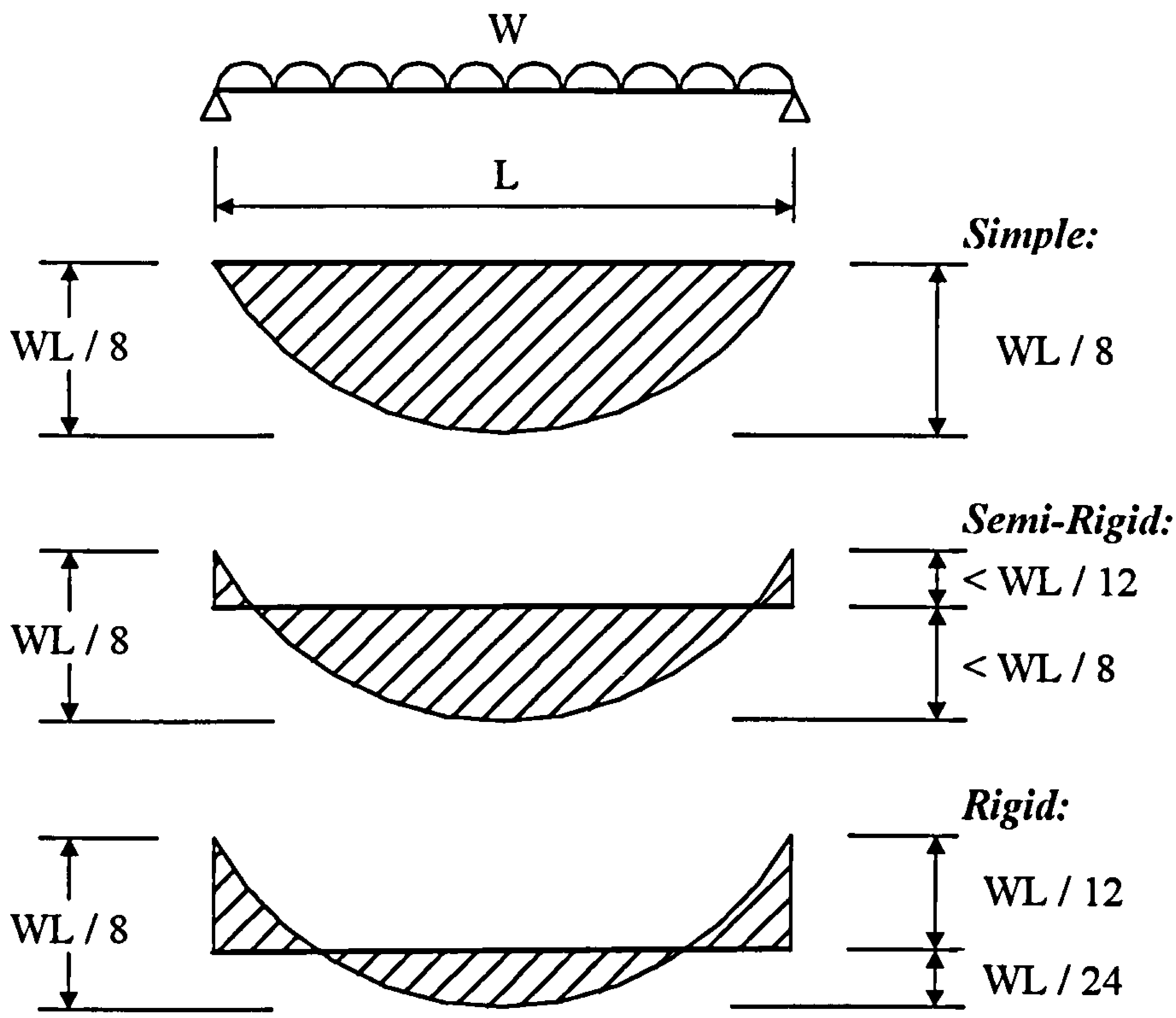


Figure 1.4. Effects of End-Restraint on Moments

Traditionally steel and composite steel and concrete connections at the fire limit state are assumed to have the same properties adopted in the design at ambient-temperatures. However, observation of fire damaged structures[11] and recent fire tests on an eight storey composite steel framed structure at Cardington[13] have suggested that connections which are assumed pinned at ambient-temperature can provide significant restraint at elevated-temperatures. The reasons for this are two fold: firstly connections tend to increase in temperature at a somewhat lower rate than the connected steel due to their relative massivity and shielded location, and secondly the levels of rotation permissible at elevated-temperatures facilitate the development of higher resistance moments within the connection.

The potential therefore exists to safely reduce the amount of fire protection currently applied to steel structures, with a resultant reduction in construction cost, by taking advantage of the continuity provided by typical connection within design. If the fire protection of beams could be reduced or eliminated by relying on the inherent continuity of steelwork connections savings of up to £75 million annually could be made throughout Europe[31].

1.6. CONNECTION RESPONSE

Experimental work into semi-rigid connections began 80 years ago when in 1917 Wilson and Moore[32] conducted experiments to determine the rigidity of riveted joints in steel structures. However this proceeded at a fairly slow rate and much interest was lost due to the moment-rotation curves being non-linear throughout the entire range of rotations, leading to complexities in modelling. A state of comparative neglect continued until the 1970s when a growing interest in research in this field became apparent. The conference *'Joints in Structural Steelwork'* which took place at Teeside Polytechnic in 1981[33] compiled much of the knowledge gained to date, and sparked further international research interest.

The incorporation of semi-rigid characteristics within design has been limited by the lack of data relating the wide range of connection types with different beam and column arrangements. Extensive data banks which summarise the numerous investigations into the behaviour of beam-to-column connections have been complied by Chen[34], Nethercot[35], Kishi[36] and Goverdham[37]. However, Allen *et. al.*[38] observed that much of the data collected fell below ideal, often because it was carried out as part of a more extensive study, with this reflecting the choice of test arrangement, loading process, instrumentation, bolt tightening procedures and/or welding details, with many tests being reported in an incomplete manner.

The flexural behaviour of a connection is commonly defined by the relationship between the moment transmitted by the connection and the relative rotation between the elements to which the connection is made. The slope of this moment-rotation curve is a measure of the rigidity of the connection, with rigidity decreasing as rotations increase. The moment-rotation characteristics of a connection are generally non-linear over the entire range of values. It was observed by Aggarwal[39] that the deviation from linearity is small in the elastic region, but becomes substantial in the post elastic-region, with this deviation generally occurring as a result of the local yielding of the connecting and connected parts of the connection. However, in the case of more flexible connections such as angles, non-linearity may be observed almost from the start of the loading cycle. The controlling factors of connection rigidity have been summarised by Nethercot[40], based on the work of a number of researchers, as:

1. Depth and length of the connected beams;
2. Cross-centre distance between bolt holes;
3. Type and size of fastener;
4. Whether connection is to a column web, column flange or a girder web;
5. Physical properties of the members and fastener materials;
6. End-plate yield load;
7. Column stiffener yielding;
8. Local beam flange buckling;
9. Column web yielding;
10. Beam and column contact during deformation.

Modelling of connection response is complicated by the non-linearity of connection moment-rotation curves. Whilst early methods of representing connection response considered connection behaviour in an elastic manner, over recent years progress in methods of structural analysis has led to increasingly sophisticated methods which consider the fully non-linear response.

The most accurate way of developing connection moment-rotation characteristics is through testing. However, due to the wide of range of connection types it is desirable to be able to predict the response of typical connection arrangements without resorting to the expense of testing. A number of methods have therefore developed for the prediction of connection response, where these range from extrapolation from existing test data to sophisticated finite element modelling. Analysis of connection response is complicated by the wide range of connection types currently in use, although there has been a move recently towards standardisation. This encourages the channelling of research, resulting in an increased understanding of connection behaviour, and the development of simplified design guidance. Annex J of EC3[41] has compiled much knowledge of the response of flush end-plate type connections, resulting in simple design guidance for the determination of connection capacity and stiffness. Aspects of connection modelling are discussed in greater detail in Chapter 4.

1.7. ELEVATED-TEMPERATURE CONNECTION RESPONSE

Steel framed buildings are generally designed as being simply supported at ambient-temperature, with lateral forces being resisted by bracing. However, it is known from ambient temperature studies that even nominally simple connections can resist significant moments at large deformations. At the severe levels of deformation encountered in a fire, moments are transferred to the connections, and the adjacent members. leading to a reduction in the mid-span moments of the beam, as illustrated in Fig. 1.1. Observations of the Broadgate[11] structure subsequent to its exposure to elevated temperatures and recent fire tests conducted by the Building Research Establishment and British Steel[13] showed evidence of the development of large forces and moments built up through restraint to free thermal expansion of various elements. Following the Broadgate Phase 8 fire it was proposed that 'The current UK and European research work on connections requires further development to ensure the necessary balance of elasticity is maintained within the frame during the fire'[11].

The only previously reported tests on steel beam-to-column connections under fire conditions are by CTICM in 1976[42], British Steel in 1982[43], and most recently the Steel Construction Institute in 1989[44]. The CTICM tests covered six connection types from 'flexible' to 'rigid' and were aimed at establishing the performance of high strength bolts. In these tests composite action was not considered, although a concrete deck provided heat resistance to the top flange of the steel beam. The results indicated that bolt failure does not occur before gross deformation of the other elements. The two British Steel tests were of 'rigid' moment resisting cleated connections. The body of the test data is small, but suggests that bolts and their connected elements can undergo considerable deformation in fire, a fact frequently supported by observations of fire damaged buildings. The most recent tests conducted by the Steel Construction Institute considered three connection types typical of those used in practice (extended end-plate, flush end-plate and web cleat), with these being selected as representative of the range of realistic rigidities. Additional tests were conducted to assess the response of composite sections. These tests once more demonstrated that failure of the connecting bolts or welds did not occur, despite relatively large deformations of the connections.

The definition of elevated temperature moment-rotation response is complicated by the introduction of the further variable. As such in order to define accurately the response of connections for the fire limit state it is necessary to conduct a series of tests. Tests conducted to date have not fully satisfied this criteria, but have considered the elevated-temperature response of connections on a single test conducted under a constant load with increasing temperatures. Whilst this represents the behaviour of connections under fire conditions, full moment-rotation-temperature characteristics are required if semi-rigid response is to be incorporated within analysis.

With increasing temperatures, and associated levels of rotation, it is important to consider the manner in which connections are modelled. It is expected that yielding of connections may occur, and it is therefore desirable that when modelling elevated-temperature response the form of curve-fit adopted is capable of following the plastic range of connection response.

The modelling of elevated-temperature connection response has not been addressed to date, and it is felt that the development of sufficiently accurate methods of predicting connection response will be instrumental in the future use of semi-rigid characteristics for fire limit state design due to the number of tests required to define accurately moment-rotation-temperature response for a single connection. The modelling of elevated-temperature connection response may follow two predominant paths:

1. The degradation of existing ambient-temperature test data for increasing temperatures.
2. The formulation of connection models which allow the prediction of elevated-temperature response, following the full range of connection response.

The former of these is attractive as it allows the utilisation of the extensive fund of ambient-temperature data which already exists. The latter facilitates the modelling of any connection arrangement. However, the accuracy of both of these models relies on an understanding of the response of constituent parts of connections, the rates of heating of connected parts, and the influence of temperature on the mode of deformation. As such it is felt that further testing is required allowing an understanding of elevated-temperature response throughout the full moment-rotation-temperature range.

1.8. SCOPE AND LAYOUT OF RESEARCH

The primary objective of the present investigation is the development of full moment-rotation-temperature characteristics for typical bare-steel and composite connections, and an assessment of the influence of semi-rigid characteristics on elevated-temperature frame response. In selecting a suitable form of connection consideration was paid to the recent move towards the standardisation of connection types[45], resulting in the use of the flush end-plate type connection[46]. The flush end-plate connection represents a typical form of shear connection adopted for ambient-temperature design, with no account being taken of its inherent stiffness and strength. It should be remembered that the aim of this research is not the development of connections capable of enhancing the structural performance of frames at elevated-temperatures, but the utilisation of existing nominally 'simple' characteristics in design for the fire limit state.

In Chapter 2 the influence of increasing temperatures on the mechanical properties of structural materials is considered for steel and concrete, and connecting elements including reinforcement, shear studs and bolts. Whilst the influence of increasing temperature on the properties of standard construction materials is well documented, insufficient consideration has been given to additional materials associated with the response of beam-to-column connections and composite slabs within existing design codes, and as such a review of elevated-temperature material tests is presented for these elements.

In Chapter 3 results are presented for a series of tests conducted to define accurately the moment-rotation relationship for a single flush end-plate connection, both as bare-steel and composite with a concrete slab, across a range of temperatures. For the bare-steel and composite arrangement an initial ambient-temperature test was conducted, with further tests being conducted under constant load with increasing temperature. A cruciform arrangement was adopted, with specimens being heated within a gas fired furnace. The influence of increasing-temperatures on the observed failure mechanism, and the rate of degradation of connection characteristics is discussed. The observed rate of degradation of connection properties is compared with that anticipated based on elevated-temperature material properties and the observed failure mechanism. The representation of connection characteristics in a form suitable for incorporation within numerical models is considered in Chapter 4, along with the additional requirements associated with representing elevated-temperature response.

The limitations of experimental studies due to the expense of testing, the wide range of connection types commonly adopted and the number of tests required to accurately define the moment-rotation response for a connection across a range of temperatures is identified in Chapter 4, and methods of modelling connection response considered.

Based on the conclusions of Chapter 4, a spring-stiffness model is presented in Chapter 5 for both bare-steel and composite flush end-plate connections, with the form of model being selected as being able to define the full range of connection response and being easy to apply. Deformation of constituent parts and the influence of increasing temperature on their response is considered in isolation, assuming that the interaction between connected parts has a negligible effect. Connection response is then obtained for increasing temperatures by superimposing the stiffnesses of individual elements in the tension and compression zones. Results obtained from the proposed spring-stiffness model are compared with those from the studies of Chapter 3 and existing test data presented by Lawson[44].

In Chapter 6 the influence of realistic connection characteristics on frame response with increasing temperatures is considered by incorporating the elevated-temperature moment-rotation relationships obtained from experimentation within analysis. An existing finite-element program developed by Bailey[22] was adopted, being capable of incorporating fully non-linear connection characteristics into three-dimensional bare-steel and composite elevated-temperature frame analysis. A two-dimensional sub-frame arrangement is considered as both bare-steel and composite, with parameters of connection response such as stiffness, capacity and temperature being varied. The sensitivity of elevated-temperature frame response to the form of curve-fit adopted, and methods of modelling connection characteristics is also considered.

In Chapter 7 frame analysis is extended to consider a typical frame in the form of recent full scale fire tests conducted by the Building Research Establishment and British Steel at the Cardington LBTF[13]. The elevated-temperature response of both bare-steel and composite connections is postulated based on existing ambient-temperature bare-steel connection test data[47]. Resultant predicted connection response is incorporated within bare-steel and composite analysis of a plane-frame test modelled as a two-dimensional structure, and of a large compartment test encompassing the area of the plane frame test. In modelling of the large compartment test, consideration was given to the influence of three-dimensional slab action on the benefit obtained from the incorporation of realistic connection characteristics.

Finally, in Chapter 8 general conclusions are drawn, and suggestions for further work are presented.

2. ELEVATED-TEMPERATURE MATERIAL PROPERTIES

2.1. INTRODUCTION

To allow an understanding of the behaviour of bare-steel and composite connections exposed to fire, it is necessary to investigate the influence of temperature on the mechanical properties of structural materials such as steel and concrete, and connecting elements including reinforcement, shear studs and bolts. The relevant mechanical properties of all materials may be listed as strength, stiffness, expansion, specific heat and thermal conductivity, and are usually obtained from experimentation. Extensive information has existed for some time describing the influence of elevated temperature on the mechanical properties of steel, much of which is detailed in existing design codes, but unfortunately insufficient consideration has been given to many of the additional elements associated with the response of beam-to-column connections and composite slabs.

2.2. DEGRADATION OF STRUCTURAL STEEL

The important parameters defining the performance of steel at elevated temperatures are strength, stiffness and thermal expansion. The strength of steel reduces at temperatures in excess of 300°C, decreasing at an approximately linear rate up to 800°C. The strength then reduces more gradually up to the melting temperature of approximately 1500°C. A number of publications[3,8,48,49,50] have made recommendations as to the rate of decay of steel properties, although the results presented are subject to a degree of variation. Differences in test procedures and the variability of the constituents of structural steels may account for the discrepancies between existing recommendations.

Two methods exist of determining stress-strain characteristics for steel. Isothermal (or steady state) tests have traditionally been used for mechanical engineering applications. The tensile specimen is subject to a constant temperature, and strain is applied at a steady state. The stress-strain response is therefore appropriate for a given temperature. Alternatively, in anisothermal (or transient) tests the specimen is subject to a constant load, and the temperature is increased at a pre-determined rate, with the resulting strains being recorded. The influence of thermal strains is deducted using 'dummy' specimens heated at the same rate in an unloaded condition. Stress-strain curves may be interpolated from a family of curves at different stress levels. Kirby and Preston[51] reviewed both methods of testing, and concluded that anisothermal tests result in lower strengths than isothermal tests, but may be claimed to be more representative of actual stress-strain characteristics in frame behaviour. The ECCS[48] data is conservative relative to the anisothermal data produced by British Steel, which is embodied in BS 5950: Part 8[3]. This is accepted in the Eurocodes[8] relating to the fire resistance of steel structures, for which data produced by British Steel has been selected to replace that of the ECCS.

The behaviour of steel at elevated temperatures is influenced by the heating rate, due to the onset of creep at temperatures above 450°C, which is defined as continuous time-dependent deformation under constant load and constant temperature[52]. This phenomenon is difficult to incorporate within the standard time-independent methods, as adopted in many design and analytical procedures. As such, experimental work has concentrated more closely on the rate of heating. By assuming a linear heating rate up to a limiting temperature of 600°C, and failure times of 30 to 120 minutes, practical heating rates may be defined as between 5°C/minute for well insulated sections and 20°C/minute for exposed sections[53]. It would be expected that sections tested within this range of heating rates would provide a reasonable representation of actual frame response.

Traditionally investigations into the mechanical properties of steel were restricted to a maximum temperature of 600°C[48], based on the assumption that detailed knowledge of steel properties outside this region was not necessary since critical conditions would normally be reached at a temperature lower than 600°C. Due to the advances in understanding of elevated-temperature structural response, there has been a gradual realisation that structures can maintain significant strength beyond these traditional bounds, and it has therefore been necessary to extend the range of temperatures considered. Both BS 5950: Part 8 and EC 3: Part 1.2 have responded to this fact, and stress-strain characteristics are detailed for temperatures of at least 800°C. It is typical to assume a linear rate of decay for temperatures in excess of this, up to the melting temperature for steel of approximately 1500°C.

The strength and deformation properties of steel at elevated temperatures are presented in EC 3: Part 1.2, for rates of heating between 2°C and 50°C/minute, by a family of stress-strain curves with a linear-elliptical shape. It may be assumed that the effect of creep is included in the stress-strain characteristics. Stress-strain characteristics are presented in Fig. 2.1, where normalised stress is presented as a fraction of the yield stress at ambient temperatures. For temperatures below 400°C, the model of mechanical properties may be extended to incorporate strain hardening, provided local failure is excluded.

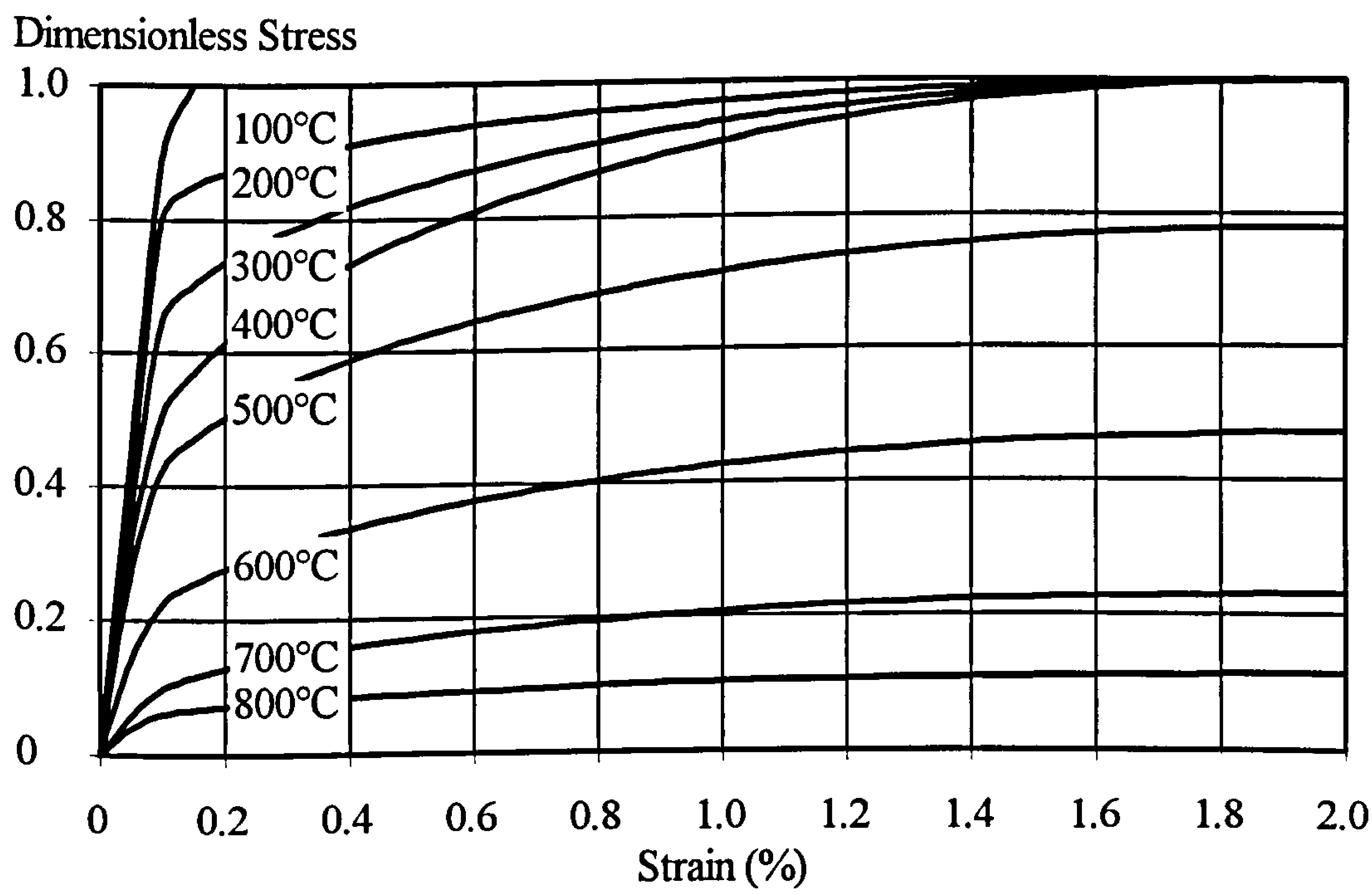


Figure 2.1. Dimensionless Stress-Strain Diagram for Grade 43 Steel

When considering the full behaviour of the structure throughout a range of temperatures or load levels the entire stress-strain relationship is normally described. However, in the case of simplified analytical methods it is typical to consider just the key elements detailing the degradation of material properties with temperature. It may be seen that at high temperatures steel does not display a well defined yield point, the non-linearity of the stress-strain curves making it difficult to define an elastic modulus and yield point.

Recommendations are presented for the degradation of the mechanical properties of structural steel in the following sections.

2.2.1. Stiffness of Steel

The stiffness of steel is defined by the elastic modulus, which is the slope of the tangent of the stress-strain curve at zero stress. It is known that the elastic modulus of steel decreases with increasing temperatures, and a number of publications exist making recommendations regarding the rate of decay. Due to the non-linearity of the stress-strain curves for steel, it is difficult to define a consistent proof strain at which to assess the Elastic Modulus of structural steels at elevated temperatures.

Stress-strain characteristics presented in EC 3: Part 1.2 remain linear up to the limit of proportionality at approximately 0.1% strain, whereas BS 5950: Part 8 adopts a fully non-linear form of stress-strain curve. As such the need to define a suitable level of strain is omitted in the case of the Eurocode curves, provided that analysis remains within the limit of proportionality. The degradation of stiffness according to the Eurocodes is illustrated in a non-dimensional form in Fig. 2.2, in which it is compared with results from BS 5950 assuming a strain of 0.1%. It may be seen that a close correlation exists between the recommendations presented in both codes of practice. There is a negligible reduction in stiffness up to a temperature of 100°C, and it then becomes more rapid up to temperatures in excess of 700°C.

2.2.2. Degradation of Steel Strength

A significant parameter in the definition of the response of structural steel at elevated temperatures is the strength retention factor, being the residual strength at a given temperature relative to the ambient temperature yield strength. The definition of the strength retention factor is complicated by the differences in test procedures previously detailed, and the determination of a suitable level of strain.

The yield strength is traditionally described as being consistent with the yield plateau in ambient temperature studies. As temperatures increase the non-linearity of stress-strain curves becomes more pronounced, with the steel ceasing to display a well defined yield point, making it difficult to define a suitable level of strain. ECCS recommended that an effective yield strain of 0.5% be assumed for structural steels at temperatures in excess of 400°C, with the yield stress reducing linearly with increasing temperatures to be consistent with a strain of 0.2% at ambient temperature. Tests conducted on isolated members at elevated temperatures have demonstrated levels of strain far in excess of the 0.5% suggested, suggesting that stresses greater than those ascertained assuming a strain of 0.5%

are generated within typical members at elevated temperatures. Considering this BS 5950: Part 8 recommended a level of strain of 1.5% for the determination of yield stress at elevated temperatures, based on anisothermal tests conducted by British Steel[53] for a heating rate of 10°C / minute.

The degradation of yield stress with temperature is illustrated in Fig. 2.2, based on a strain of 1.5% for the material properties presented in both BS 5950: Part 8, and a 2% strain for the material properties presented in EC 3: Part 1.2, corresponding with the adopted yield strain. It may be seen that once more a close correlation exists between results presented in BS 5950 and EC 3, as would be expected as both codes are based on the same test data. The proposed relationship suggests a negligible degradation in capacity up to comparatively high temperatures, in the region of 400°C, which is then followed by a rapid reduction in strength.

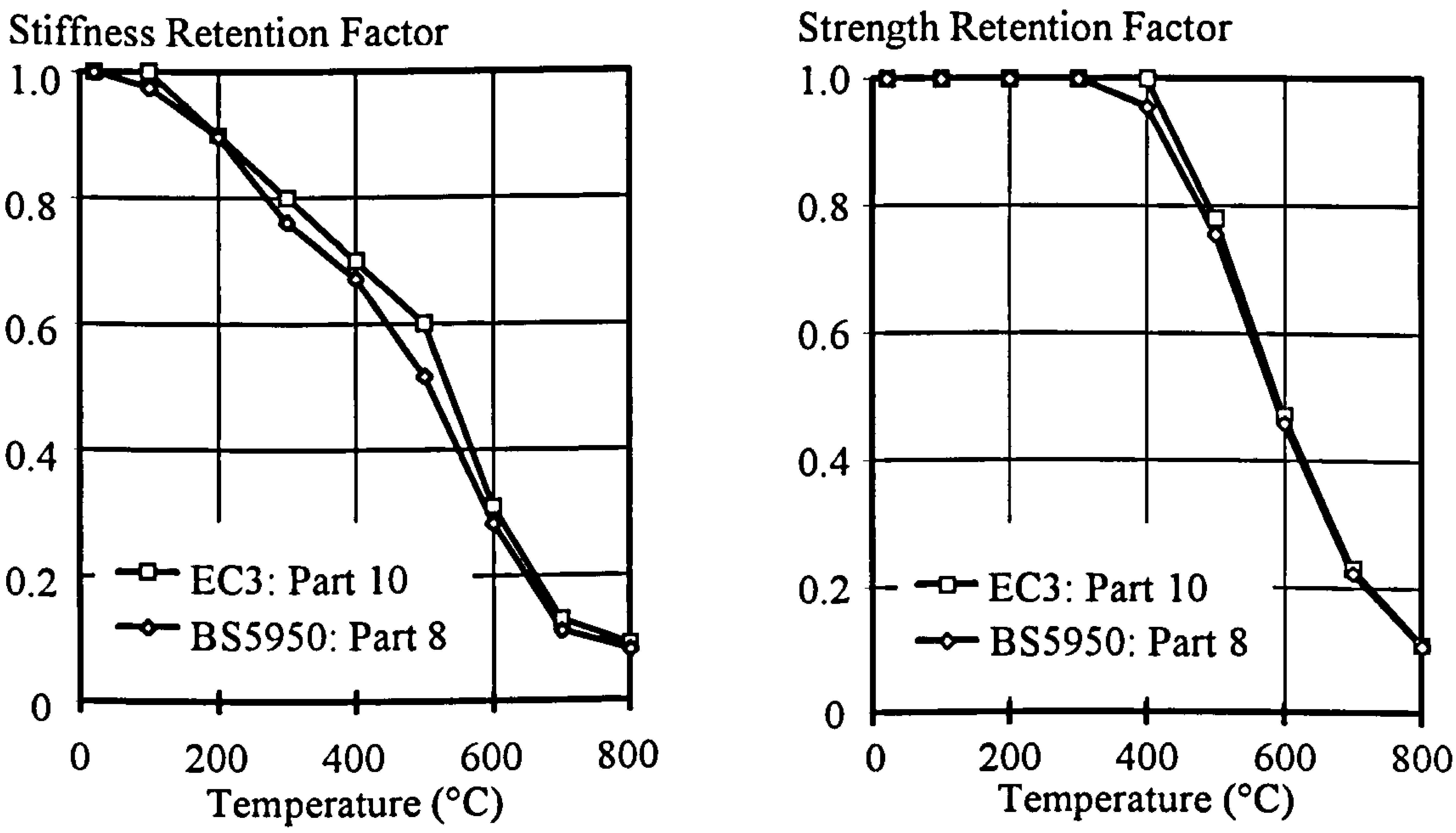


Figure 2.2. Degradation of Stiffness and Strength for Grade 43 Steel with Temperature

2.2.3. Thermal Expansion of Structural Steel

It is known that the expansion of steel becomes significant at elevated temperatures. The coefficient of thermal expansion, α_s, for steel is typically assumed to be 12×10^{-6}/°C at ambient temperatures, increasing slightly with temperature, to an approximate value of 14×10^{-6}/°C for temperatures in the range of 200°C to 600°C. At temperatures of approximately 720°C steel undergoes a phase change and there is a reduction in rate of thermal expansion as energy is absorbed and the material adopts a denser internal structure.

The total extension δ_s from 20°C up to the point of phase change is defined by a single equation in BS 5950: Part 8, with no account being taken of the subsequent behaviour. This has been replaced by a tri-linear relationship in EC 3: Part 1.2 to account for the described phase change:

$$\delta_s = \left(-2.416x10^{-4} + 1.2x10^{-5}t_s + 0.4x10^{-8}t_s^2\right).l \qquad 20°C < t_s \leq 750°C$$

$$\delta_s = \left(11.0x10^{-3}\right).l \qquad 750°C < t_s \leq 860°C$$

$$\delta_s = \left(-6.2x10^{-3} + 2.0x10^{-5}t_s\right).l \qquad 860°C < t_s \leq 1200°C \qquad \text{Eq. 2.1.}$$

Where l is the original length of the specimen and t_s is the temperature of the steel (°C).

2.2.4. Specific Heat of Steel

The specific heat of steel, C_s, is the heat stored (Joules) in a unit mass of steel for 1°C temperature rise. The greater the specific heat of a material, the smaller its temperature rise for a given amount of heat absorbed. For most calculations a constant value of specific heat of 520J/kg°C may be used, but at temperatures above 600°C it rises rapidly due to changes in the molecular structure. More accurately for the full range of temperatures the specific heat of steel may be defined[8] as:

$$C_s = 425 + 7.73x10^{-1}t_s - 1.69x10^{-3}t_s^2 + 2.22x10^{-6}t_s^3 \qquad 20°C < t_s \leq 600°C$$

$$C_s = 666 + \frac{-13003}{t_s - 738} \qquad 600°C < t_s \leq 735°C$$

$$C_s = 545 + \frac{17822}{t_s - 731} \qquad 735°C < t_s \leq 900°C$$

$$C_s = 650 \qquad 900°C < t_s \leq 1200°C$$

Eq. 2.2.

2.2.5. Thermal Conductivity of Steel

Thermal conductivity, k_s, is defined as the amount of heat in unit time (Watts) which passes through a unit cross-sectional area of material for a unit temperature gradient (i.e. 1°C temperature change per unit length). For steel the rate of thermal conductivity is high, being approximately 50 times greater than that for concrete, and some 500 times greater than vermiculite-cement, which is commonly used to provide fire protection. Rates of thermal conductivity are primarily of concern when considering thermal insulation of sections. Thermal conductivity for steel may be taken as 45W/m°C or more accurately[8]:

$$k_s = 54 - 3.33x10^{-2}t_s \qquad 20°C < t_s \leq 800°C$$

$$k_s = 27.3 \qquad 800°C < t_s \leq 1200°C \qquad \text{Eq. 2.3.}$$

2.2.6. Comments

Recommendations have been presented for the degradation of the mechanical and thermal properties of structural steel according to both BS 5950: Part 8 and EC 3: Part 1.2. It may be seen that both these documents consider a similar response, with them both being based around a series of anisothermal tests conducted by British Steel. The Eurocodes have refined existing recommendations, allowing the assessment of properties at temperatures beyond the phase change, in the region of 720°C. Recommendations presented in EC 3:

Part 1.2 are also independent of the grade of steel, making the application more general. Linear interpolation is permitted for temperatures other than those presented in both EC 3: Part 1.2 and BS 5950: Part 8.

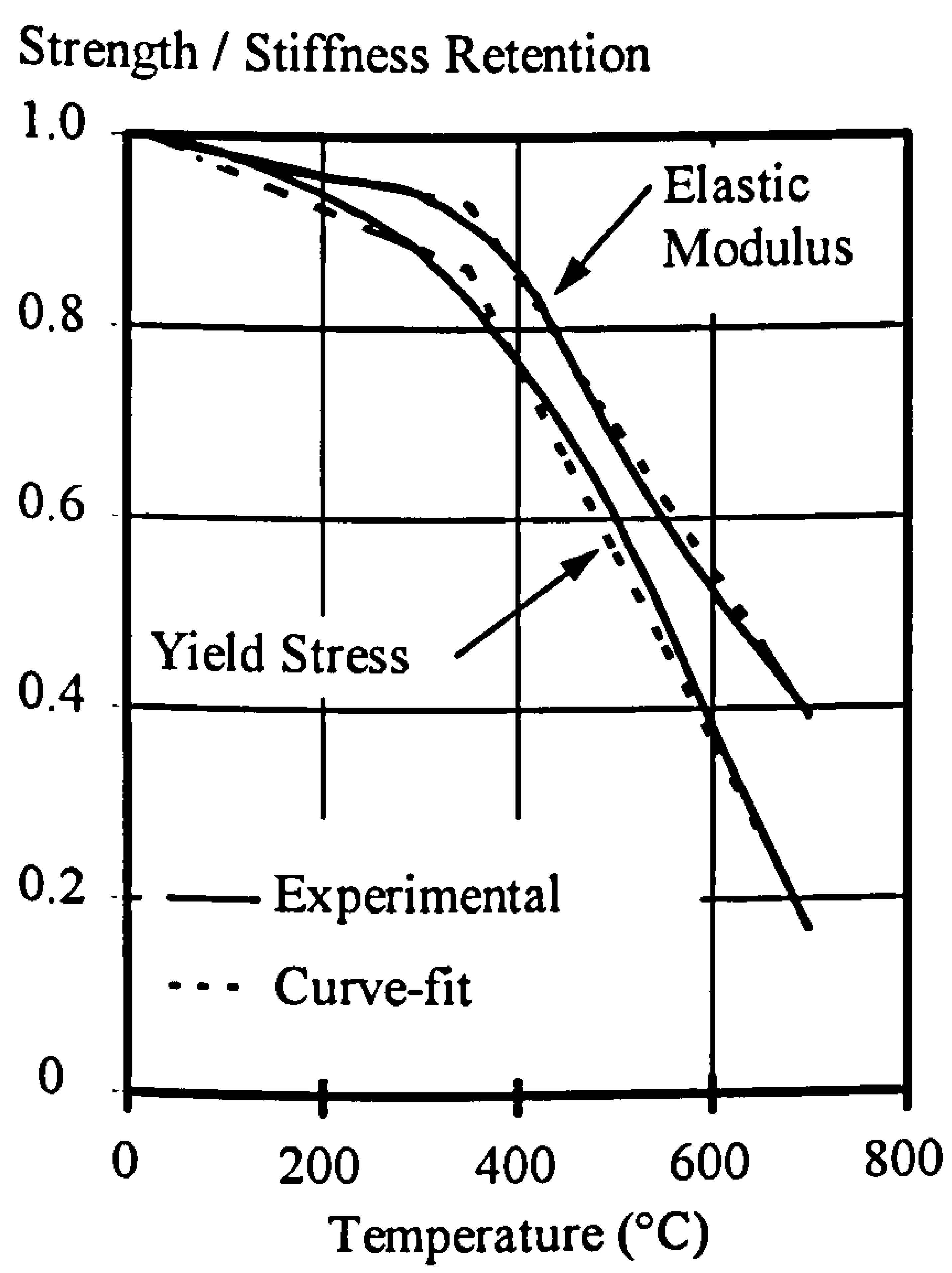
Poisson's ratio and density of steel are considered to be independent of temperature, and may be taken as 0.3 and 7850kg/m^3 respectively.

2.3. DEGRADATION OF REINFORCEMENT

A series of tests has been conducted by Holmes *et. al.*[54] investigating the influence of elevated temperatures on the strength and stiffness properties of varying forms of reinforcement, within the temperature range 20°C to 700°C. The test programme was designed to provide data for three major strength parameters - yield stress (or 0.2% proof stress), ultimate strength and elastic modulus.

Three types of reinforcement were tested, consisting of mild steel, hot-rolled high yield steel and cold-worked high yield steel, with bar diameters of 8mm, 12mm and 25mm, allowing assessment of the influence of size on behaviour. Reinforcement was tested in a purpose-built tensile test rig, with specimens being heated by a cylindrical tube furnace, with a maximum operating temperature of 1000°C. Testing was conducted under constant temperature, with increasing load.

It was observed that the size of the section had little influence on recorded properties, that the hot rolled steels (including one high yield) performed equally well, and that the two cold-worked steels could not be distinguished, once the characteristics were normalised. Results from elevated temperature testing are presented in Fig. 2.3.



Stiffness Retention Factor

$$20^\circ C < t_r \leq 350^\circ C$$
$$= 1.008 - 42.424x10^{-5} t_r$$

$$350^\circ C < t_r \leq 700^\circ C$$
$$= 1.550 - 1.971x10^{-3} t_r$$

Eq. 2.4.

Strength Retention Factor

$$20^\circ C < t_r \leq 350^\circ C$$
$$= 1.004 - 21.212x10^{-5} t_r$$

$$350^\circ C < t_r \leq 700^\circ C$$
$$= 1.470 - 1.543x10^{-3} t_r$$

Eq. 2.5.

Where t_r is the temperature of the reinforcement.

Figure 2.3. Degradation of Reinforcement Properties

It was suggested that, whilst existing design recommendations[55] compared well with the experimental observations in the mid-range of temperatures, in the lower and upper ranges of temperature design curves did not form a lower-bound limit. Based on the results presented by Holmes *et. al.*, a bi-linear representation is presented for the degradation of both capacity and stiffness of reinforcement at elevated temperatures, in terms of strength and stiffness retention factors, as described in Eqs. 2.4 and 2.5. The range of temperatures has been restricted to 700°C, due to the range of test data available, but it is unlikely that reinforcement would be subjected to higher temperatures, due to the insulating properties of concrete.

Values have not been presented for the degradation of ultimate strength, as this is not of primary concern. Assuming ultimate strength to degrade at the same rate as yield strength will result in a close correlation at high temperatures, and conservative values throughout the full range of temperatures.

2.4. DEGRADATION OF BOLTS

The behaviour of bolts at elevated temperatures is insufficiently considered within existing codes. The draft Eurocode proposals make no recommendations for the degradation of bolt characteristics at elevated temperatures, whilst at the time of publication of BS 5950: Part 8 no suitable experimental data existed, and consequently the capacity of bolts at elevated temperatures was simply described as for structural steels at 5% strain.

A series of tests has recently been conducted by Kirby[56] to assess the degradation of high strength Grade 8.8 bolt characteristics at elevated temperatures. In all tests a similar pattern of behaviour was observed, with the bolts showing a marked reduction in strength between 300°C and 700°C. The test results suggest that the present design curves are conservative, particularly at low-to-intermediate temperatures. Tensile tests also highlighted problems of premature failure due to thread stripping. Based on the findings of the study a proposal was made to amend the guidance presented in BS 5950: Part 8 to reflect more closely the influence of temperature on ultimate bolt capacity, taking into account the possible occurrence of thread failure in tension. A strength retention factor (*SRF*) was defined using a tri-linear relationship as:

$$\begin{aligned} SRF &= 1.0 && t_b \leq 300^\circ C \\ &= 1.0 - (t_b - 300)0.2128x10^{-2} && 300^\circ C < t_b \leq 680^\circ C \\ &= 0.17 - (t_b - 680)x0.513x10^{-3} && 680^\circ C < t_b \leq 1000^\circ C \end{aligned} \qquad \text{Eq. 2.6.}$$

Where t_b is the temperature of the bolt.

Based on nominal or experimental bolt properties at ambient temperatures, it is thus possible to ascertain the tensile strength of a bolt at any given temperature.

As no recommendations are presented for the degradation of modulus of elasticity for bolts at elevated temperatures, it is suggested that this be degraded according to the recommendations presented in EC 3: Part 1.2 for Grade 50 steel, assuming a strain of 0.1%.

2.5. DEGRADATION OF CONCRETE

The nature of concrete is such that temperatures produced by fires cause no sudden and possibly disastrous changes in properties. Concrete initially expands with increasing temperatures, but progressive loss of moisture from the concrete paste causes shrinkage and thus helps offset the thermal expansion of the aggregate. Energy is consumed in driving off the moisture contained within the concrete, reducing the rate of increase in temperature. Further, the thermal conductivity of concrete is low, so that a rise in surface temperature is not immediately transferred throughout the section. Loss of concrete strength due to dehydration may thus be confined to the surface layers.

Although all forms of concrete demonstrate significant resistance to fire, the degree of resistance varies slightly with the type of aggregate used, those with low or regular rates of thermal expansion giving best results. Minerals such as gravel, flint and granite which consist of, or contain, a high silica content are liable to undergo sudden increases in volume at certain temperatures because of crystal changes particular to this compound. In severe fires the temperature may rise rapidly enough for these aggregates to generate internal stresses capable of forcing off the surface layer of the concrete. Prolonged exposure to such conditions may result in progressive spalling to such an extent that the reinforcement is no longer protected from extremes of temperature. Lightweight aggregates, blast-furnace slag and limestone show no sudden changes in volume with increasing temperatures, and result in excellent fire resistance. The strength retention factor for normal-weight concrete may be expressed according to the recommendations of BS 8110: Part 2:

$$SRF = 0.8(800 - t_c)/450 + 0.2 \qquad 350^oC < t_c < 800^oC \qquad \text{Eq. 2.7.}$$

Lightweight concrete has beneficial properties in fire because of its reduced rate of thermal conductivity, and enhanced strength in fire. This has recently been verified experimentally by a series of tests conducted by Jau and Wu[57] investigating the performance of lightweight concrete panels subjected to fire. Jau concluded that lightweight concrete showed lower thermal conductivity, lower thermal expansion and a higher percentage of residual strength than normal-weight concrete at any temperature. The strength retention factor for lightweight concrete is given in BS 8110: Part 2 as:

$$SRF = 0.6(800 - t_c)/300 + 0.4 \qquad 500^oC < t_c < 800^oC \qquad \text{Eq. 2.8.}$$

Where t_c is the temperature of the concrete.

Strength retention factors for both lightweight and normal-weight concrete, as described above, are compared with those for structural steel according to the recommendations of EC3: Part 1.2 in Fig. 2.4. It may be seen that the rate of decay for normal-weight concrete compares closely to that for structural steel, whilst lightweight concrete demonstrates a significant enhancement in strength at elevated temperatures. It should be remembered that concrete is unable to recover its strength when temperatures decrease.

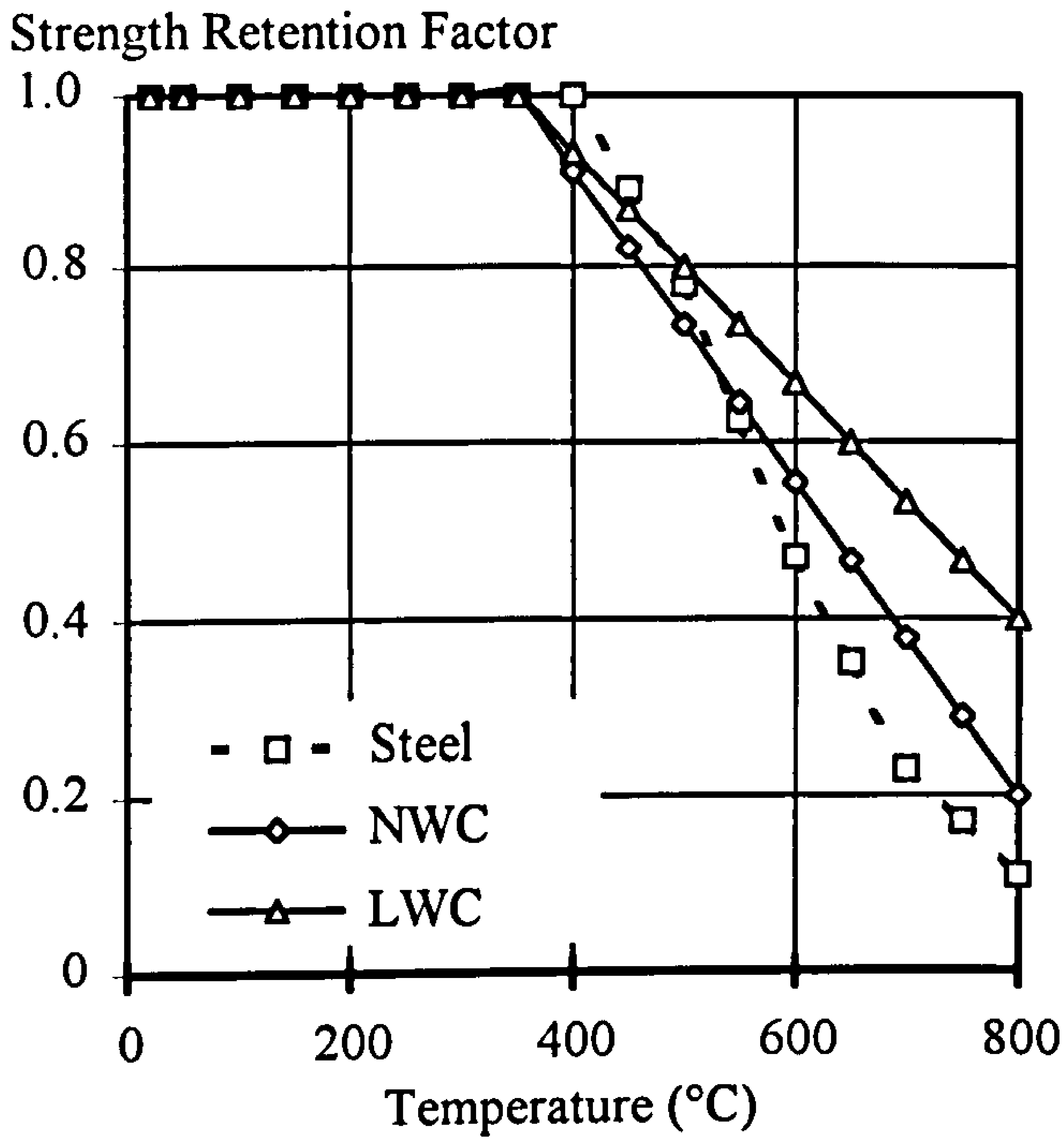


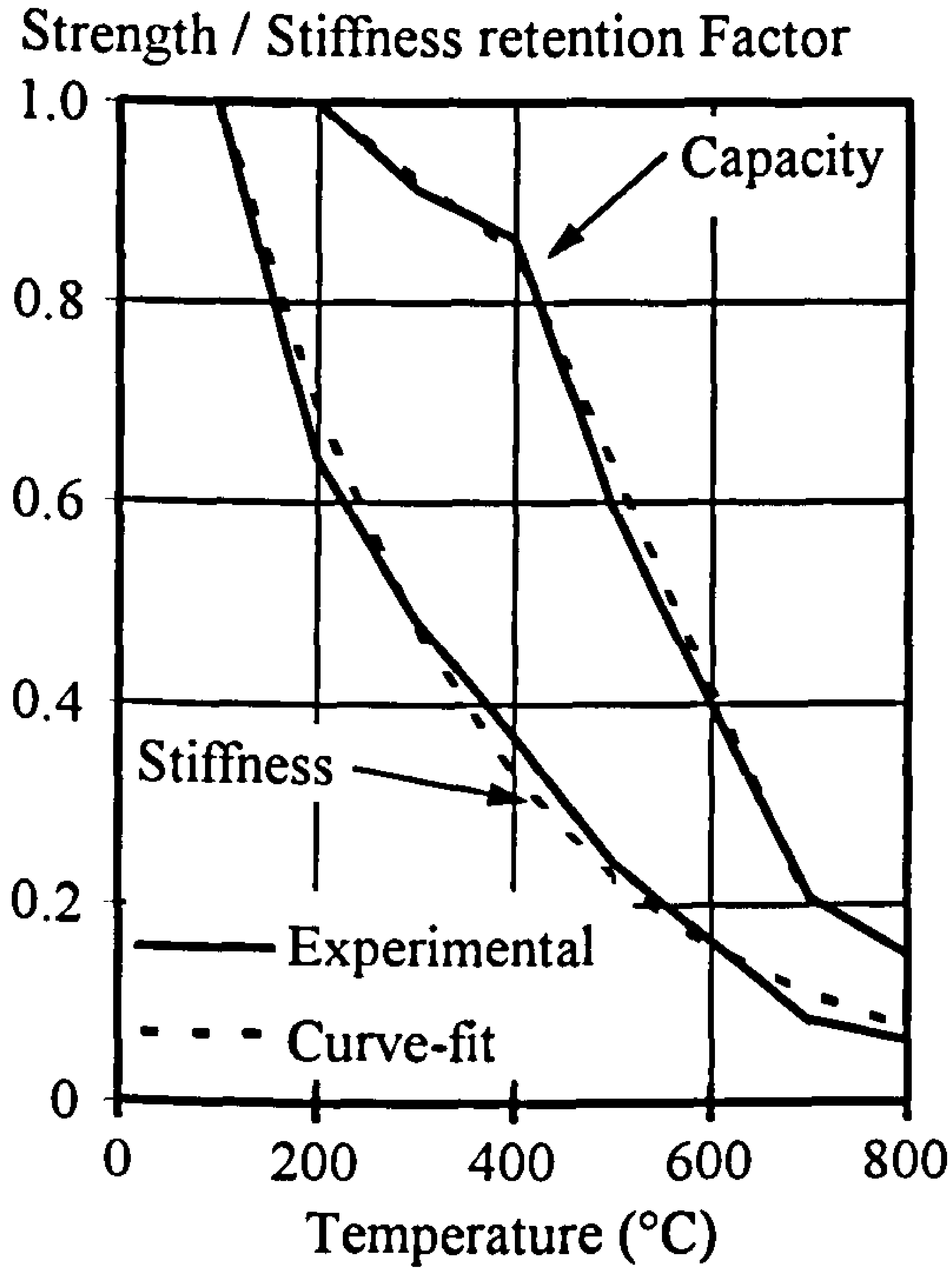
Figure 2.4. Comparison of the Degradation of Strength for Concrete and Steel

2.6. DEGRADATION OF SHEAR STUDS

Bond at the steel-concrete interface in composite construction is typically provided by shear studs, where a bolt is electrically welded to the steel member, with the shank resisting longitudinal shear, whilst the head resists tensile loads normal to the interface. Although empirical relationships[58] exist defining the performance of shear studs, it is commonly accepted that the only way to date of obtaining accurate data defining the response is through physical 'push-out' tests, due to the large number of influencing factors.

A number of tests have been conducted to establish the response of shear studs contained within both solid slabs[59] and profiled-deck floor systems[60]. The use of profiled-deck flooring results in a reduction in the performance of the shear studs, and this is accounted for in design by the use of reduction factors[59].

Whilst there is a reasonable understanding of the response of shear studs at ambient temperatures, little consideration has been given to the influence of elevated temperatures on their performance. A series of tests has recently been conducted by Twilt[61,62] investigating elevated temperature shear stud response, but unfortunately the scope of these tests was restricted to a limited number of structural arrangements. As such, the results presented are assumed to be applicable to typical structural arrangements until such a time as more specific data becomes available. Results from these tests have been summarised as non-dimensionalized strength and stiffness retention factors in Fig. 2.5.



Stiffness Retention Factor

$20^{\circ}C < t_s \leq 100^{\circ}C$

$$= 1.000$$

$100^{\circ}C < t_s \leq 800^{\circ}C$

$$= 1.445x10^{-1.6x10^{-3}t_s} \qquad \text{Eq. 2.9.}$$

Strength Retention Factor

$20^{\circ}C < t_s \leq 200^{\circ}C$

$$= 1.000$$

$200^{\circ}C < t_s \leq 400^{\circ}C$

$$= 1.150 - 7.5x10^{-4}t_s$$

$400^{\circ}C < t_s \leq 700^{\circ}C$

$$= 1.717 - 2.167x10^{-3}t_s \qquad \text{Eq. 2.10.}$$

Figure 2.5. Degradation of Shear Stud Strength and Capacity

The stiffness of the shear connection begins to decrease at relatively low temperatures, at a greater rate than that for structural steel. It is suggested that this may be due to the form of loading used. Material properties are typically obtained from simple tensile or compressive testing as appropriate, giving a direct indication of material response, whereas in push-out tests shear studs are subject to a transverse shear force, and act as a structural arrangement. An exponential curve-fit has been applied to the stiffness retention curve, as described in Equation 2.9, providing a close representation of the non-linear form of behaviour for temperatures in excess of 100°C. It may also be seen that the capacity of the shear-studs begins to reduce at temperatures of approximately 200°C, with a kink in the response for temperatures in excess of 400°C. For this reason a tri-linear curve-fit has been adopted to describe the decay of capacity for the shear-studs.

3. ELEVATED-TEMPERATURE MOMENT - ROTATION TESTS ON FLUSH END-PLATE CONNECTIONS

3.1. INTRODUCTION

Considerable advances have recently been made in the analysis of steel-framed structures in fire, so that realistic structural simulations are now possible. One of the important outcomes of this is that the rigidity of real beam-to-column connections, nominally designed as 'pinned', can be seen to have a significant influence on survival times. Analytical software exists which is capable of incorporating semi-rigid connection characteristics, in the form of non-linear moment-rotation relationships which degrade with temperature, but unfortunately little data exists for defining the precise detail of these relationships.

A limited number of studies[22], based on postulated connection characteristics and a reasonable understanding of moment-rotation curves, have confirmed that connection rigidities can be significant in improving the performance of steel frames in fire. Clearly to take advantage of this experimental data it is necessary to postulate a justifiable representation of the connection behaviour.

For this purpose, a series of tests has been conducted to define accurately the moment-rotation relationships for a single flush end-plate connection, both as bare-steel and as composite with a concrete slab, across a range of temperatures. Determination of such curves by furnace testing is expensive, and a prime objective of the present study is to postulate rules for elevated-temperature degradation of connection characteristics. These may enable the large body of data that now exists on ambient-temperature connection behaviour to be put to use in the simulation of structural performance in fire. All of the experimental work described was conducted by the author in the Structures Laboratory at the Building Research Establishment, Garston.

3.2. BARE-STEEL FLUSH END-PLATE CONNECTION TESTS

A total of seven tests were conducted in order to establish moment-rotation relationships for a bare-steel flush end-plate connection across a range of temperatures; one at ambient-temperature throughout the entire moment-rotation range, one in an unloaded state subject to various rates of heating, and five elevated-temperature tests at different constant load levels. Load levels for the elevated-temperature tests were decided after the ambient-temperature test, on the basis of postulated moment-rotation curves, so as to provide data throughout the entire range of the connection's response. The test programme for the bare-steel connection is detailed in Table 3.1. The scope of the programme was restricted to a single connection type by the resources available and the number of tests required to define accurately the connection characteristics at elevated-temperatures. The most common connection type used on non-composite building frames[46], namely the flush end-plate, was used in this series.

A cruciform arrangement was chosen consisting of two 254x102x22UB Grade 43 beams 1700mm long, symmetrically framing into the flanges of a single 152x152x23UC Grade 43 column 2700mm in length, these dimensions largely being dictated by the physical restrictions imposed by the test furnace. Cruciform tests require a less extensive test rig than the corresponding single-cantilever arrangement, whilst providing an indication of the variability of nominally identical connections. A full-depth end-plate connection was used as shown in Fig. 3.1. This is a popular type of connection, being simple to fabricate and neatly contained within the beam depth. It is often designed as a simple shear joint with no account taken of its inherent rotational stiffness. For this study a 12mm thick end-plate was selected with six M16 Grade 8.8 bolts in 18mm diameter clearance holes, although an 8mm plate thickness might be more representative of current practice[63]. This detail has been used in previous experimental work by Gibbons[64] and Davison[65], providing a useful comparison with ambient-temperature tests. To maintain continuity between tests, all bolts were tightened to a torque of approximately 160Nm, this having been previously suggested as corresponding to the torque typically obtained from 'hand tightening'[65], which is approximately 50% of the proof load of the bolts considered.

Description:	**Applied Moment:**	**Temperature:**	**Comments:**
BFEP AMB	Full Range.	Ambient.	Ambient-temperature M-θ.
BFEP TEMP	None.	Various.	Influence of rate of heating.
BFEP 5	5kNm.	10°C / minute.	Bare-steel fire test 1.
BFEP 10	10kNm.	10°C / minute.	Bare-steel fire test 2.
BFEP 15	15kNm.	10°C / minute.	Bare-steel fire test 3.
BFEP 20	20kNm.	10°C / minute.	Bare-steel fire test 4.
BFEP 25	25kNm.	10°C / minute.	Bare-steel fire test 5.

Table 3.1. Bare-Steel Flush End-Plate Experimental Programme

The strength of the connection was assessed according to Horne and Morris[66] based on nominal sectional and material properties, with the moment capacity, bearing resistance of the column flange and end-plate thickness being checked. The moment capacity, stiffness and failure mechanisms of the joint were also calculated in accordance with the method proposed in EC3[41]. Calculations according to Horne and Morris indicated column flange failure, while EC3 predicted that the failure mechanism would be column web bearing. Moment capacities of the connection at ambient-temperature were predicted as 18.14kNm and 14.07 kNm according to EC3 and Horne and Morris respectively, assuming nominal material and section properties. Connection stiffness was predicted to be 8.7×10^9 Nmm/rad according to the recommendations presented in EC3, which would reduce to 7.1×10^9 Nmm/rad for an 8mm plate thickness.

Prior to testing, ambient-temperature material and geometrical properties were measured for all specimens, and are presented in Appendix A. It was observed that section properties for beams and columns were typically marginally less than nominal values, due to reductions in flange thickness. However, these reductions in the section properties were compensated for by the enhanced strength of the sections. Elevated-temperature material properties were not assessed due to the expense of testing and the extent of data already in existence describing the degradation of material properties with increasing temperatures, as summarised in Chapter 2.

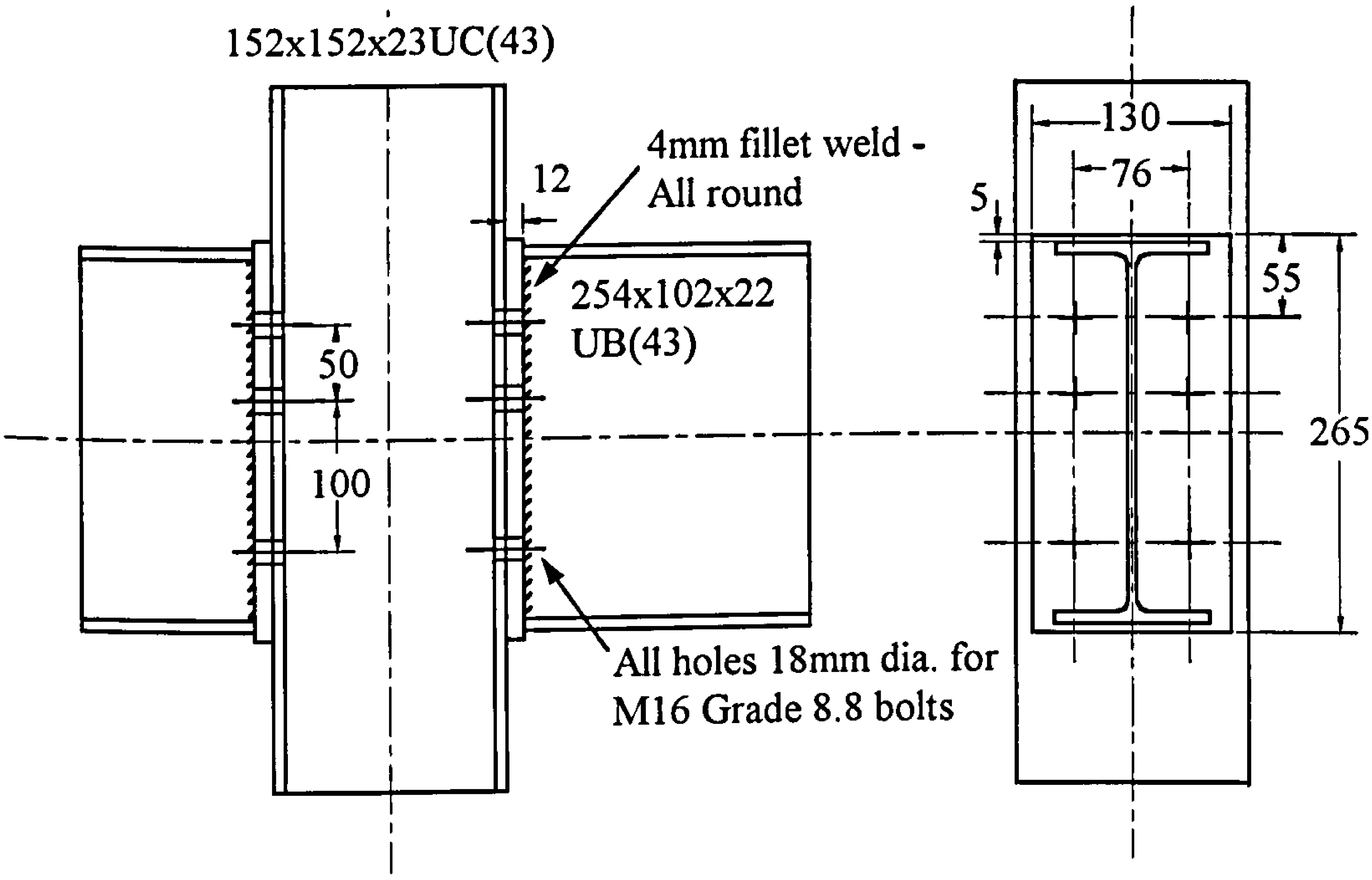


Figure 3.1. Bare-Steel Flush End-Plate Connection Detail

3.2.1. Ambient-Temperature Test

For the ambient-temperature test a reduced column length of 1400mm was used, and the specimen was tested in an inverted position, due to the physical restrictions imposed by the test rig. A small incremental load was applied to the column head, with the beams being restrained in position at a distance of 1524mm from the column centre-line, resulting in a loading arrangement similar to that used in the elevated-temperature tests. The ambient-temperature test arrangement is illustrated in Figs. 3.2. and 3.3.

3.2.1.1. Instrumentation

Instrumentation used for the tests included displacement transducers, rotation devices and load control. The data from all tests was recorded using an Orion Delta data logger and processed using AXIS software. As the test rig used was load-controlled, channels were scanned at regular intervals corresponding to an increment of moment at the connection of approximately 750Nm. Displacement transducers were situated at four locations along the centre-line of each beam, at distances of 200mm, 400mm, 600mm and 1000mm from the face of the column flange. These were used as a check on direct rotation measurements, and to describe the displaced shapes of the beams. An additional transducer located at the centre-line of the column web was used to measure the vertical displacement of the column as the specimen was loaded.

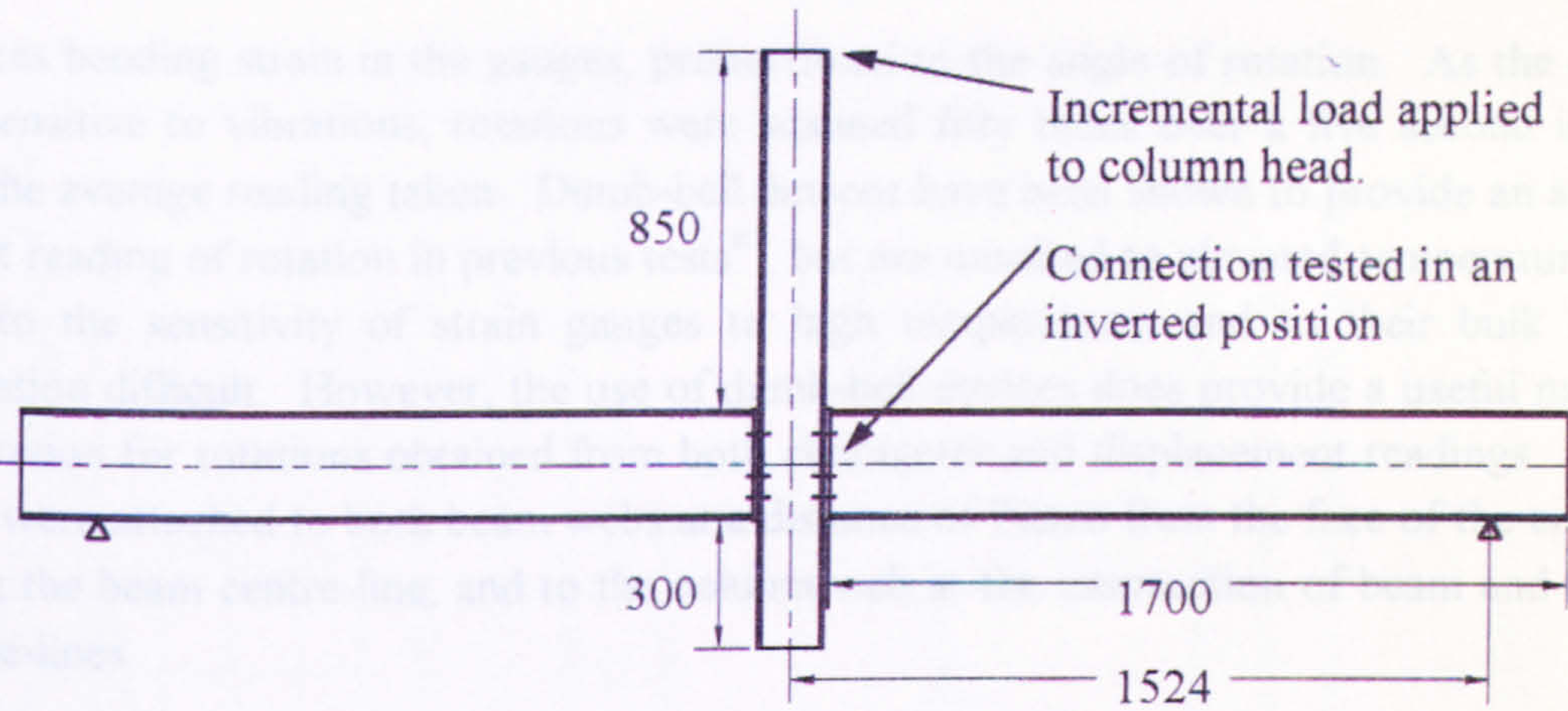


Figure 3.2. Ambient-Temperature Test Arrangement

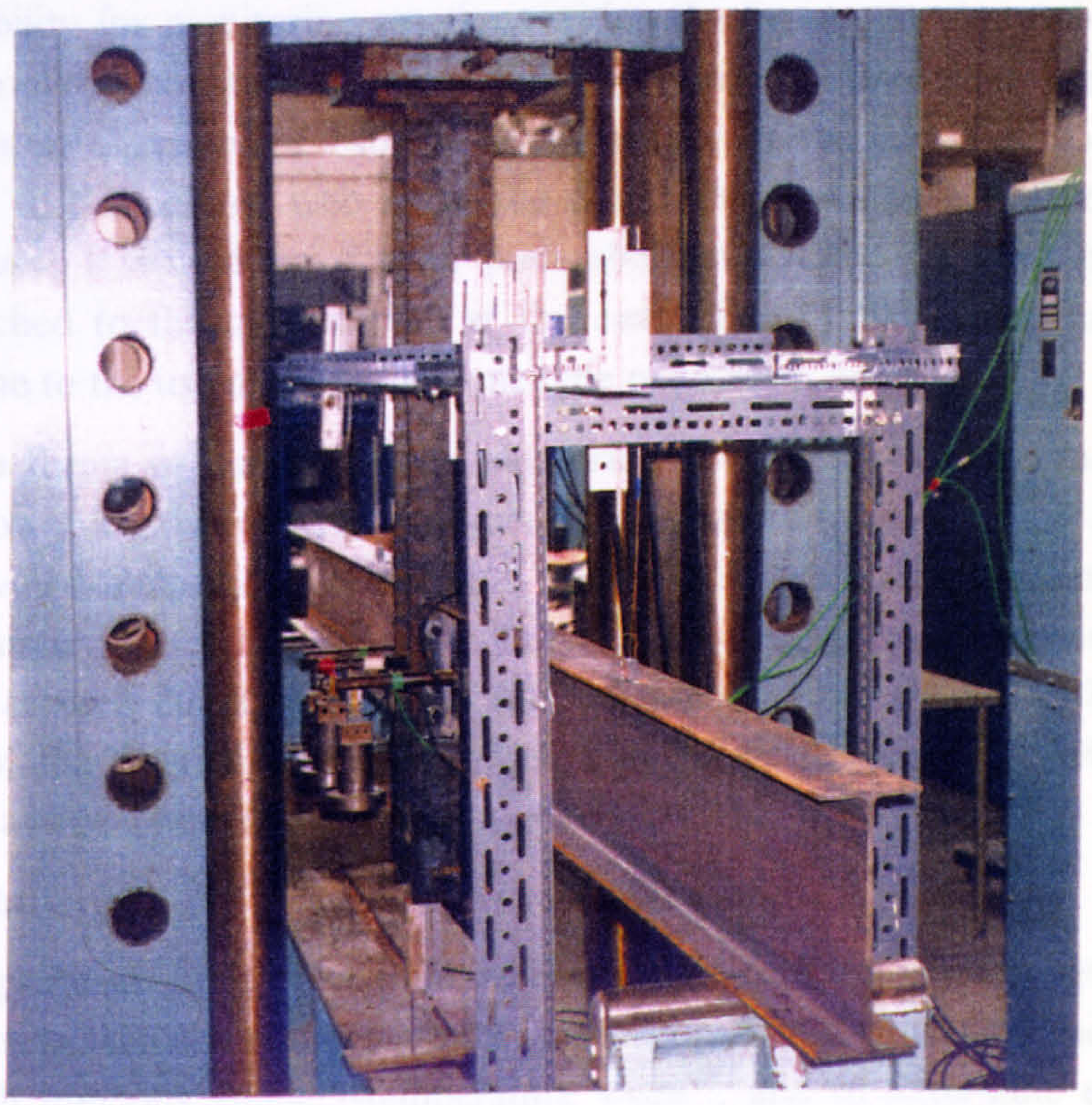


Figure 3.3. Ambient-Temperature Connection Test

In addition to the use of displacement transducers, "hanging dumb-bell" and "clinometer" devices were used to monitor connection rotations directly. An arrangement of three rotation devices was required to record connection rotations for a cruciform arrangement, two recording absolute beam rotations and an additional device to monitor absolute rotation of the column.

Dumb-bell devices consist of a 105mm by 25mm strip of 1mm thick spring steel with four strain gauges mounted two on each side of the strip. The strip was securely fastened into a clamping-bar so that it was perpendicular to the bar. The bar was then clamped by its base to the test specimen, and a heavy weight suspended from the other end of the strip. As the members within the arrangement rotate, the weight maintains a vertical position and thus induces bending strain in the gauges, proportional to the angle of rotation. As the devices are sensitive to vibrations, rotations were scanned fifty times over a five second interval, and the average reading taken. Dumb-bell devices have been shown to provide an accurate direct reading of rotation in previous tests[67], but are unsuited to elevated-temperature work due to the sensitivity of strain gauges to high temperatures and to their bulk making insulation difficult. However, the use of dumb-bell devices does provide a useful means of calibration for rotations obtained from both clinometer and displacement readings. Dumb-bells were attached to both beam webs at a distance of 70mm from the face of the end-plate along the beam centre-line, and to the column web at the intersection of beam and column centre-lines.

Clinometers are extremely sensitive gravity-based transducers that measure rotation to virtually infinite resolution, and were selected as their small size and self-contained nature suggested suitability for monitoring rotations within the furnace at elevated-temperatures, once shielded from the extremes of temperature experienced. Clinometers were attached to both beam webs at distances of 140mm from the face of the end-plate along the beam centre-line, and to the column web along the centre-line, a distance of 90mm above the beam centre-line. It would have been preferable once more to have positioned the clinometer attached to the column web at the centre-line of the beam, but this proved impracticable due to the use of more than one type of rotation device.

The use of two forms of direct rotation-measuring devices, in addition to displacement transducers, allowed the various rotation-measuring devices to be assessed and calibrated prior to the elevated-temperature connection tests. Rotations obtained from displacement readings were assumed relative to the column centre-line, rather than the face of the column flange, as with direct readings of rotation. This is compatible with the form of moment-rotation characteristics typically required in numerical modelling, where members are represented as line elements along their centre-lines.

3.2.1.2. Results

The three main purposes of this test were: to assess the suitability of clinometers compared with the dumb-bells used in a number of previous moment-rotation tests, to provide a direct comparison with previous ambient-temperature work[65], and to determine experimentally the moment-rotation characteristics for the connection at ambient-temperature, enabling suitable load levels to be defined for the elevated-temperature tests.

Recorded moment-rotation characteristics for all rotation devices are summarised in Fig. 3.4. It may be seen that the connection demonstrated an almost linear stiffness up to moments of approximately 17kNm, after which there was a curved knee in the response, representing plastification of one or more of the elements within the connection, followed by a more flexible response up to moments of approximately 40kNm. Connections were subject to rotations in the region of 100 millirads (approximately 6°), far greater than those typically experienced in ambient-temperature connection tests, representing the large levels of deformation permissible in fire engineering methods. It may be seen that there was a close correlation between rotations of East and West beams, indicating symmetry of the

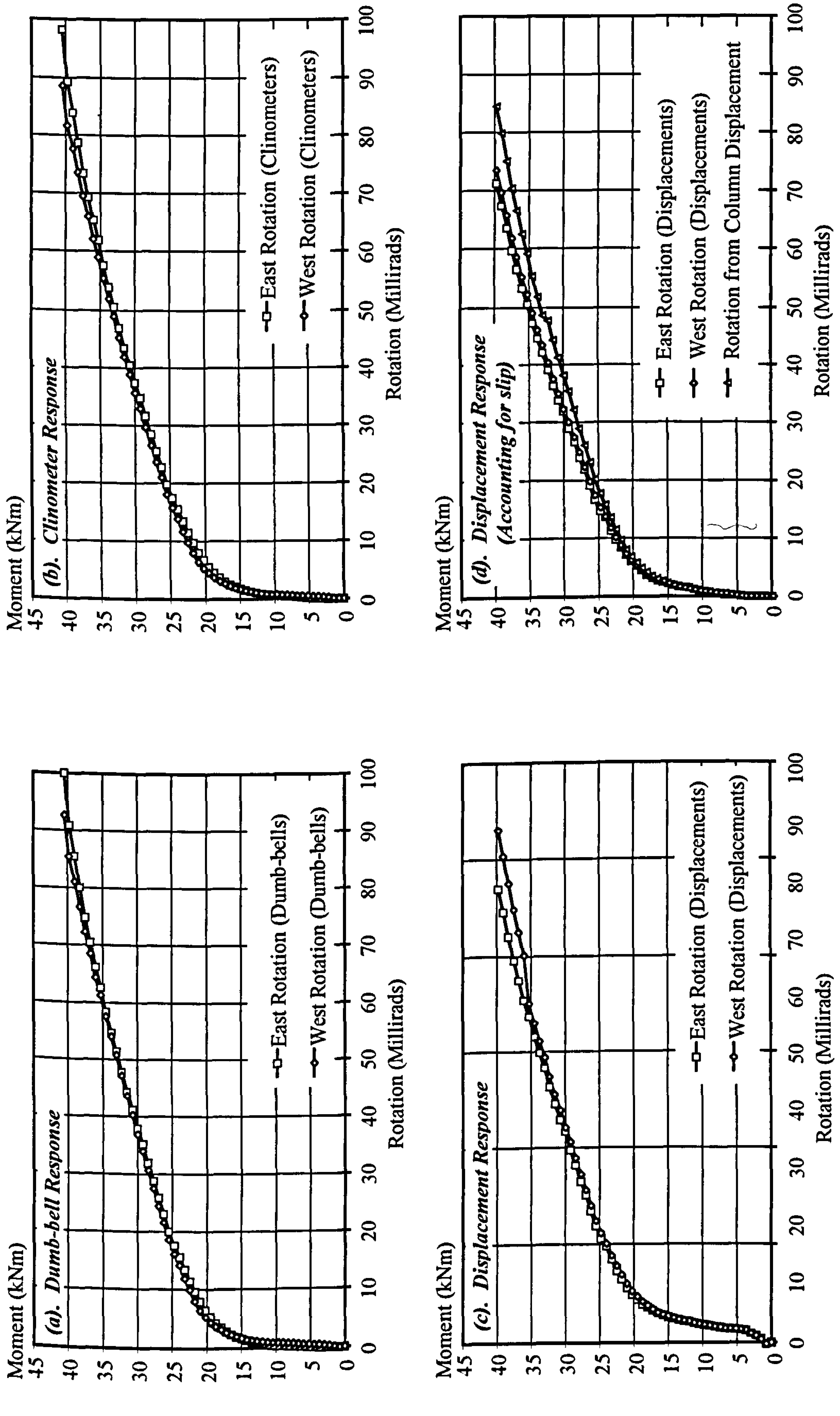


Figure 3.4. Summary of Results from Ambient-Temperature Bare-Steel Connection Test (BFEP AMB)

test arrangement and loading, resulting in approximately equal moments being applied to both connections. Rotations obtained from displacement readings, as illustrated in Fig. 3.4(c), suggest a reduced initial stiffness compared to those obtained from readings of direct rotation. It is felt that this occurred as a result of slip at the connection interface with the application of initial loading. Consideration of axial displacements showed a consistent deformation along the length of the beams upon the application of load, corresponding to a level of slip of approximately 1.3mm. This seems a reasonable value as 16mm bolts were positioned in 18mm diameter holes, allowing a tolerance of 2mm. This high value of slip probably occurred as a consequence of the connection being fabricated in an inverted position, and although the specimen was tested in this way, the form of loading is effectively applied in the conventional manner. Such large levels of slip would not be anticipated for the elevated-temperature connection tests, as these were fabricated and tested in an upright position. Fig. 3.4(d) illustrates the influence of removing slip from displacement readings, based on the assumed slip of 1.3mm. It may be seen that this results in a form of behaviour closer to that observed from direct rotations.

Connection characteristics recorded from the various forms of rotation device are compared in Fig. 3.5. Direct rotation readings compare well, and the close correlation between clinometer and dumb-bell devices provides confidence in the use of clinometer devices to record direct rotations in the elevated-temperature connection tests, subsequent to the development of a suitable form of protective housing. Rotations obtained from the displacement of the column head demonstrated an almost indiscernible deviation from direct rotations recorded. Similarly, the measurement of displacements along the beam provides good correlation at lower levels of moment, but as loads are increased this seems to suggest a slightly stiffer connection than is indicated by direct rotation measurement.

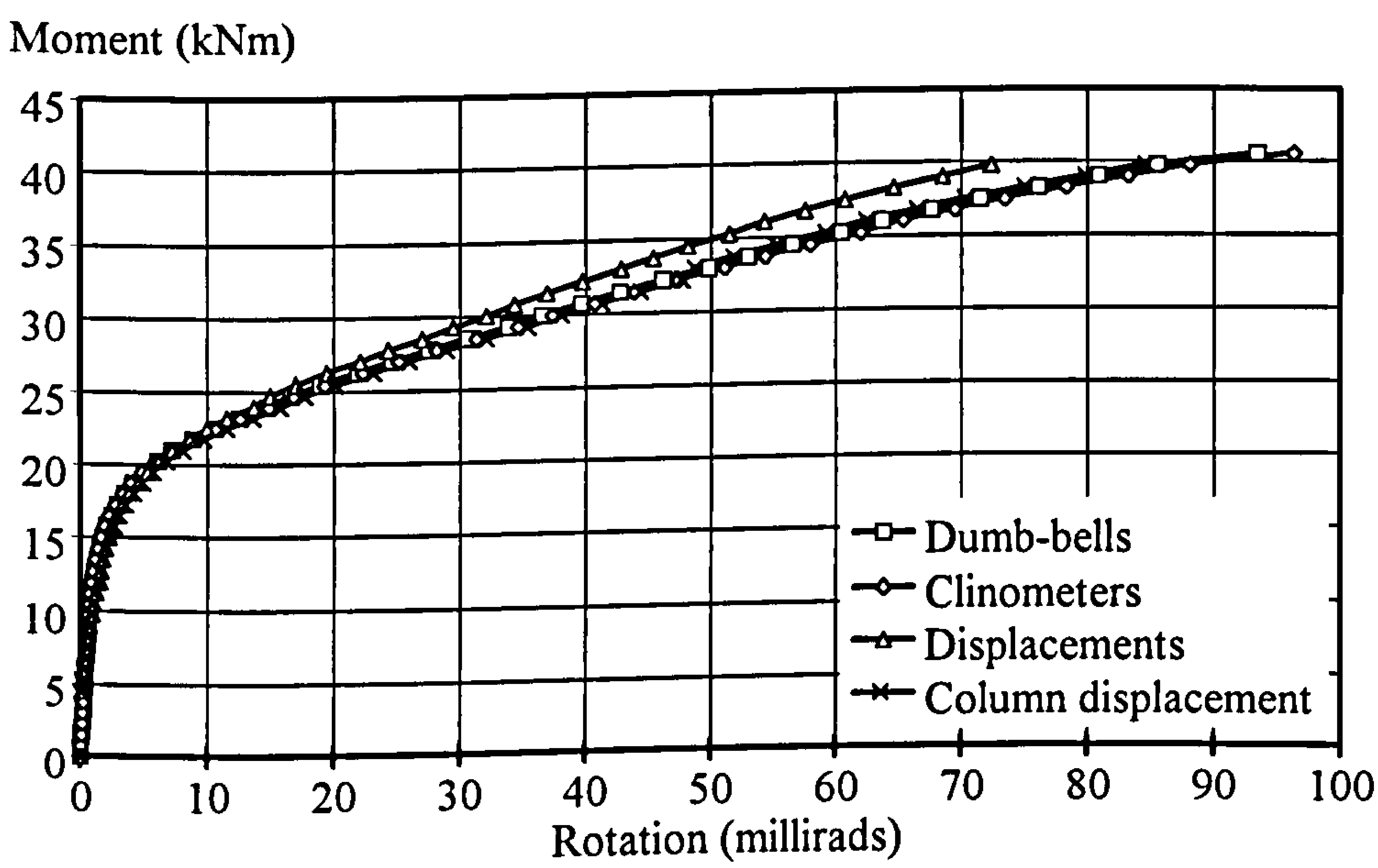


Figure 3.5. Comparison of Ambient-Temperature Rotation Devices

Significant deformation of the column web in the compression zone and the column flange in the tension zone was observed, whilst there was very little damage to either of the beams or the end-plate. Given the relative dimensions of the end-plate and the unstiffened column flange this is not surprising. It would be anticipated that end-plate deformation would become more significant as its thickness is reduced below that of the column flanges. There was little detectable deformation of the bolts. Physical observation indicated that the beams were subject to negligible deformation along their length, and this was supported by the displacements recorded at regular intervals along each beam. The mode of failure is illustrated in Fig. 3.6. Testing was terminated due to the connection's inability to sustain any further increase in loading, because of increasing flexibility.

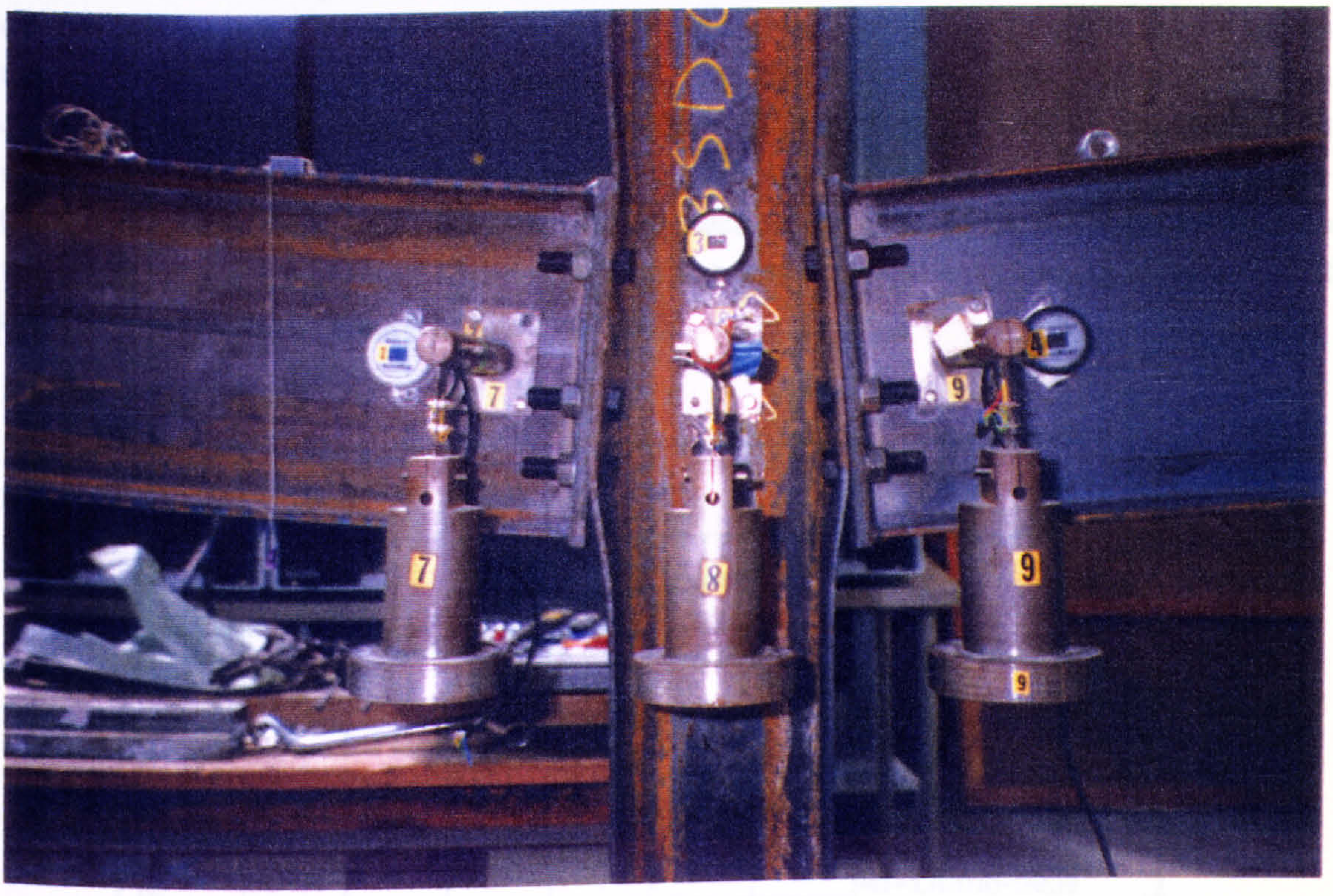


Figure 3.6. Ambient-Temperature Connection Failure Mechanism

Calculations according to Horne and Morris and EC3 accurately predicted failure of the connection as being controlled by column flange failure in the tension zone and column web bearing in the compression zone. The bare-steel connection resisted moments in excess of 30kNm, whilst still maintaining structural integrity. However, the limit of proportionality was observed to be in the region of 17kNm, comparing closely with the predicted capacities. Connection stiffness was observed experimentally as approximately $17x10^9$ Nmm/radian, compared to a predicted value of $8.7x10^9$ Nmm/radian. This suggests a connection of far greater stiffness than is predicted by the method proposed in Annex J of EC3. The method presented in EC3 assumes a linear stiffness up to a moment of two-thirds of the calculated plastic capacity of the connection, correlating to the secant stiffness of the connection, whereas the information presented from experimental observations is based on the tangent stiffness, corresponding with the slope of the moment-rotation curve at zero moment. If an assessment is made of the secant stiffness from experimental results, based on a moment at the limit of proportionality, a reduced stiffness of approximately 8.5×10^9 Nmm/radian is obtained, correlating far better with that predicted from the recommendations of Annex J of EC3.

Davison[65] conducted a series of tests on cruciform connection arrangements, including a flush end-plate connection nominally identical to that described above. Load was applied to the column by a screw jack, with the beams being restrained in position at a distance of 1000mm from the face of the column flange. Rotations were recorded using displacement transducers connected to an arrangement of wires and pulleys. The resultant connection behaviour observed by Davison is compared with the average results from the dumb-bell devices in Fig. 3.7. It can be seen that there is a close correlation between results, given the variation in experimental arrangements and the fact that there was a significant difference in the performance of left and right hand connections tested by Davison. This was attributed to bolt orientation (washers were adjacent to the column flange on the right-hand connection, whereas in the left-hand connection the head of the bolt was located on the inside of the flange) and eccentricities in the test arrangement. An initial stiffness of approximately 20×10^9 Nmm/rad was recorded.

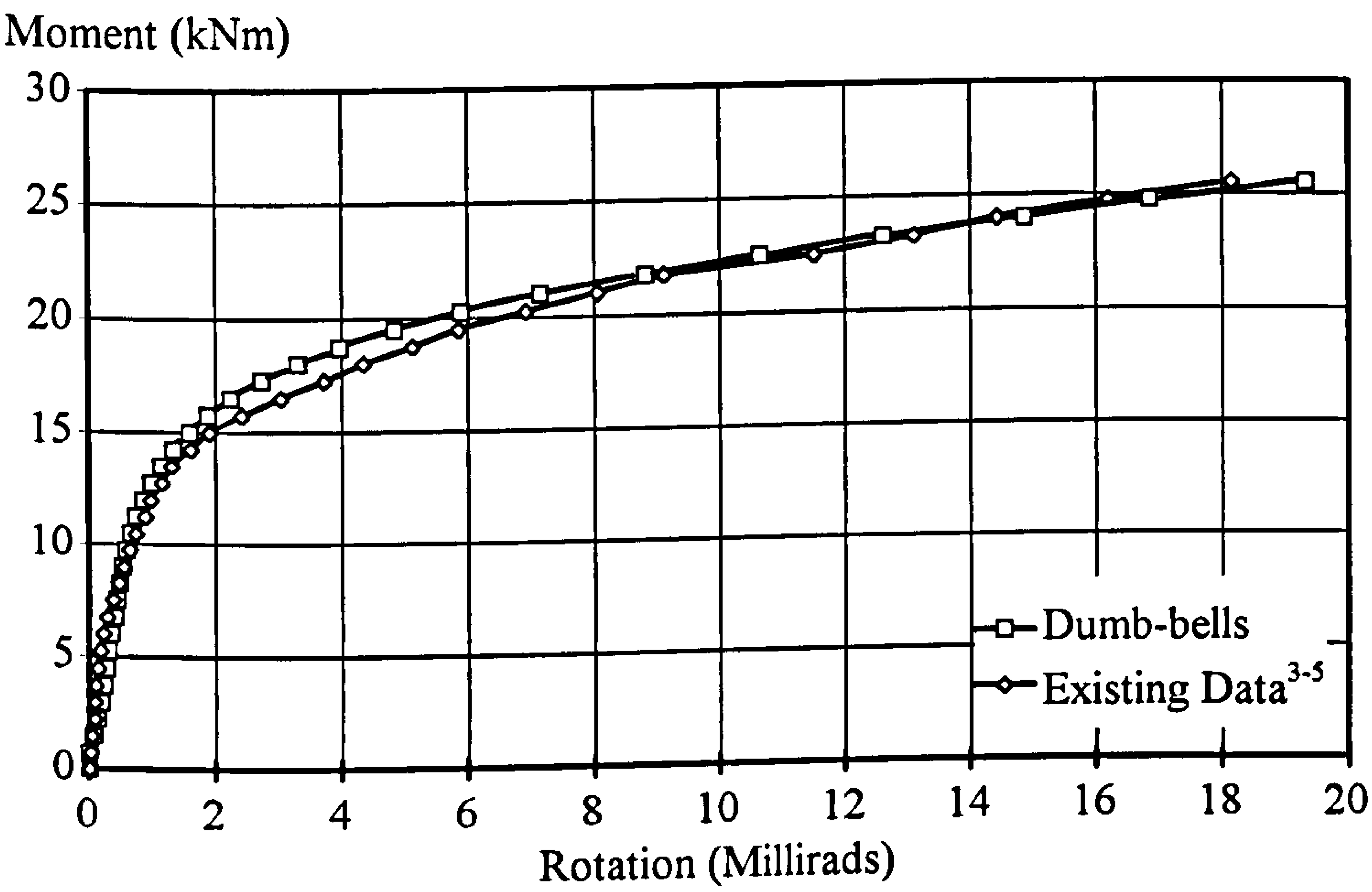


Figure 3.7. Comparison of Connection Response with Existing Data

There was no sign of slip at the column interface in the tests conducted by Davison, despite efforts to centralise the bolts by inserting circular bars of 18mm diameter into the bolt holes whilst the bolts were tightened. It was suggested that this was due to the clamping force developed by the level of torque applied to the bolts. In the case of the test presented above, bolts were tightened to an equal level of torque, and were subject to a reduced shear force as the lever arm to the point where beams were restrained was increased. As such, it would seem unlikely that slip would be experienced in the test conducted.

A similar minor-axis arrangement was also tested by Davison, with the beams framing into the column web. This resulted in a connection of far enhanced stiffness, as would be anticipated due to the removal of column flange and web flexibility. Failure in this case occurred as a result of weld failure and bolt stripping. The minor axis arrangement was capable of resisting moments in the region of 50kNm.

3.2.2. Elevated-Temperature Tests

To derive a complete set of moment-rotation curves at elevated-temperatures it is necessary to carry out a series of tests. It is possible to determine the elevated-temperature behaviour by conducting tests similar to that described above, at varying levels of constant temperature. However, it was decided to conduct connection tests under constant moment, but with similarly increasing temperatures. It is difficult to maintain a desired temperature distribution representative of real situations over a period of time, due to heat conduction within the steel. In addition, the regime of constant-load with increasing temperature is much more representative of the conditions that occur in most building fires, in which temperature distributions in the steel are simply those caused by a progressively growing fire. The basic form of data from such tests is as temperatures and corresponding rotations, which may be translated to generate a family of moment-rotation curves across a range of constant temperatures.

3.2.2.1. Test Arrangement

Following a feasibility study[68] into the potential use of a wrap-around, high-temperature portable test facility, a number of furnace modules were manufactured for the Building Research Establishment by Hotwork Development Ltd. of Dewsbury in 1992. The facility consists of four 'barrel' modules suitable for testing beams or columns, and a junction furnace designed for testing connections within a two- or three-dimensional framework. The various modules may be connected together, allowing the testing of an arrangement of beams and columns, along with the corresponding connection. The furnaces use natural gas, employing a system of tangential firing in which a high-velocity burner is fired into a circular chamber to induce a circulating gas flow pattern, promoting good gas mixing and temperature uniformity. The use of ceramic fibre lining gives rapid heating times and results in a lightweight construction that can be handled with relative ease. The basic layout of the furnace is shown in Fig. 3.8. A more detailed description of the capacity and limitations of the system may be found in Ref.: 68. This particular programme was the first in which the junction furnace had been used, although the barrel furnaces had been used previously for testing columns in a full-scale building[69,70].

The cruciform sub-assemblage was located within the junction furnace, with beams and columns projecting approximately 600mm through specially prepared plates. The column was firmly fixed at its base and secured in position at its head whilst allowing free thermal expansion. Monolux fibre-board doors were positioned at the point where the beams protruded from the furnace, allowing for vertical displacement. The elevated-temperature test arrangement is illustrated in Figs. 3.9 and 3.10.

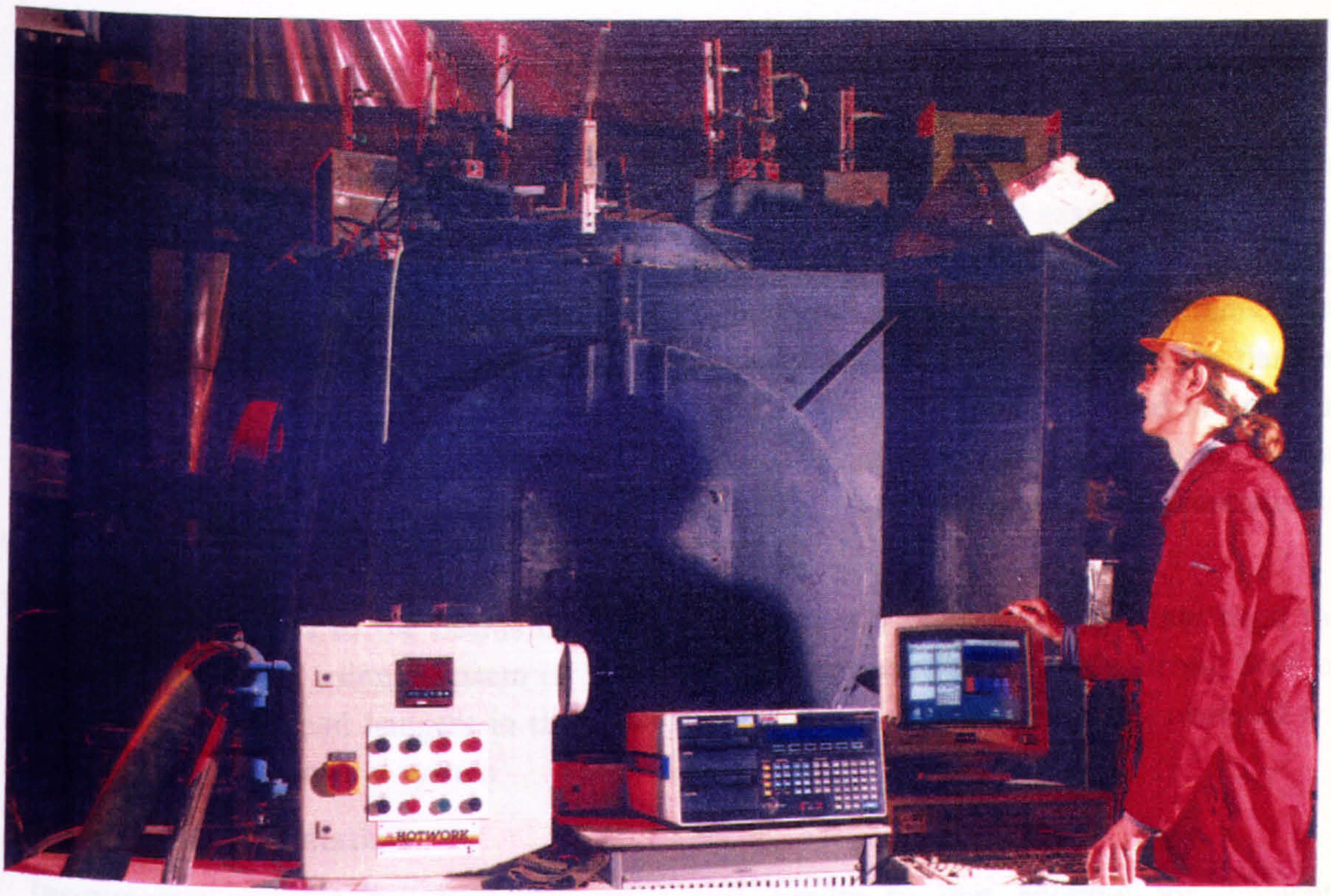


Figure 3.9. Elevated-Temperature Connection Test

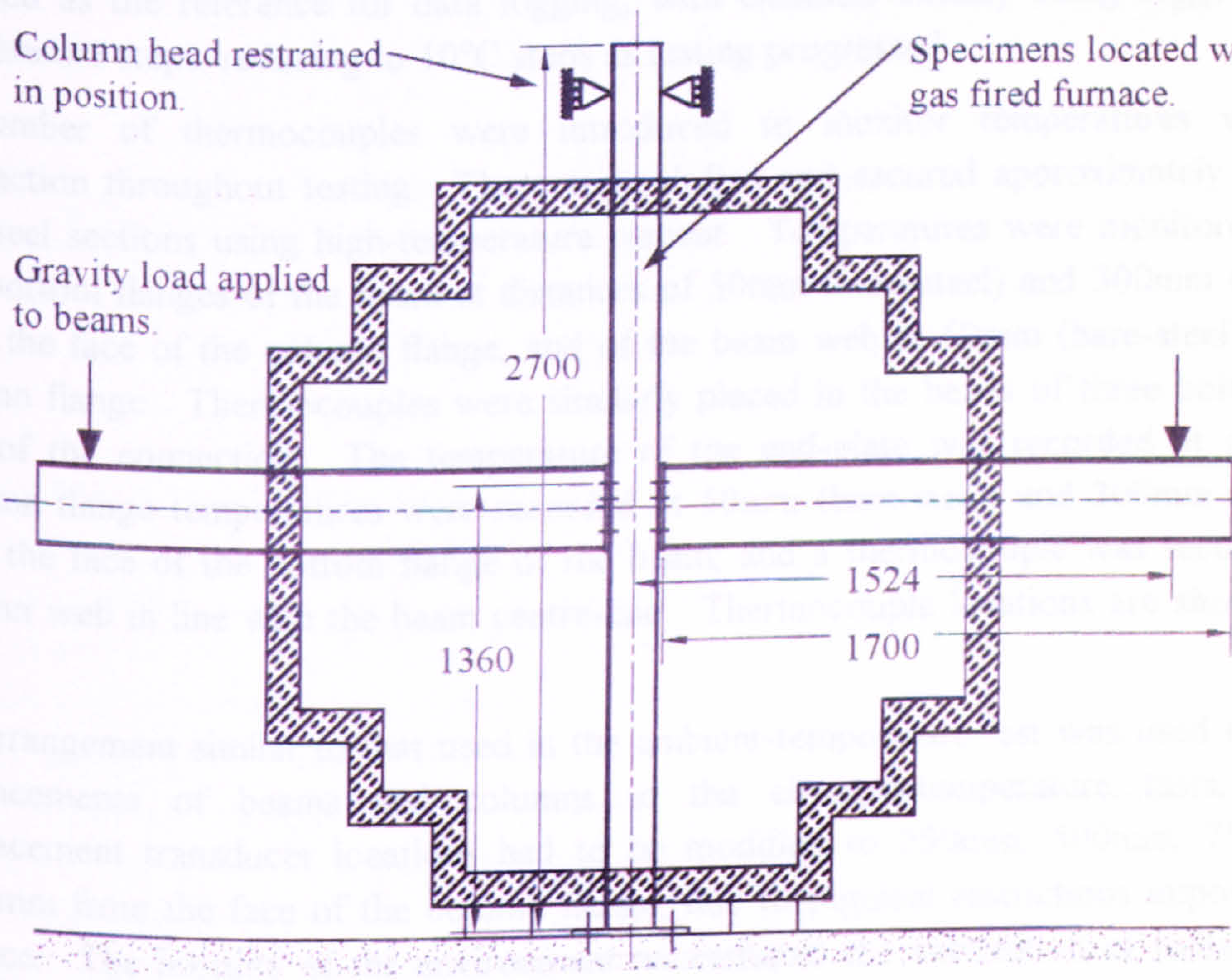


Figure 3.10. Elevated-Temperature Test Arrangement

The original intention was that the beams should support a 130mm thick non-composite concrete slab to create a temperature distribution across the connection representative of realistic conditions. Preliminary testing carried out using ceramic fibre insulation, at modest temperatures, showed that a realistic temperature profile could be achieved through the use of a 50mm thick ceramic fibre blanket wrapped around the top flanges of the beams, and secured in place with ceramic rope. This was not only easier to fix but also avoided any ambiguity associated with possible interaction at the beam-slab interface. Beams and column sections remote from the connection were protected using ceramic fibre blocks located between opposite flanges and ceramic blanket wrapped around the flanges, to reduce the possibility of premature failure of the sections, as had occurred in previous testing by Lawson[44]. Column sections, and lower flanges and webs of beams within approximately 100mm from the face of the connection, were left exposed as illustrated in Fig. 3.11.

Loads were applied to the beams outside the furnace at a distance of 1524mm from the column centre-line, using a system of Macalloy bars connected through the strong floor of the laboratory to load hangers in the basement. The use of gravity loading obviated the need for any load control system.

3.2.2.2. Instrumentation

Instrumentation used for data acquisition was similar to that adopted for ambient-temperature testing, with some alterations due to the hostility of the environment and the need to record temperature distributions. The exposed column flange temperature was selected as the reference for data logging, with channels initially being logged at 25°C temperature steps, reducing to 10°C steps as testing progressed.

A number of thermocouples were introduced to monitor temperatures within the connection throughout testing. These were drilled and secured approximately 5mm into the steel sections using high-temperature cement. Temperatures were monitored for top and bottom flanges of the beam at distances of 50mm (bare-steel) and 300mm (insulated) from the face of the column flange, and of the beam web at 50mm (bare-steel) from the column flange. Thermocouples were similarly placed in the heads of three bolts on each side of the connection. The temperature of the end-plate was recorded at mid-depth. Column flange temperatures were recorded at 50mm (bare-steel) and 300mm (insulated) from the face of the bottom flange of the beam, and a thermocouple was secured to the column web in line with the beam centre-line. Thermocouple locations are shown in Fig. 3.11.

An arrangement similar to that used in the ambient-temperature test was used to monitor displacements of beams and columns in the elevated-temperature tests, although displacement transducer locations had to be modified to 250mm, 500mm, 750mm and 1300mm from the face of the column flange, due to physical restrictions imposed by the furnace. The hostility of the environment necessitated the connection of transducers via silica rods, passing through holes in the top of the furnace and cemented to the top face of the beam flange using high-temperature cement. The rate of thermal conductivity and low thermal expansion of silica allows direct reading of displacements, rates of thermal expansion being in the region of $2.5 \times 10^{-6}/°C$, compared to an approximate value of 14x

$10^{-6}/°C$ for steel; suggesting a maximum error from reliance on displacement readings of approximately 1 millirad as the connection approached failure, with this value being far less in the elastic region. Displacement transducers were located at three positions along the length of each beam within the furnace, along with a single transducer on the beam outside the furnace. Additional displacement transducers were attached to the column head, recording the rate of expansion. Calibrated compression load cells were used to measure loads applied to the beams throughout the elevated-temperature testing.

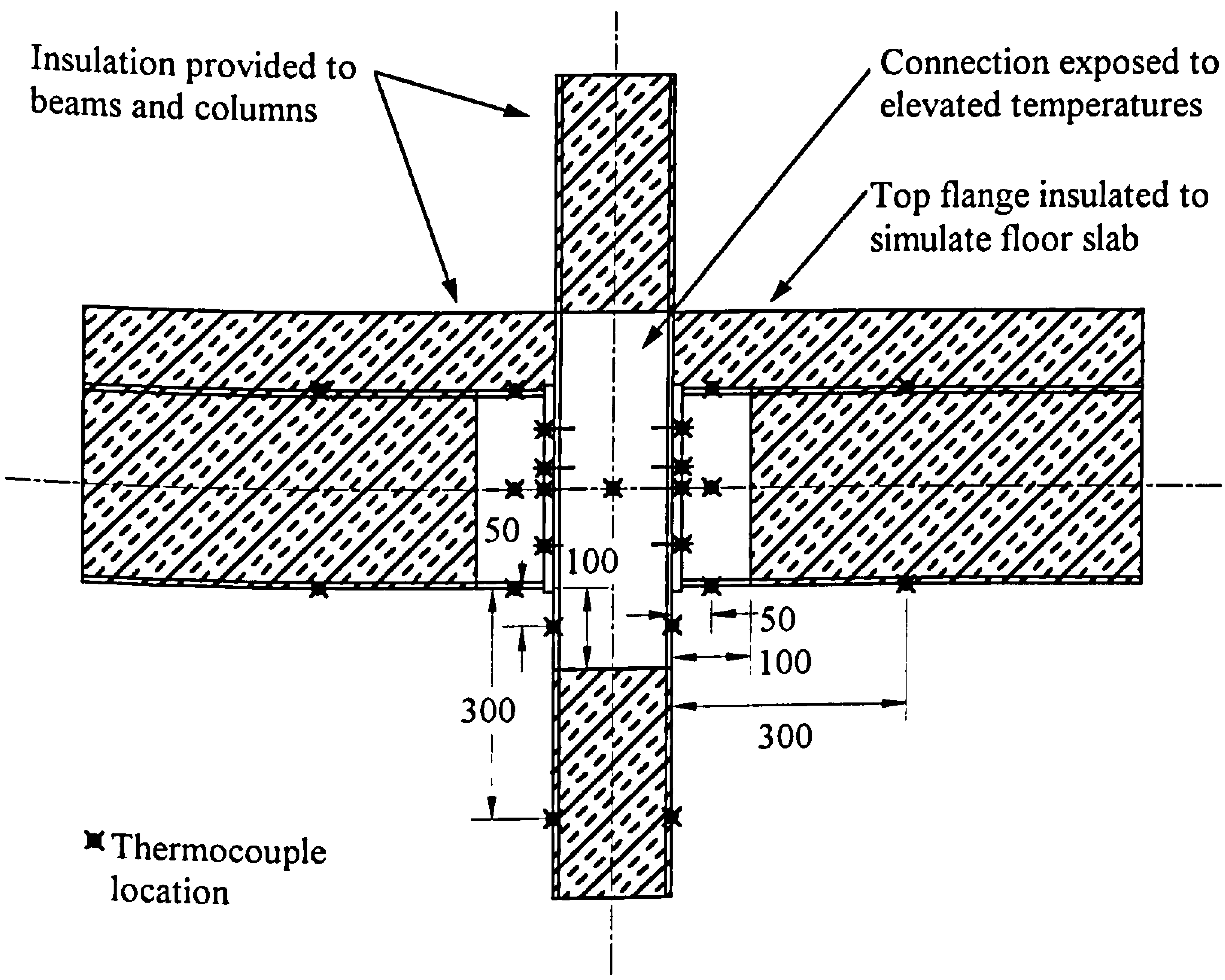


Figure 3.11. Thermocouple Locations

Direct measurement of connection rotation within the furnace initially posed a problem due to the high temperatures involved. Suggested remedies included reliance on displacement transducers alone, optical devices, and rigid arms extending outside the furnace, but none of these proved practicable. The final solution involved the use of clinometers previously used for ambient-temperature testing, in addition to displacement readings. The maximum operating temperature of the clinometers was approximately 70°C. To maintain such low temperatures within the furnace clinometers were situated within a high-temperature housing insulated with ceramic fibre, and cooled by a flow of compressed air fed from outside the furnace. Cables connected to the clinometers were capable of resisting temperatures up to approximately 700°C, and additional protection was provided using ceramic fibre. Clinometers were located at the mid-depth of the beam web, 250mm from the column face. Due to the anticipated degree of column deformation, and the need to avoid insulation in the region of the connection, it was impracticable to locate a rotation device along the centre-line of the column. Beam rotations were therefore assessed based on the average of the two readings where possible.

3.2.2.3. Results

Before conducting the first elevated-temperature test several trial runs were undertaken on unloaded specimens up to temperatures of approximately 300°C to determine an appropriate time-temperature regime to produce a realistic temperature distribution. Subsequently it was decided to program the furnace to follow a linear steel heating rate of 10°C per minute. In addition to the influence of the rate of heating on temperature gradients, the behaviour of steel at high temperatures is affected by the rate of heating due to the effects of thermal creep. BS5950: Part 8[3] suggests practical rates of heating for steel sections within the range of 5°C/minute (for well insulated sections) to 20°C/minute (for poorly insulated sections); clearly the selected rate of heating is within the range described as being 'practical'. The specified rate of heating was used for all subsequent tests, the control temperature being that of the exposed column flange. The average temperature profile for all five tests is shown in Table 3.2 as a proportion of the beam lower flange temperature, which has been selected as the reference temperature for all information presented, corresponding with typical design assumptions. It was observed that very little deviation from this profile occurred during testing or between any of the tests[71].

As previously described, a series of five elevated-temperature tests was conducted under constant moment with increasing temperatures, to describe the connection characteristics across a realistic range of temperatures. Individual tests are described below.

3.2.2.3.1. Bare-Steel Connection Fire Test 1 (BFEP 5)

The first fire test was conducted at a comparatively low load level, corresponding to a moment at the connection of approximately 5kNm. The use of low levels of load for initial testing allowed familiarisation with the test arrangement, whilst providing information on the degradation of connection stiffness with increasing temperatures. The response of the connection is summarised in Fig. 3.13. The connection was capable of resisting temperatures up to approximately 600°C whilst undergoing negligible deformation. This was followed by a curved knee in the response between temperatures of 600°C and 700°C, indicating plastification of one or more elements within the connection; it is not possible to comment on the form of deformation of the connection during testing as there was no facility to view the specimen until after the termination of the test. At temperatures above 700°C the rate of rotation increased rapidly, resulting in a plateau in the connection response.

The observed connection failure mechanism is illustrated in Fig. 3.12. As with the ambient-temperature connection, it may be seen that there was significant deformation of the column web in the compression zone and the column flange in the tension zone, whilst there was little damage to either the beams or the end-plate.

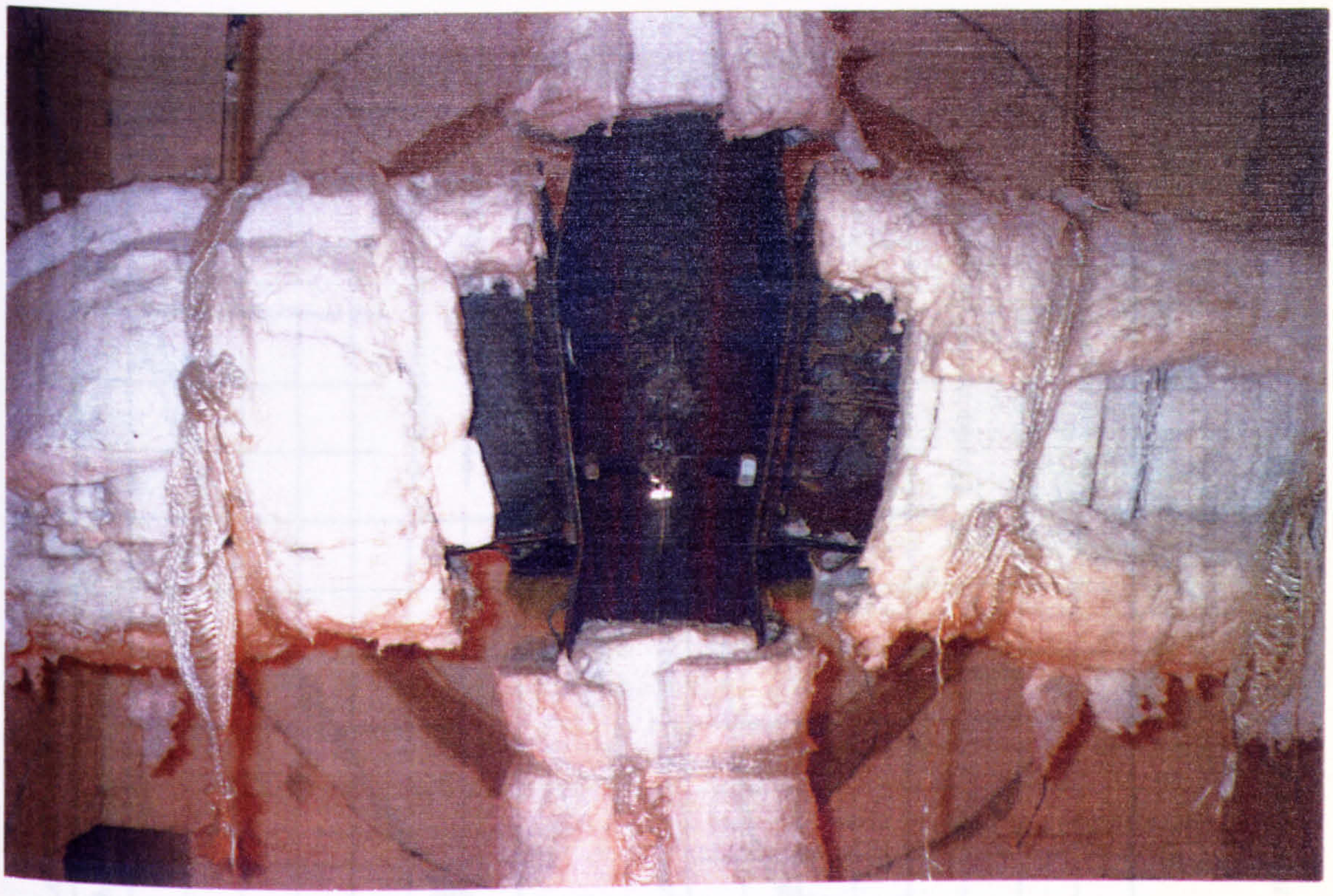


Figure 3.12. Elevated-Temperature Connection Failure Mechanism

Recorded temperature distributions are summarised for all tests in Table 3.2. There was negligible variation between temperature profiles recorded for the East and West sides of the connection, despite the burner being located on the West side of the arrangement, indicating that the use of a tangential burner induces sufficient gas mixing to provide uniform temperature distribution throughout the furnace. An almost constant temperature gradient was maintained throughout the duration of the test. Clinometers reached a maximum temperature of approximately 100°C, above their maximum operating temperature, without resulting in failure. Subsequent to the termination of the test, the temperature of the housing continued to increase, due to the effects of thermal conduction, despite atmospheric and exposed steel temperatures reducing, resulting in the eventual destruction of the clinometer devices. Hence, in all subsequent tests, furnace doors were removed immediately after testing, and the furnace was cooled by a flow of compressed air to induce as rapid a reduction in furnace temperature as was practicable.

It may be seen from fig. 3.13 that a consistent moment was maintained for the East beam up to temperatures of approximately 600°C, whilst there was a gradual reduction in the moment recorded for the West beam, despite equal loading being applied to both beams in the form of dead load. It is possible that the reduction in moment recorded for the East beam occurred as a result of friction as the Macalloy bars passed through small holes in the loading floor. At temperatures in excess of 600°C recorded moments became variable for both beams. This occurred as load cells located at the point of loading for each beam were not fitted with ball seatings, resulting in inaccurate readings with increasing rotations, due to the angle of bearing of the loads on the load cells. As dead load was adopted for the bare-steel connection tests, confidence is maintained in the actual force applied to the

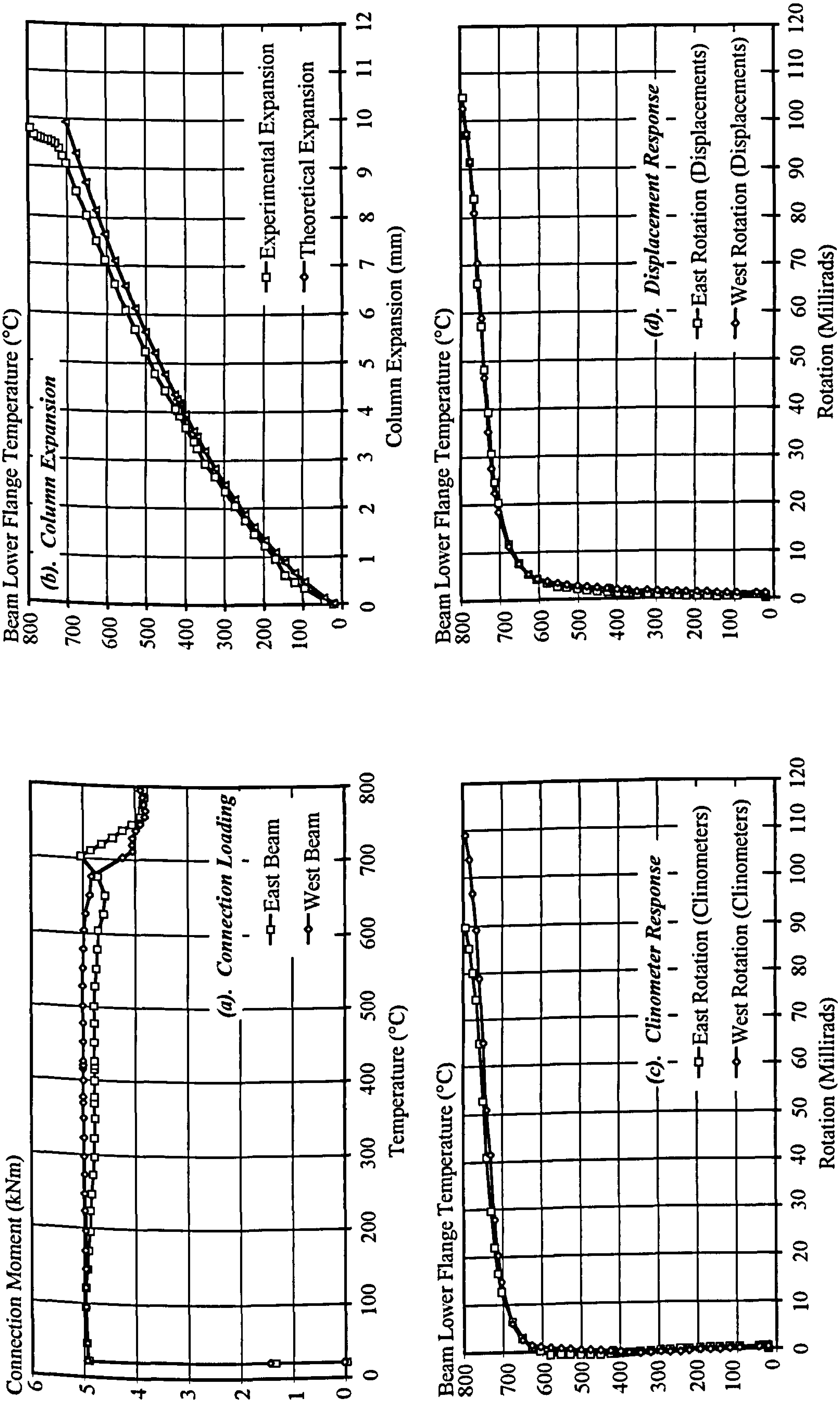


Figure 3.13. Summary of Results from Bare-Steel Connection Fire Test 1 (BFEP 5)

beams. The average connection moment was observed to be approximately 4.9kNm, corresponding closely with the desired value of 5kNm.

Location:	BFEP 5:	BFEP 10:	BFEP 15:	BFEP 20:	BFEP 25:	Average:
Beam Lower Flange	1.000	1.000	1.000	1.000	1.000	1.000
Beam Centre Web	0.971	1.026	0.973	0.972	0.983	0.985
Beam Top Flange	0.685	0.699	0.685	0.647	0.668	0.677
Beam Lower Flange *	0.293	0.238	0.242	0.256	0.290	0.264
Beam Top Flange *	0.291	0.264	0.246	0.280	0.260	0.268
Lower Bolt	0.954	1.037	0.983	0.972	0.988	0.987
Middle Bolt	0.930	1.014	0.974	0.946	0.965	0.966
Top Bolt	0.875	0.967	0.946	0.924	0.926	0.928
Column Web	1.066	1.180	1.150	1.133	1.188	1.143
Column Flange	0.998	1.095	1.022	1.057	1.008	1.036
Column Flange *	0.305	0.332	0.343	0.339	0.296	0.323
End-plate	0.929	1.023	1.010	0.964	0.986	0.982
Clinometer	0.121	0.102	0.129	0.207	0.104	0.133
Furnace Atmosphere	-	0.715	0.690	0.691	0.691	0.697

Note: * identifies insulated thermocouple locations.

Table 3.2. Average Relative Temperature Profiles for Bare-Steel Connection

Experimental column expansion is illustrated in Fig. 3.13(b), and compared with that predicted theoretically by the equations describing thermal expansion of steel presented in Chapter 2. Theoretical column expansion was calculated accounting for the lengths of column exposed or protected, and the relative temperatures of these as recorded by thermocouples, resulting in a close correlation between predicted and actual values for column expansion. As connections yielded, there was a reduction in the rate of column expansion. It is suggested that the reasons for this are twofold; firstly this response is observed at temperatures between 700°C and 800°C, corresponding with the plateau in steel expansion due to its phase-change, and secondly due to the yielding of the column resulting in a reduction in overall length.

Rotations recorded for the East and West connections by clinometer devices are compared in Fig. 3.13(c). These compare well as temperatures increase, although the West connection may be seen to be rotating at a greater rate than the East at high temperatures, possibly due to the enhanced level of loading recorded for the West beam. At intermediate temperatures small negative rotations were observed relative to the position at ambient-temperature. It was felt that this might be attributable to thermal bowing of the beam with increasing temperatures, due to differential rates of thermal expansion of the upper and lower beam flanges, causing a reversal in the rotation of clinometer devices. The maximum anticipated rotations from the effects of thermal bowing were calculated to be in the region of 0.5 to 1.0 millirad, at a beam lower flange temperature of 600°C. This was assessed based on the proportion of the steel exposed, and the relative temperatures of the upper and lower beam flanges. The influence of thermal bowing has been neglected, due to the uncertainty regarding the proportions of deformation occurring as a result of thermal bowing and as a result of the loading of beams, and the limited influence that this would be expected to have.

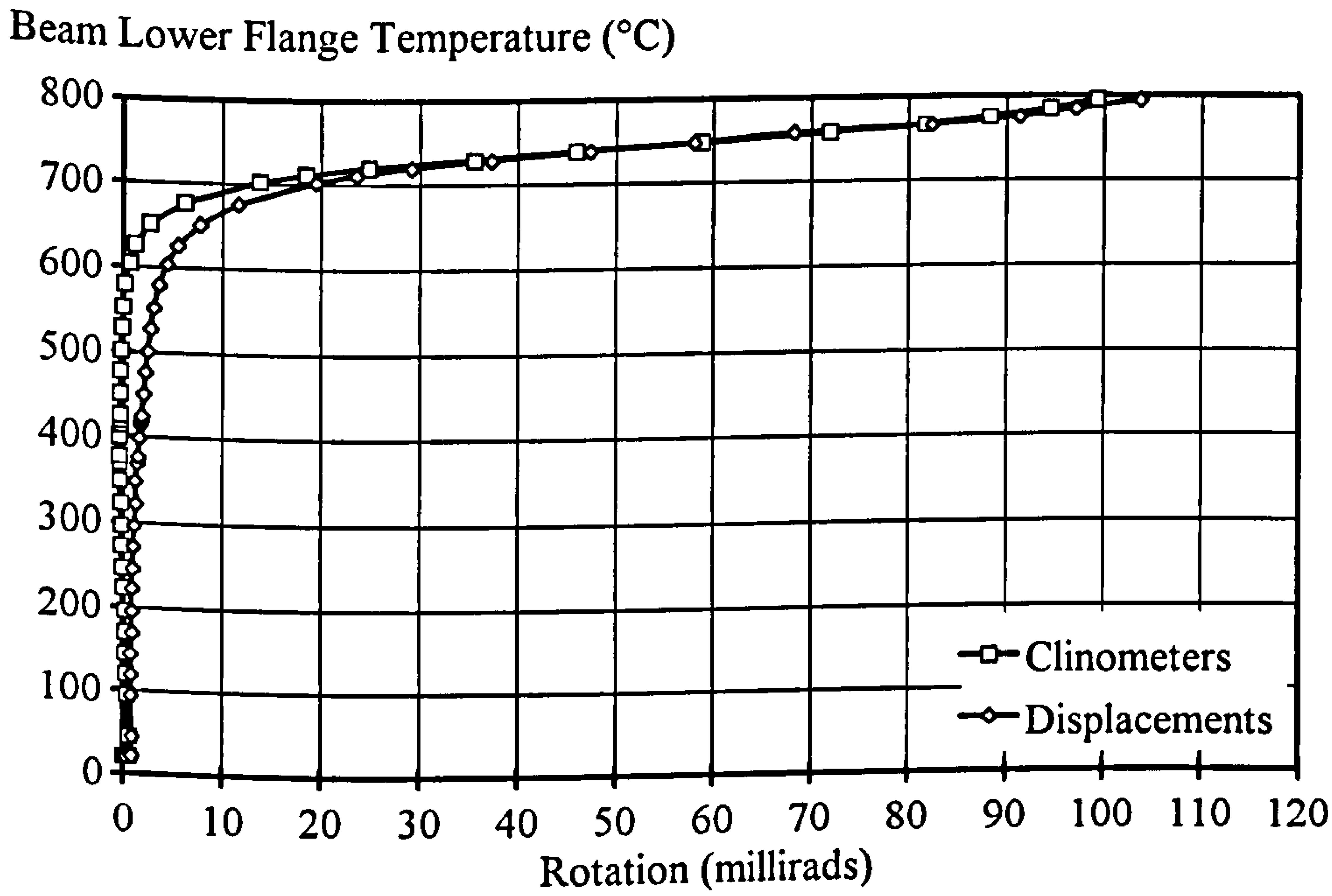


Figure 3.14. Comparison of Results from Test BFEP 5

Rotations obtained from displacement readings are illustrated in Fig. 3.13(d). To obtain relative beam displacements it was necessary to deduct the element of displacement occurring as a result of column expansion. Column expansion was calculated based on the proportions of the column that were exposed and protected, and their relative temperatures. This value was then calibrated against the actual column expansion, and a prediction made of the expansion at the top face of the beam, corresponding with the location of the displacement transducers. Once more rotations for East and West beams compare closely. Examination of recorded displacements along the length of each beam once more suggest an undeformed shape, despite the influence of elevated-temperatures. This illustrates the necessity to protect the arrangement remote from the connection from increasing temperatures, as elevated-temperature tests previously conducted by Lawson[44] had to be terminated before the connection had undergone significant rotation due to beam failure. There was no sign of slip at the connection interface. This was anticipated, as it was believed that the connection was bearing on the bolts when fabricated, as is typical of site practice.

Average rotations recorded by clinometers and displacement transducers are compared in Fig. 3.14. It may be seen that while there is an acceptable correlation between the rotations predicted by both devices, the use of clinometer devices does suggest a slightly stiffer connection. At temperatures in excess of 700°C there is an indiscernible difference between recorded rotations.

3.2.2.3.2. Bare-Steel Connection Fire Test 2 (BFEP 10)

The second fire test was conducted under an increased moment of 10kNm, and its results are summarised in Fig. 3.15. Failure of the connection was similar to that observed in both the ambient-temperature connection test and the first fire test. The connection withstood temperatures of approximately 500°C with little deformation, followed by a knee in the rotation-temperature response, levelling out at temperatures in excess of 600°C.

Once more there was negligible variation in temperature distribution throughout the test, and also between the East and West beams. It may be seen that the atmosphere temperature was recorded as approximately 70% of the beam lower flange temperature, which is highly illogical. However, the thermocouple recording atmosphere temperature was located in one corner of the furnace, and was subject to a degree of shielding from the ceramic lining, which results in an inaccurate representation of the actual atmospheric temperature.

There was a slight reduction in the level of moment applied to both beams with increasing temperatures, with the West beam being subject to a lower moment throughout testing. The average moment applied to the connections was recorded as approximately 9.3kNm.

Column expansion is shown in Fig. 3.15(b), and can be seen to compare closely to theoretical values. Once more, there was a reversal in the column expansion subsequent to the plastification of the connection, at temperatures of approximately 600°C, indicating that the reversal in column expansion occurs as a result of progressive yielding of the column web, rather than changes in the rate of thermal expansion for steel at temperatures in the range of 750°C to 860°C.

Rotations recorded by clinometer devices show a reduction in the stiffness and capacity of the connection compared with the first fire test, due to the increased moment. There is an indiscernible difference between rotations recorded for the East and West beams. Displacement readings indicate a stiffer connection response than the first test, despite the increase in loading. Once more, displacement readings suggest that no slip occurred at the connection interface, and that the beam remained relatively undeformed along its length.

Rotations recorded by clinometers and displacement transducers are compared in Fig. 3.16. Once more both devices are seen to predict a similar response, although in this case displacement readings suggest a stiffer connection than the corresponding readings of direct rotation. This is contrary to the response observed in the first elevated-temperature connection test, and suggests that it is attributable to inherent inaccuracies in the test

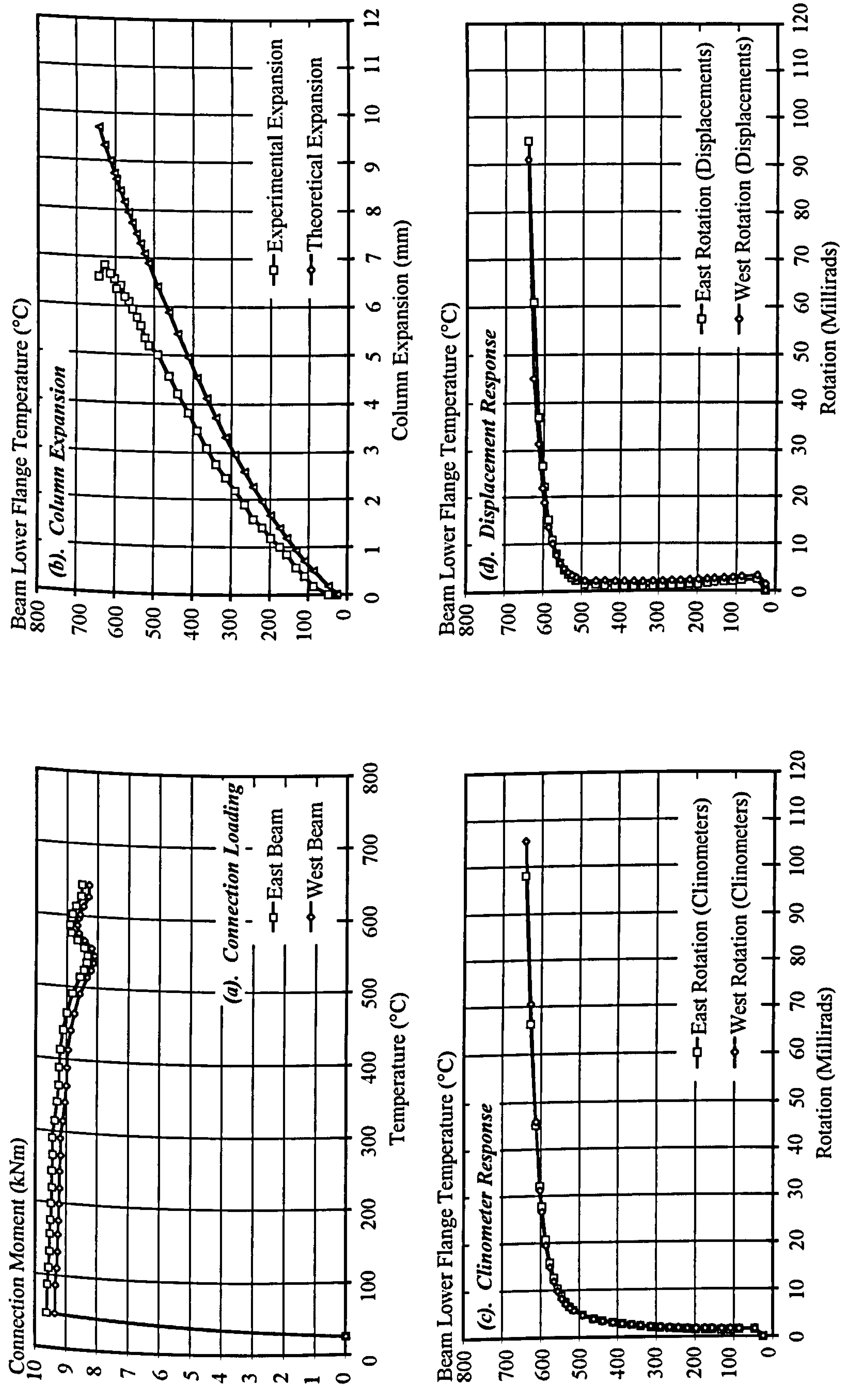


Figure 3.15. Summary of Results from Bare-Steel Connection Fire Test 2 (BFEP 10)

arrangement, and the low level of load adopted in the first two tests, rather than possible discrepancies in the form of instrumentation adopted.

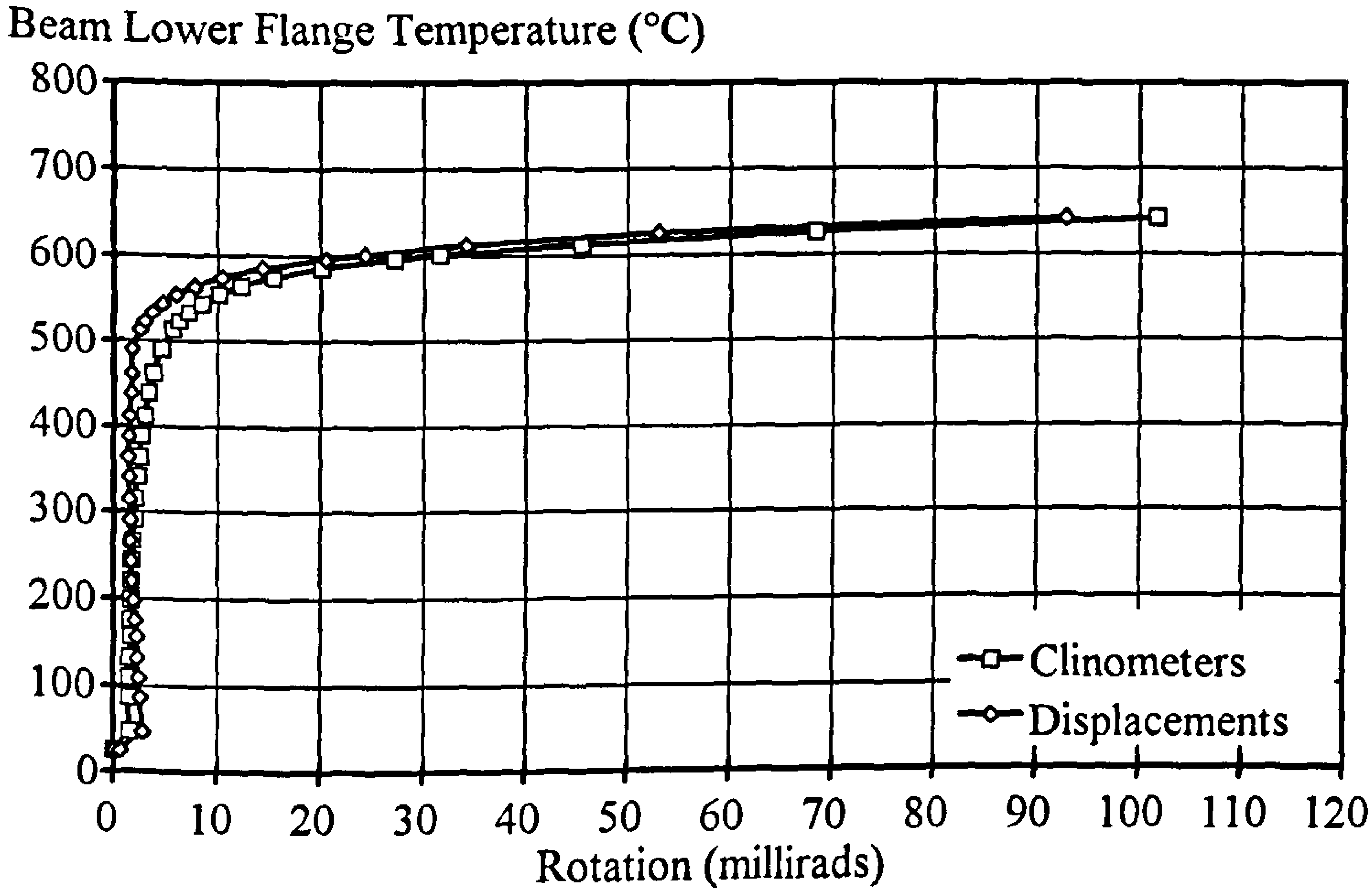


Figure 3.16. Comparison of Results from Test BFEP 10

3.2.2.3.3. Bare-Steel Connection Fire Test 3 (BFEP 15)

A third elevated-temperature test was conducted at a nominal moment of 15kNm, corresponding approximately with the moment causing plastification of the connection in ambient-temperature testing. Results from the test are summarised in Fig. 3.17. It may be seen that a consistent load was maintained for both connections, in the region of 14.4kNm.

A more flexible response at lower temperatures was observed than in previous tests. This was expected as plastification of the connection would be anticipated given a small increase in temperature. Once more, the failure mechanism of the connection was similar to that observed previously. There is a very close correlation between theoretical and recorded column expansion, until temperatures approaching 600°C, after which there is a reversal in column expansion.

Rotations recorded by the East clinometer are shown in Fig. 3.17(c). No results are presented for the West clinometer as this produced erratic results throughout the test. Rotations obtained from displacement readings are shown in Fig. 3.17(d). A similar response is observed for both East and West connections, which provides confidence in the use of the East clinometer reading, without accounting for any possible rotation of the column.

Average rotations obtained from displacement readings are compared with the East clinometer in Fig. 3.18. It may be seen that both devices show a similar response, once more supporting the reliance on direct rotations obtained from the East clinometer, without accounting for the possibility of column rotation.

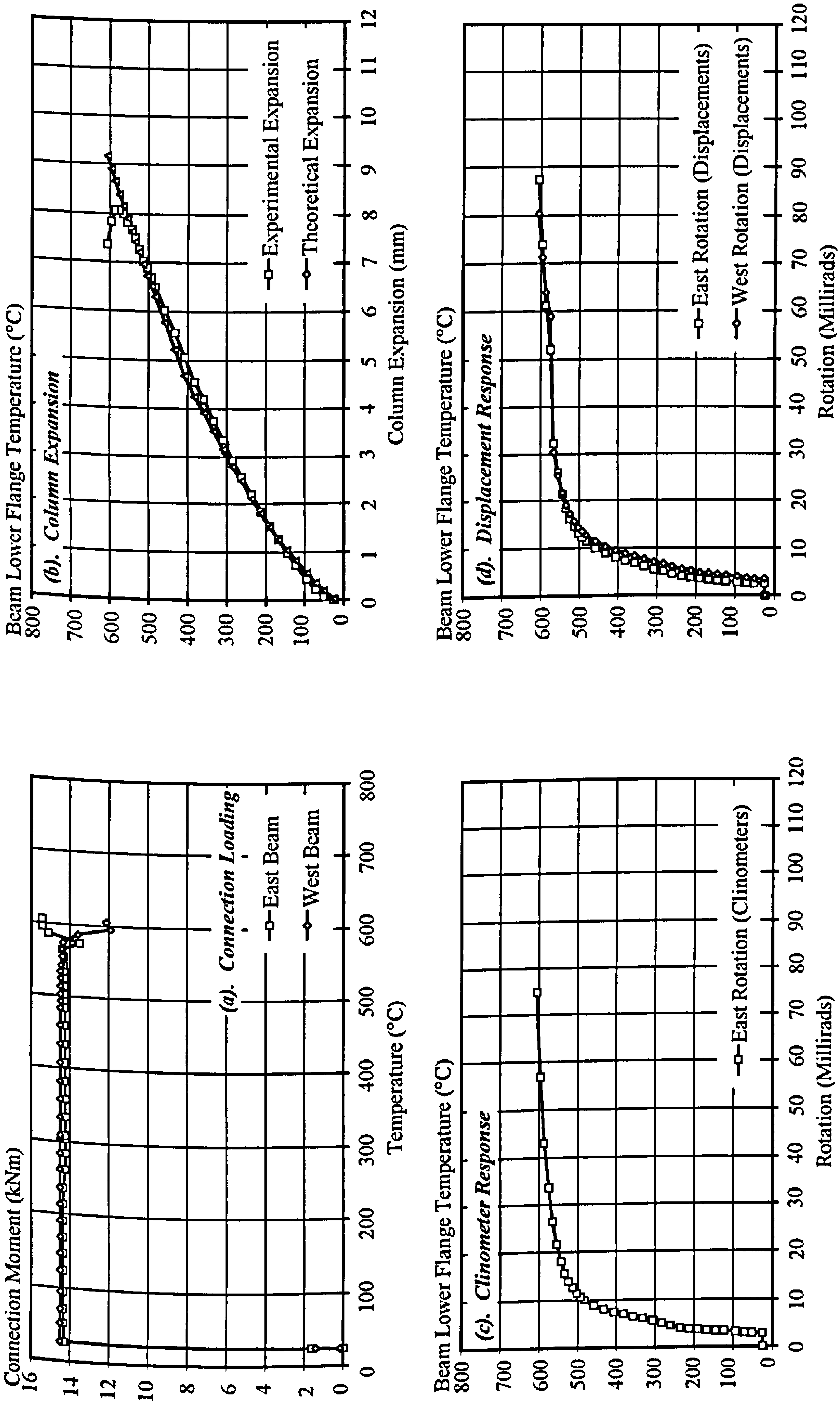


Figure 3.17. Summary of Results from Bare-Steel Connection Fire Test 3 (BFEP 15)

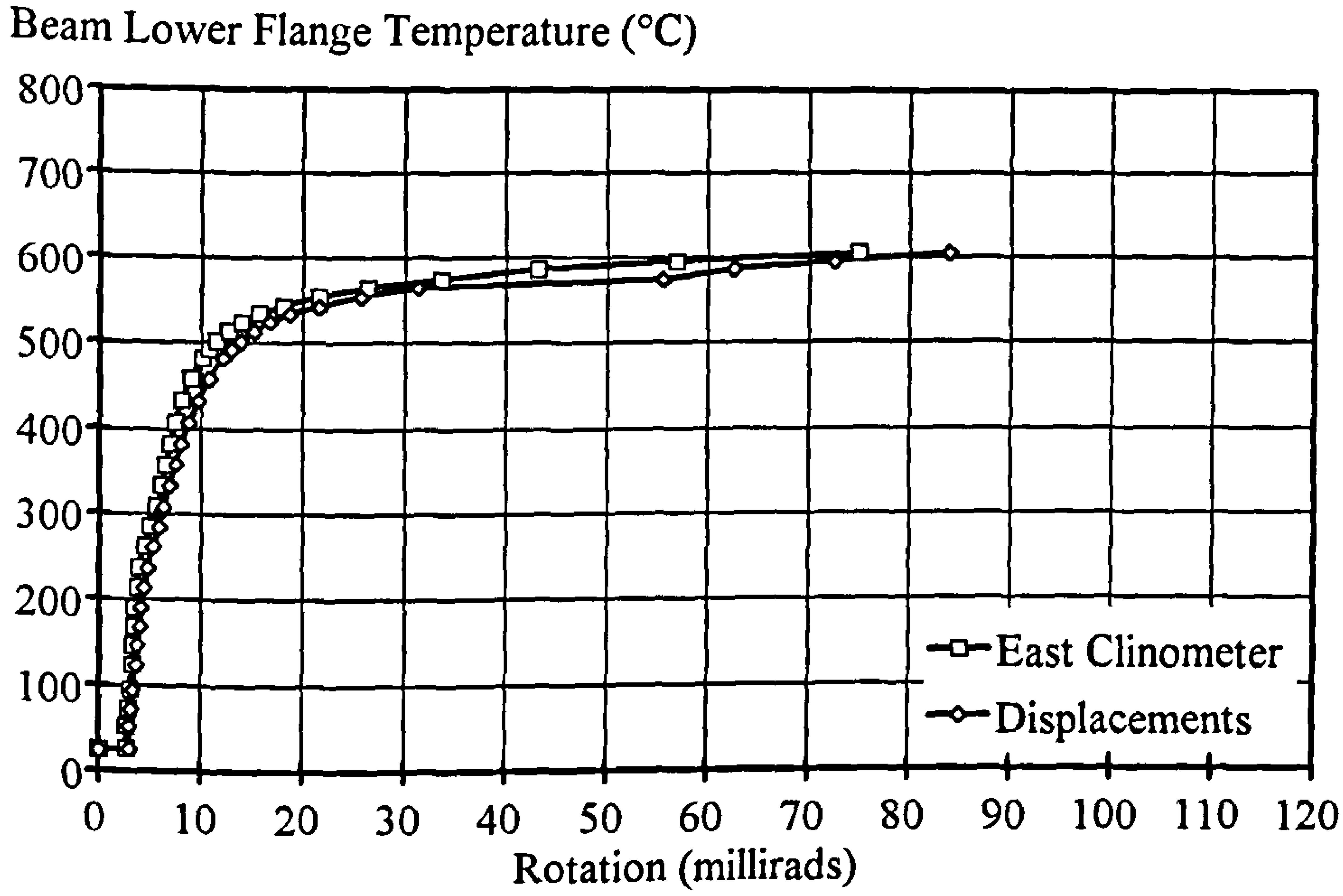


Figure 3.18. Comparison of Results from Test BFEP 15

3.2.2.3.4. Bare-Steel Connection Fire Test 4 (BFEP 20)

The fourth fire test was specified to be conducted at a nominal moment of 20kNm, although actual levels of moment were recorded as approximately 19kNm. Results from the test are summarised in Fig. 3.19. It may be seen that load levels for both East and West beams were similar throughout testing. Column expansion compares well with that predicted. Response of the connection was similar to that observed in the third elevated-temperature test, with the connection demonstrating further flexibility at low temperatures.

It may be seen from Figs. 3.19(c) and 3.19(d) that there was significant difference in the response recorded for the East and West beams, with the West beam indicating greater levels of rotation at ambient-temperatures. This effect was observed as load was applied, and in consequence attempts were made to ensure that the load was applied symmetrically. The removal and re-application of load was seen to have no influence, and so testing continued. A similar response was observed throughout testing, up to the plateau in the rotation-temperature curve, at which point rotations for both beams converged. On opening the furnace it was seen that the nut of the top bolt on the West connection had fractured, as shown in Fig. 3.20. As it was not possible to view the specimen during the test, no comment can be made regarding when this failure occurred. It is conceivable that the nut fractured when the initial load of approximately 20kNm was applied to the connection, which would account for the difference in response recorded for East and West beams, although this seems to be a low force at which to experience such a brittle form of failure, a moment of 19kNm corresponding with a bolt force of approximately 30kN or 40% of the proof load for the bolts adopted.

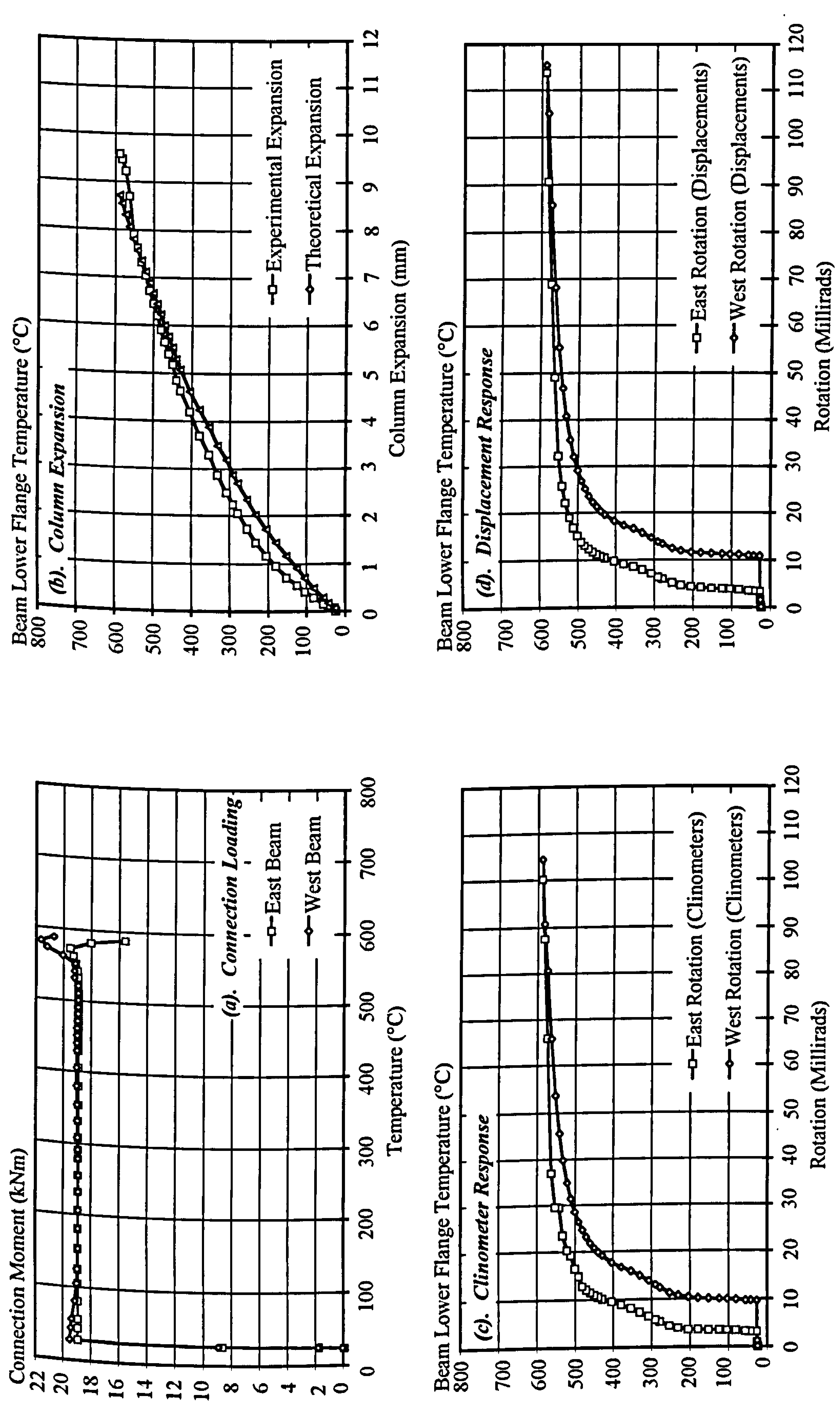


Figure 3.19. Summary of Results from Bare-Steel Connection Fire Test 4 (BFEP 20)

Figure 3.20. Fracture of Nut on West Connection

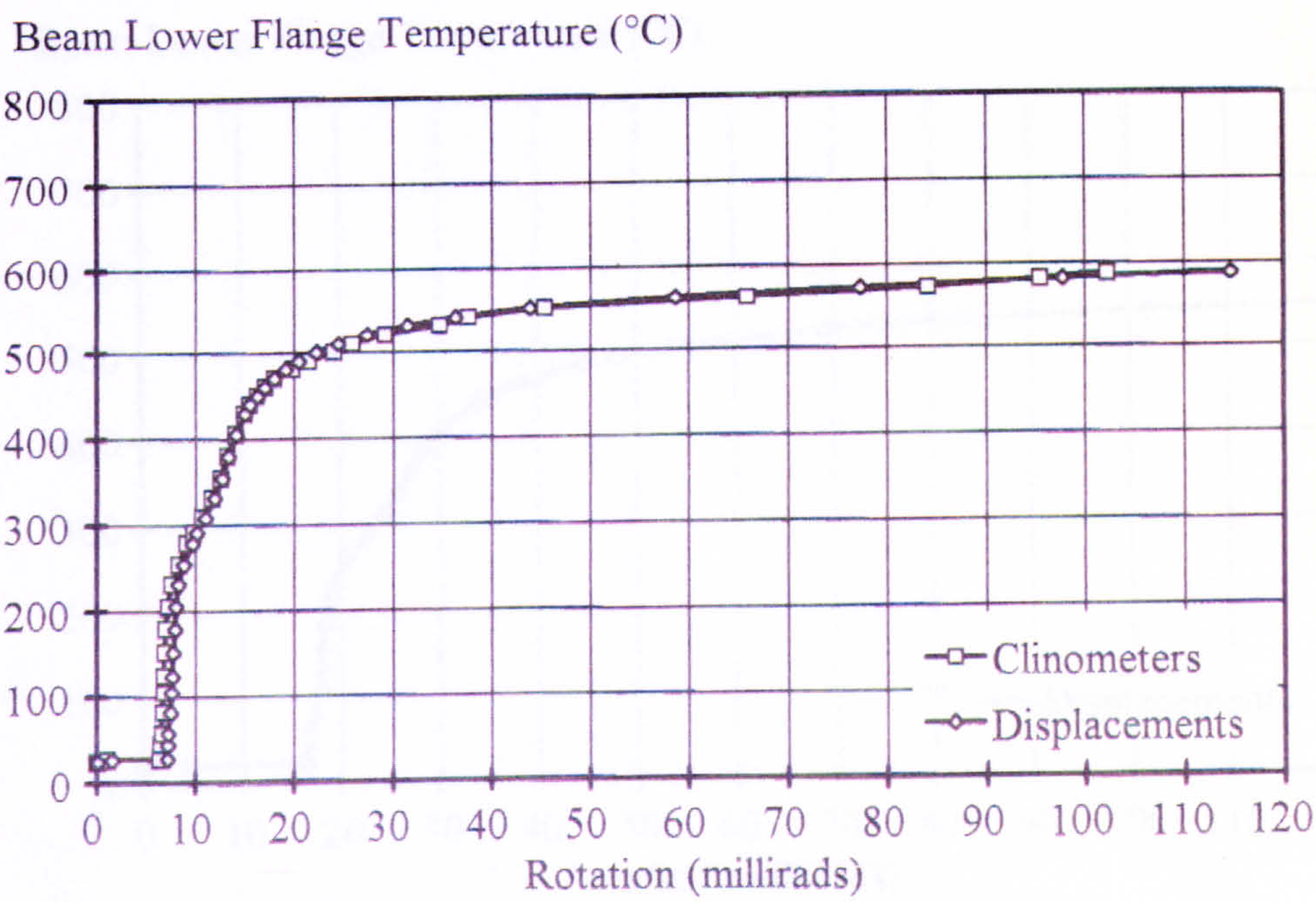


Figure 3.21. Comparison of Results from Test BFEP 20

Average rotations recorded by clinometer devices and displacement readings are compared in Fig. 3.21. It may be seen that there is a close correlation between the response recorded by both devices, despite the difference in the rotations recorded for the East and West beams. This suggests that the difference observed between East and west rotations is not attributable to inaccuracies within the instrumentation.

3.2.2.3.5. Bare-Steel Connection Fire Test 5 (BFEP 25)

A final elevated-temperature test was conducted for a nominal moment of 25kNm, providing information relating more closely to the degradation of connection capacity. Results from the test are summarised in Fig. 3.23. It may be seen that the East beam was subject to a higher load level than the West beam. Once more it is possible that this occurred as a result of friction in the loading arrangement. The average moment applied to the connection was observed to be approximately 23kNm.

Once more there was an increase in the flexibility of the connection at lower temperatures, and a significantly greater rotation of the connection at ambient-temperatures, indicating that the selected load level is within the region of plastic response of the connection at ambient-temperatures. Predicted and actual column expansions compared closely.

Both clinometers gave erratic results throughout testing due to failure of the cabling connecting them to the data logger, and have therefore been disregarded, necessitating reliance on displacement readings. Rotations from displacement readings are presented in Fig. 3.23(d). Once more there is a significant difference between the responses recorded for the East and West beams, with the East beam undergoing greater rotation at ambient-temperatures. Average rotations obtained from displacement readings are presented in Fig. 3.21.

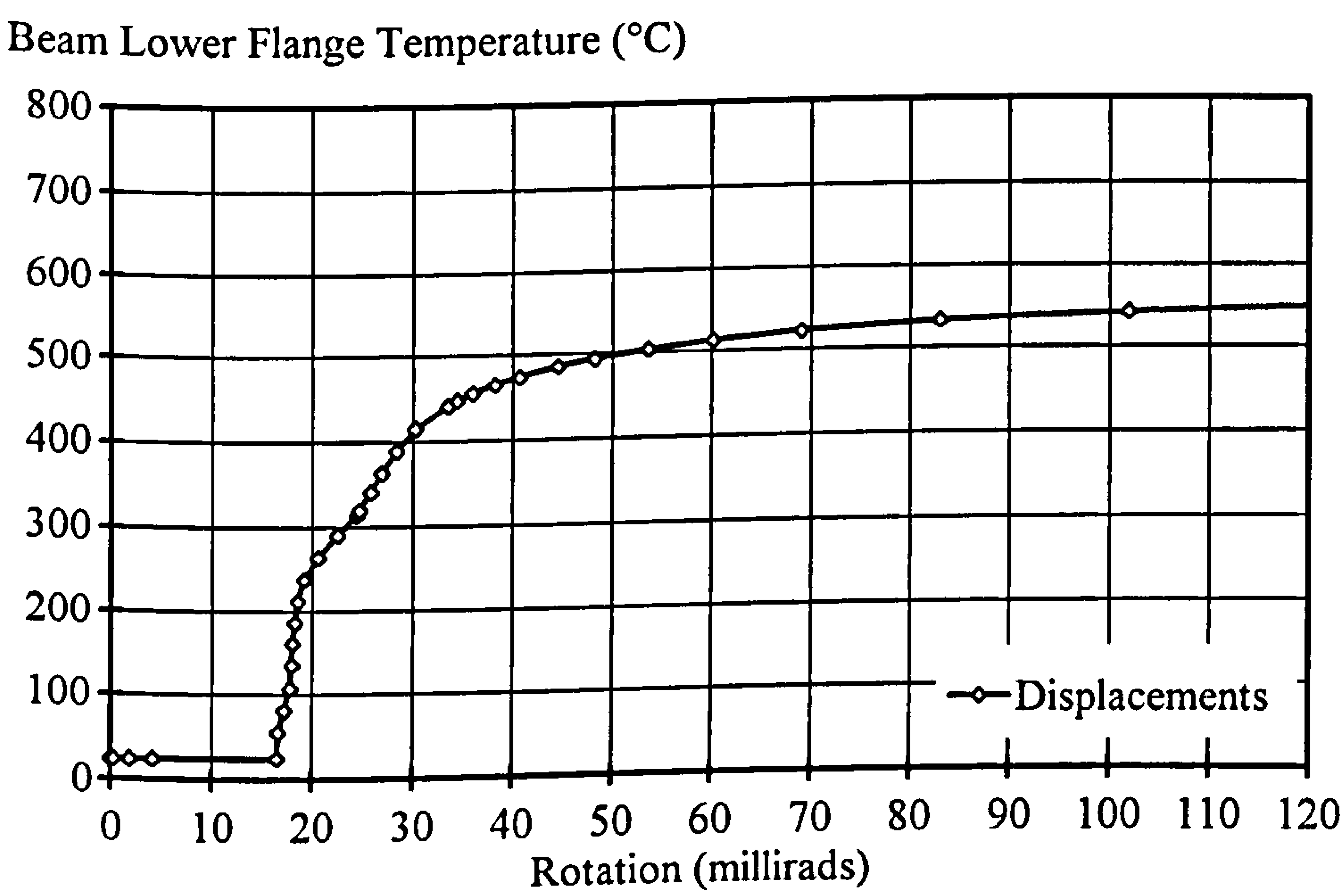


Figure 3.22. Response Recorded by Displacements from Test BFEP 25

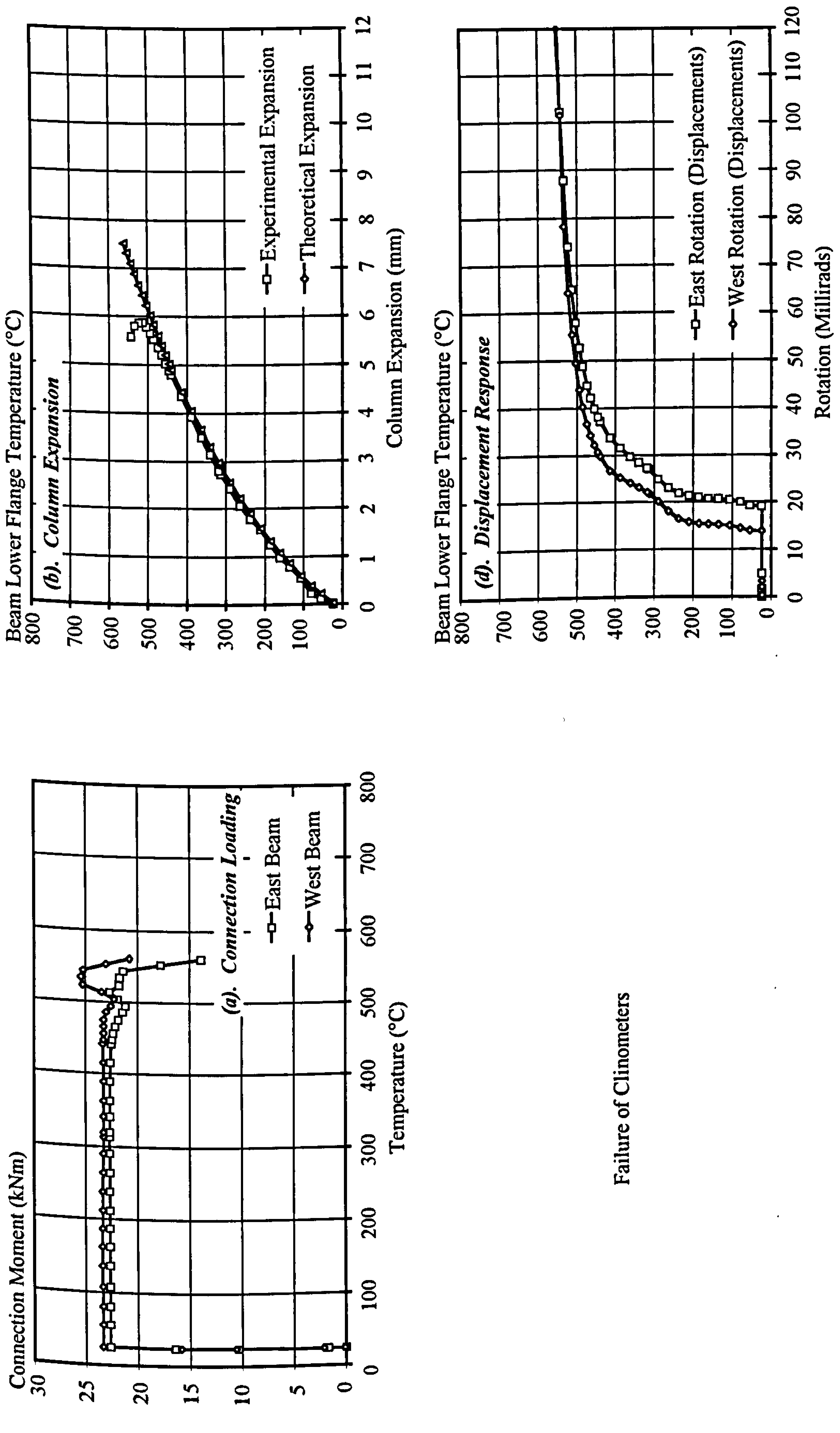


Figure 3.23. Summary of Results from Bare-Steel Connection Fire Test 5 (BFEP 25)

3.2.3. Comparison of Results from Elevated-Temperature Connection Tests

Having defined the temperature-rotation response for the connection at a number of load levels it is possible to define the moment-rotation characteristics for the connection across a range of temperatures. Rotation-temperature responses measured by clinometer devices for the first four tests are compared in Fig. 3.24. These are based on the average of the readings for both connections, so as to account for any rotation of the column, with the exception of the results presented for the third test, in which failure of the West clinometer necessitated reliance on results obtained from the East clinometer without any modification to account for column rotation. Rotations for the final test were based on displacement readings, as the clinometers gave erratic results throughout the duration of the test, due to failure of the connecting cables. The earlier tests had shown displacement readings to correlate closely with clinometer readings.

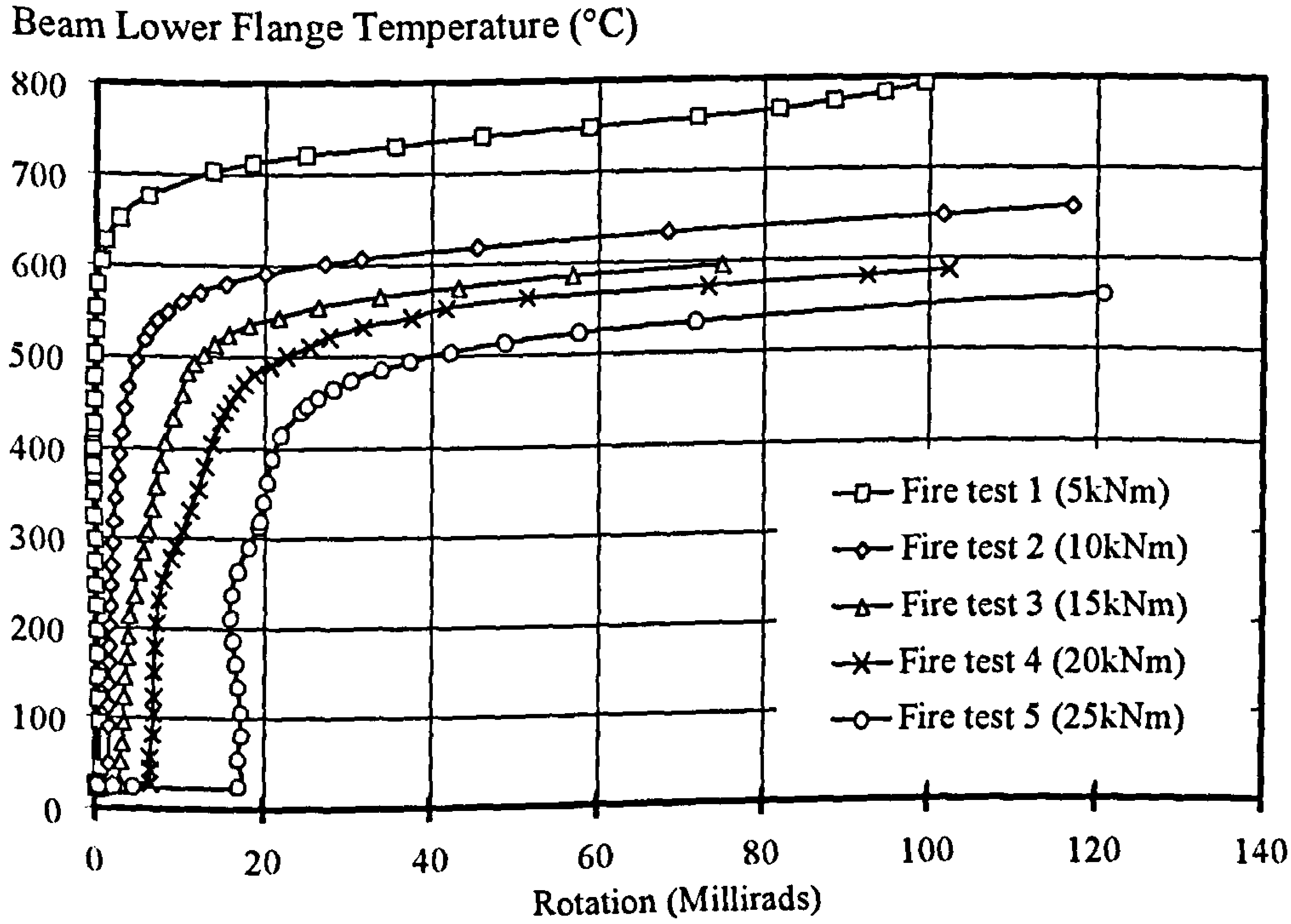


Figure 3.24. Elevated-Temperature Connection Response

Results from the series of tests compare well, demonstrating a consistent degradation of capacity and stiffness with increasing load and temperature, as would be anticipated. For tests three to five there was a predominant kink in the temperature-rotation response for temperatures in the temperature range of 200°C to 300°C. It is possible that this may have occurred as a result of thermal bowing, but the fact that the form of behaviour became more pronounced for tests conducted at increasing levels of load (in which the effects of thermal bowing would be anticipated to become less pronounced), and the relatively low temperatures at which this occurs seems to suggest that thermal bowing is not the cause. Results presented for test CFEP25 were based solely on rotations recorded by displacement transducers, it is possible that an inaccurate assessment of column expansion at the centre-line of the beams may result in misleading calculations of connection rotation. However, a similar response was observed in earlier tests based on clinometers, suggesting that the calculation of rotations from beam displacements is sufficiently accurate.

Deformation of the connection at the application of initial loading in the case of the elevated-temperature tests would be expected to correlate with the ambient-temperature moment-rotation response. Results from the ambient-temperature test are compared with those from furnace tests at ambient-temperatures, but in a loaded state in Fig. 3.25. Rotations plotted are based on the form of instrumentation described above. Where possible, rotations for both the East and West connections are plotted, along with average results, providing information on the variation in rotations observed in the fourth and fifth elevated-temperature connection tests.

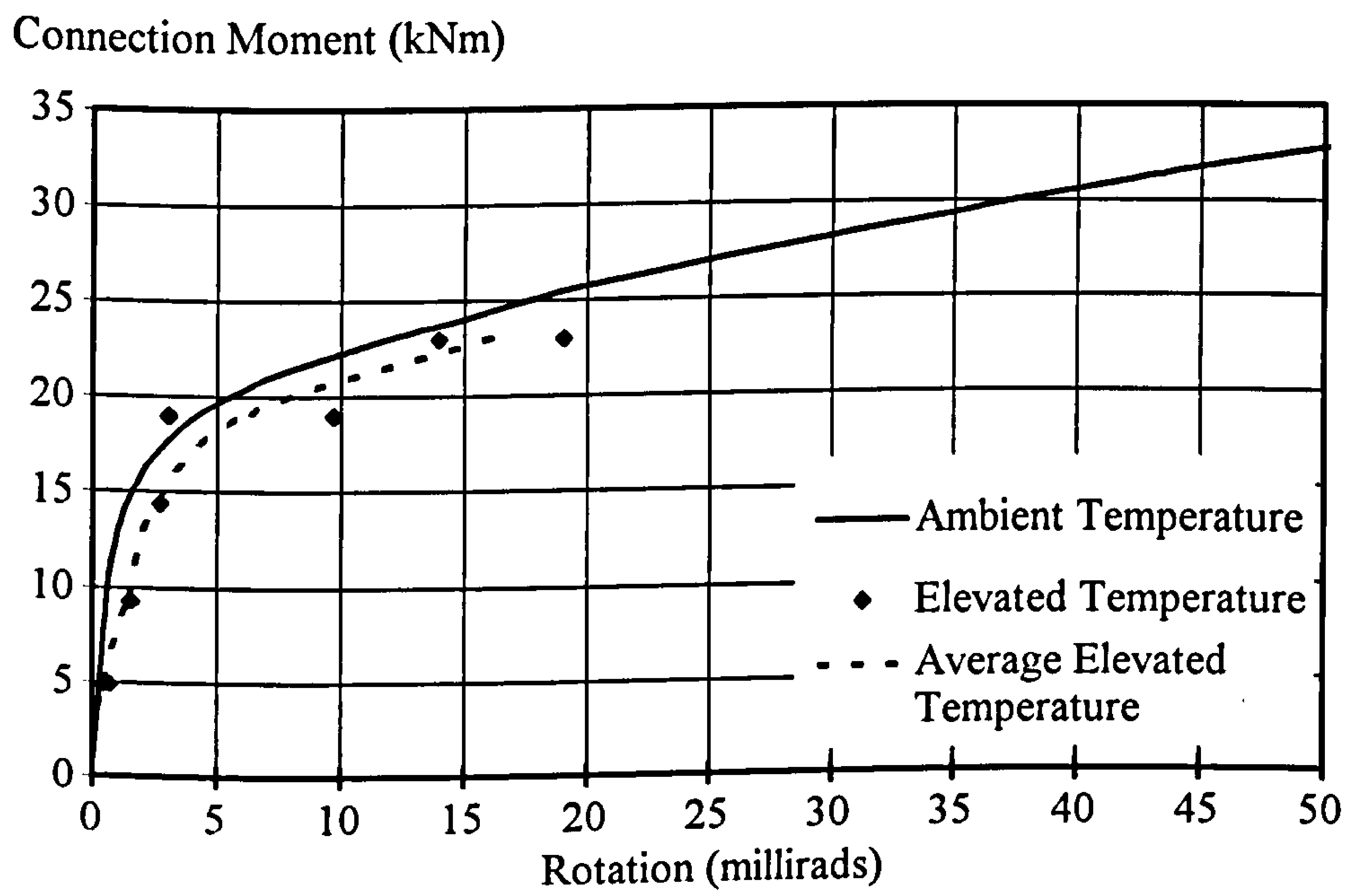


Figure 3.25. Response with Specimen Located in Furnace at Ambient-Temperatures Compared to Ambient-Temperature Connection Test Results

It may be seen that when average results are plotted these follow a similar form of behaviour to that observed in the ambient-temperature test, although they do suggest a more flexible connection. The ambient-temperature and elevated-temperature tests were conducted with different test arrangements, although the arrangements were selected to be representative of one another, with loading being applied at the same locations. However, the form of instrumentation used for recording loading for the two test arrangements differed considerably. Results from the ambient-temperature test were obtained from a single load-cell located at the centre of the column whilst beams were restrained in position, whereas in the case of tests conducted within the furnace load was applied to each beam and recorded independently. Although both of these arrangements would be expected to generate similar results, it may be expected that a degree of variation may occur. It should also be noted that the actual form of loading differed for the two test arrangements. In the case of the ambient-temperature test load was applied at a steadily increasing rate, and although the rate of loading was low it may be that the level of rotation would still be anticipated to be greater in a truly static test, such as those with the specimen located inside the furnace. In the latter the use of gravity loading necessitated the lapse of a considerable period of time from the commencement of loading to the recording of rotations. It is interesting to note that in the case of the test conducted by Lawson, in which the form of loading adopted was similar to that used in the ambient-temperature test described above, there was a very close correlation between recorded rotations and those from the ambient-temperature test as shown in Fig. 3.7.

Rotations recorded for East and West connections in tests BFEP5 and BFEP10 compare well. However, there was a considerable degree of variation in rotations recorded for the East and West beams in tests BFEP20 and BFEP25. As previously described, it was believed that this was due to actual variation in connection rotations, and not as a result of errors in the instrumentation, as both forms of rotation device indicated a similar response for the fourth elevated-temperature connection test. This assumption is supported by the observations above, from which it can be seen that the average of the rotations from fire tests four and five correlate with the rotations which would be anticipated based on the shape of the moment-rotation curve from the ambient-temperature test, and results from the first three elevated-temperature connection tests. This suggests that the variation observed between East and West rotations was attributable to column rotation, which it was not possible to monitor in the elevated-temperature test.

Although the values presented in Table 3.2 indicate an almost linear temperature profile across the depth of the connection, it is important to consider the influence of the test procedure. The furnace was designed to provide uniform heating throughout, using a process of tangential firing and this, combined with the relatively slow rate of heating, provides a somewhat unrepresentative fire compartment compared with a typical structure. It is anticipated that, due to the experimental arrangement, the connection may achieve a more uniform temperature profile for a given temperature than would be expected in reality. Given the difficulties associated with elevated-temperature tests this is an unavoidable problem with the current test facility. It is reassuring that the use of an insulating layer on the upper beam-flanges can be seen to produce a representative temperature profile across the depth of the beams. Unfortunately data defining the temperature profiles for typical connections is at present restricted to that derived from furnace testing[44], and as such is not truly representative of that which would exist within a real fire situation.

The mode of failure was qualitatively similar to that observed at ambient-temperature in all of the tests. In each case significant deformation of the column web in the compression zone, and of the column flange in the tension zone, was observed with very little damage to either the beams or end-plates. If the material properties were degraded in calculating connection capacity according to EC3[41], then a consistent mode of failure would be anticipated for any given temperature.

The initial tangent stiffness at ambient-temperature was recorded as approximately 9 x 10^9 Nmm/radian with the specimen located inside the furnace subject to an initial level of load, comparing closely with the predicted value of 8.7×10^9 obtained from the recommendations presented in Annex J of EC3.

3.3. COMPOSITE CONNECTION TESTS

It was anticipated that the performance of semi-rigid connections at elevated-temperatures would be enhanced by the incorporation of a composite slab, as the capacity of the connection would degrade at a lower rate due to the influence of even 'nominal' reinforcement, at a significantly lower temperature than the exposed connection and surrounding structure.

To investigate the influence of composite action on the performance of connections at elevated-temperatures, a series of tests was conducted on a connection nominally identical to the bare-steel arrangement presented above, with the incorporation of a composite slab in the tension zone. The test programme is detailed in Table 3.3. An initial test was conducted to develop ambient-temperature moment-rotation characteristics, with three further tests being conducted at constant moment, with increasing temperatures, based on the rate of heating previously adopted for the bare-steel connection tests. In the case of the composite connection, the number of tests conducted at elevated-temperatures was restricted to three by the resources available. However, consideration of the bare-steel results suggests that a reasonable representation of connection response may be determined from three elevated-temperature tests, and a single ambient-temperature test. This allows assessment of the significance of the incorporation of a composite slab on elevated-temperature performance.

Description:	Applied Moment:	Temperature:	Comments:
CFEP AMB	Full Range.	Ambient.	Ambient-temperature M-θ.
CFEP 15	15kNm.	10°C / minute.	Composite fire test 1.
CFEP 25	25kNm.	10°C / minute.	Composite fire test 2.
CFEP 32	32kNm.	10°C / minute.	Composite fire test 3.

Table 3.3. Composite Flush End-Plate Experimental Programme

The composite slab was detailed to the specification adopted in the Cardington test frame[123], as this was felt to be representative of typical constructional forms. As such a 130mm thick, Grade 35 Lightweight slab was adopted, attached to the beam by 100mm x 19mm diameter shear studs at 300mm centres. PMF COMFLOR 70 decking was used with 'nominal' A142 deformed reinforcing mesh, typically detailed to avoid cracking, and not taken account of in connection design. The composite connection is shown in Fig. 3.26.

The use of lightweight concrete results in a reduction in the temperature of the reinforcement, as its rate of thermal conductivity is approximately 1W/m°C, compared to 2W/m°C for normal weight concrete, and 45W/m°C for steel. Lightweight concrete is often adopted in office buildings in order to reduce the weight of the structure, having a typical density of 1760kg/m^3 compared to 2400kg/m^3 for normal-weight concrete, and often allowing the use of thinner floor slabs due to its enhanced fire resistance, permitting a reduction in the reinforcement cover. Although the Cardington slab was detailed with a slab thickness of 130mm, a survey recorded actual slab thicknesses in localised areas of over 160mm, some 30mm thicker than that specified[72]. There was also variation in the location of the reinforcement within the slab. This was specified to be laid with the lower bars bearing on the ribs of the steel decking[123], whilst actual observation suggests that in places reinforcement may have been far closer to the surface of the concrete, illustrating the possible extent of deviation from specification in the construction process.

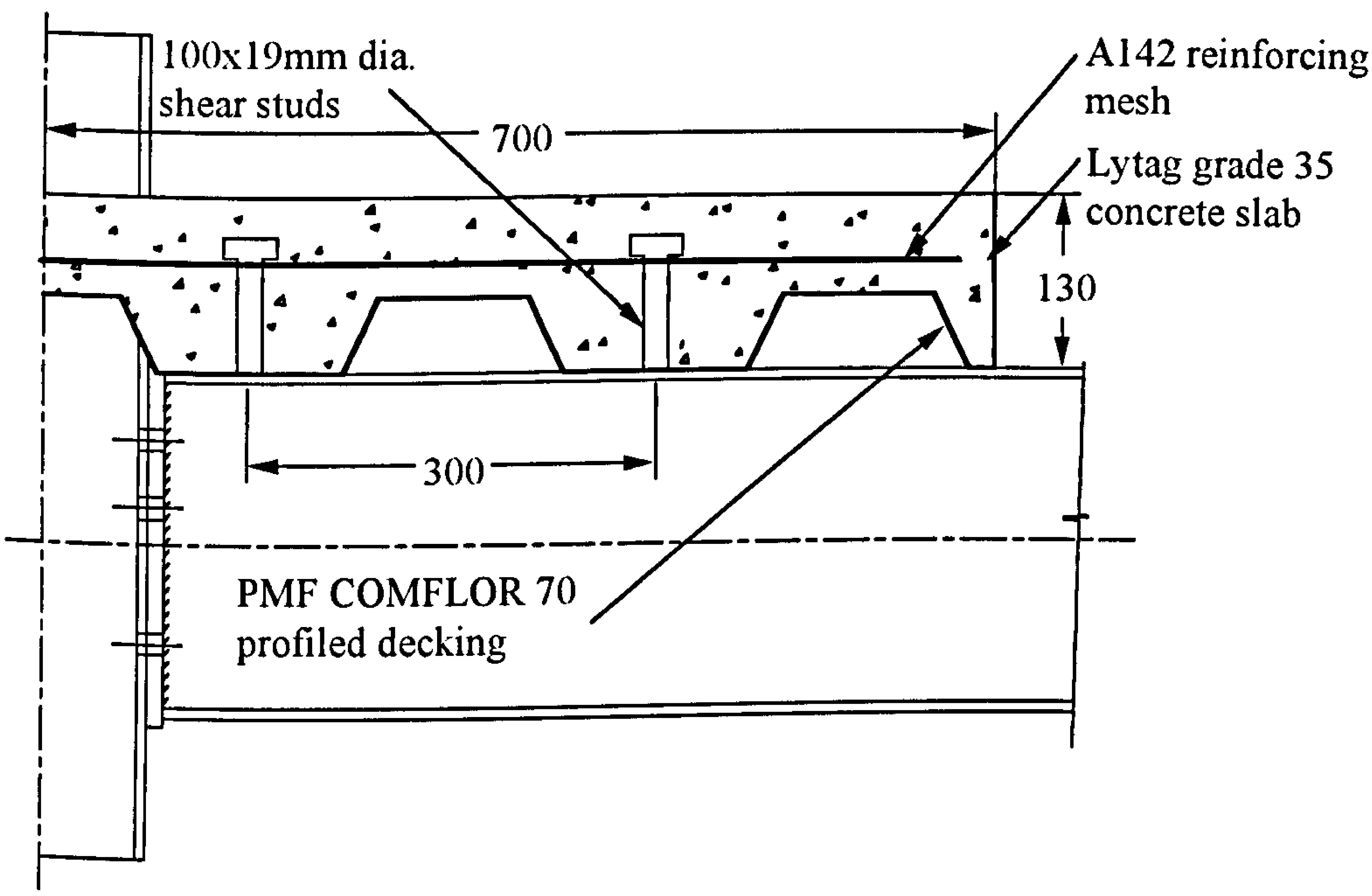


Figure 3.26. Composite Flush End-Plate Connection Detail

In the connection test specimen the slab was 1400mm long and 1000mm wide, these dimensions being largely dictated by the physical restrictions imposed by the furnace arrangement, and was designed assuming full interaction at ambient-temperatures. The moment capacity of the composite beam is approximately 210kNm, with the plastic neutral axis lying in the concrete flange. These are based on nominal material properties and the recommendation presented in BS5950: Part 3.1[73].

The capacity of composite connections is often approximated by imposing the influence of reinforcement onto the response of the bare-steel connection, where the bare-steel connection is assessed through analytical or design methods (such as Annex J of EC3), or obtained directly from experimentation. Based on a capacity of approximately 17kNm, obtained from the bare-steel connection tests, and nominal reinforcement properties, this suggests that yield of the composite connection would occur at a moment of approximately 33kNm. This relates to an approximate value of $0.16M_b$ compared to $0.18M_b$ for the bare-steel connection. However, the bare-steel connection demonstrated a considerably enhanced ultimate capacity, in the region of 40kNm, or $0.5M_b$, which may not be experienced for the composite connection due to a reduction in the ductility of the arrangement. It should also be noted that the influence of composite connections on overall structural response is complicated by the presence of the concrete slab acting in compression, in which its strength degrades at a greatly reduced rate compared to the exposed steel sections.

Mechanical and geometrical properties for the concrete, reinforcing mesh and steel sections are once more presented in Appendix A. The mechanical and geometrical properties of the steel section are similar to those for the bare-steel connection tests, as all the steel was from the same batch. The cross-sectional area of the reinforcing mesh was below the nominal value, with an area of approximately 130mm^2/metre, but this was compensated for by the yield strength being 25% greater than the nominal value. Compressive concrete strength was assessed at 7 days, 28 days, and on the day of each connection test. Additional tensile splitting tests were conducted at 28 days. A typical compressive concrete strength of 46N/mm^2 was obtained from a series of cube tests, compared with a tensile splitting strength of 3.6N/mm^2.

3.3.1. Ambient-Temperature Composite Connection Test

The connection was tested in an inverted position, with a small incremental load being applied to the column head, whilst beams were restrained in position at a distance of 1524mm from the column centre-line, as with the bare-steel connection test. The experimental arrangement is illustrated in Fig. 3.27.

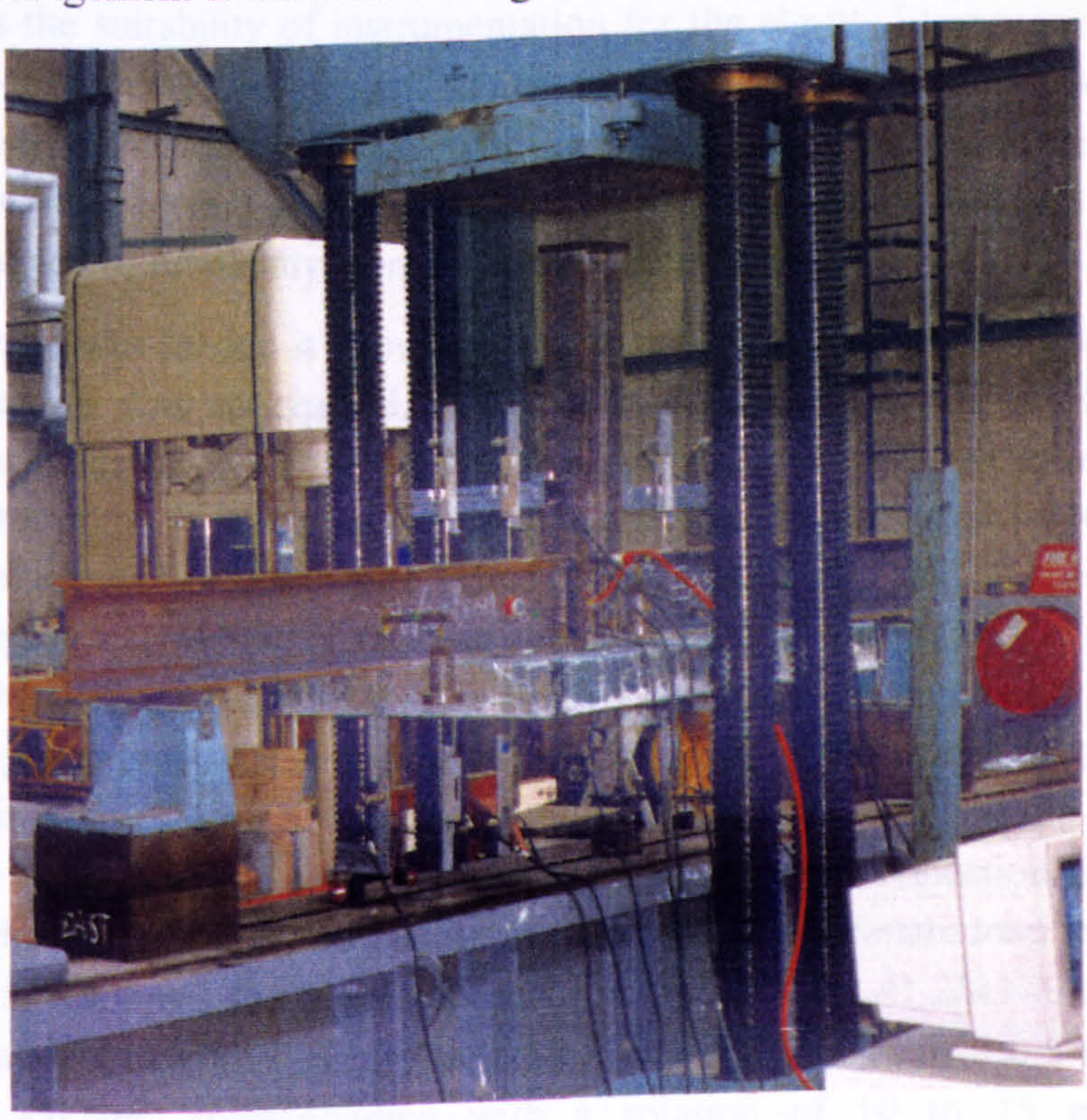


Figure 3.27. Ambient-Temperature Composite Connection Test

3.3.1.1. Instrumentation

Instrumentation was similar to that adopted previously. Displacement transducers were located at distances of 250mm, 500mm, 750mm and 1300mm from the face of the column flange, corresponding with displacement transducer locations in the elevated-temperature tests. Displacement readings were taken from face of the slab and from the exposed flange of the beam, as concern was felt regarding the possibility of the separation of the slab from the beam at high levels of rotation, in order to assess the feasibility of recording displacements from the face of the concrete slab in the elevated-temperature tests.

Clinometer devices were attached to the beam web along the centre-line, a distance of 160mm from the face of the end-plate, and to the column web at the intersection of beam and column centre-lines. Dumb-bell devices had to be positioned remote from the connection due to the slab obstructing their rotation. These were therefore positioned at a distance of 720mm from the face of the end-plate along the centre-line of each beam, with the dumb-bell attached to the column web along the centre-line, a distance of 125mm above the beam centre-line.

Once more, as the test rig was load-controlled there was no need to incorporate load cells in the ambient-temperature arrangement.

3.3.1.2. Results

As with the bare-steel ambient-temperature connection test, the main purposes of this test were to assess the suitability of instrumentation for the elevated-temperature tests, and to determine experimentally the ambient-temperature moment-rotation characteristics of the connection, enabling suitable load levels to be defined for the elevated-temperature tests. Ambient-temperature testing also allows the significance to be assessed of composite action on the performance of nominally identical connections.

As the connection was loaded it demonstrated an enhanced stiffness compared to the bare-steel connection, as was anticipated. The observed failure mechanism of the composite connection was similar to that for the bare-steel arrangement, although column deformation was concentrated more in the compression zone, due to the increased force applied to the column web as a result of composite action. Cracking of the slab was observed at load levels in the region of 34kNm. Cracks propagated from the edges of the column flanges, spreading to the perimeter of the slab as loading increased. Crack width increased until moments of approximately 45kNm were achieved in both connections. At this point failure of the inner reinforcement on both sides of the slab was observed, and the load applied to the connection decreased due to the reduced stiffness of the connection, and the loading regime adopted. Unfortunately no results were recorded at ultimate load levels due to the abrupt change in response, the highest moment recorded being 41.25kNm. Subsequent to the failure of the inner reinforcement, the connection regained equilibrium at a moment of approximately 35kNm, corresponding with a rotation of 10 to 15 millirads. The performance of the connection remained above that for the bare-steel connection, with the outer reinforcement carrying additional forces. Testing was eventually terminated at a moment of approximately 40kNm due to the connection being unable to sustain any further increase in loading. The failure of the connection is illustrated in Fig. 3.28, with crack locations being summarised for the ambient-temperature test and all subsequent composite tests in Fig. 3.29. It may be seen that for test CFEP32 the test arrangement was reoriented. However, a nominally identical test arrangement was adopted and so results from all tests should remain comparable.

Figure 3.28. Ambient-Temperature Composite Connection Failure Mechanism

Moment-rotation characteristics from rotation devices are summarised in Fig. 3.30. It may be seen that the failure of the inner reinforcement occurred at rotations of approximately 5 millirads. Assuming the connection to rotate about the beam lower flange as a conservative approximation, and a de-bonded length corresponding with the first crossing bar in the reinforcing mesh, failure would be anticipated to occur at a rotation of approximately 45 millirads, based on the material properties recorded. It is suggested that this dramatic reduction in the level of rotation undergone was due to confinement of the concrete between the column flanges, resulting in a reduction in the de-bonded length for the reinforcing mesh.

The East dumb-bell device produced erratic results, necessitating reliance on recorded West rotations, having modified these to account for the influence of column rotation. At low load levels dumb-bell devices appear to predict a negative rotations, possibly due to the enhanced stiffness of the composite connection, and the inherent inaccuracies existent within the test arrangement, with a similar response having been observed by a number of authors in the past. Clinometer devices suggest a more flexible response than dumb-bell devices, and there was some variation in the behaviour of East and West connections. East and West rotations recorded by displacement transducers compare well, both suggesting a

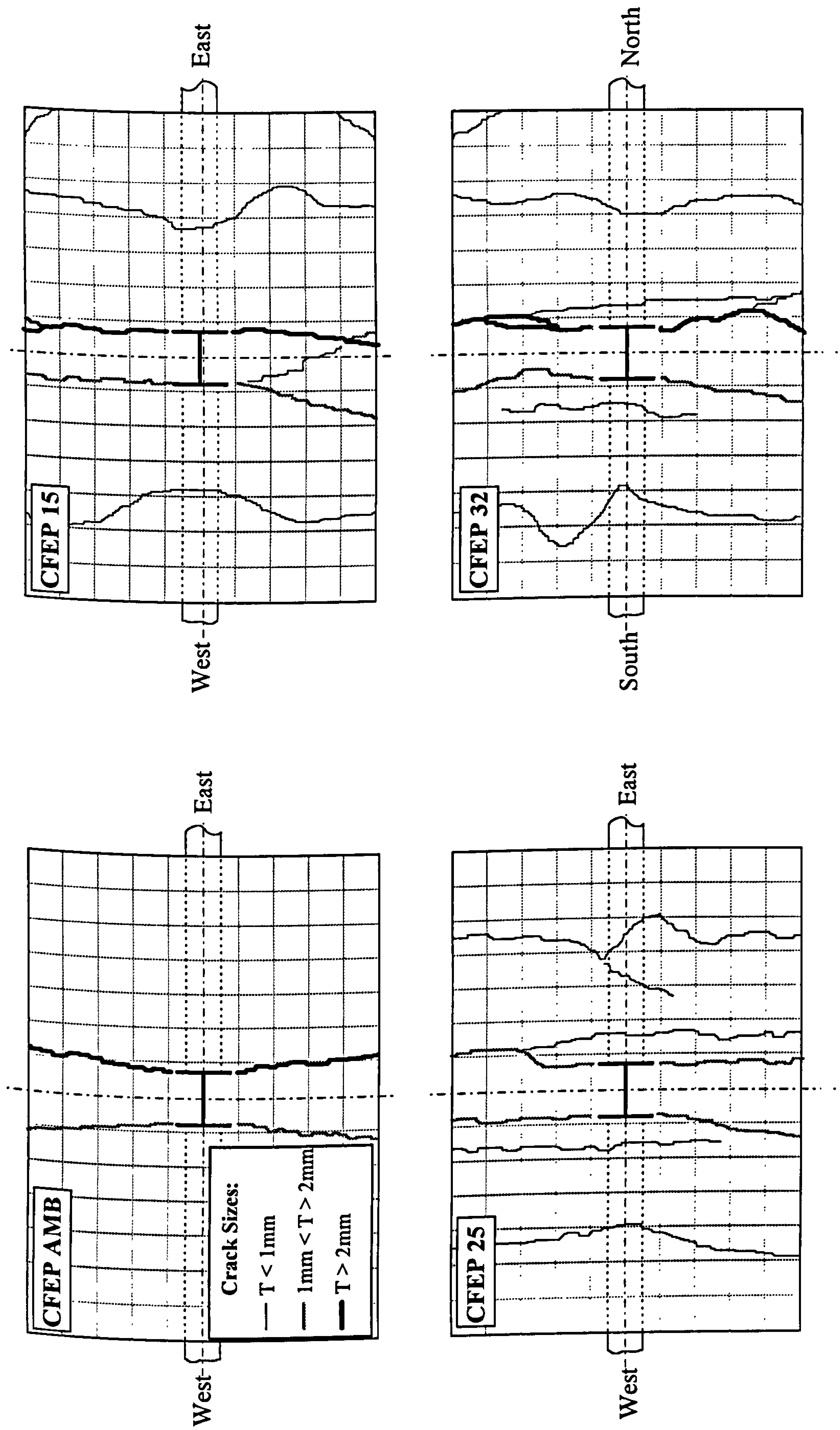


Figure 3.29. Composite Slab Crack Locations

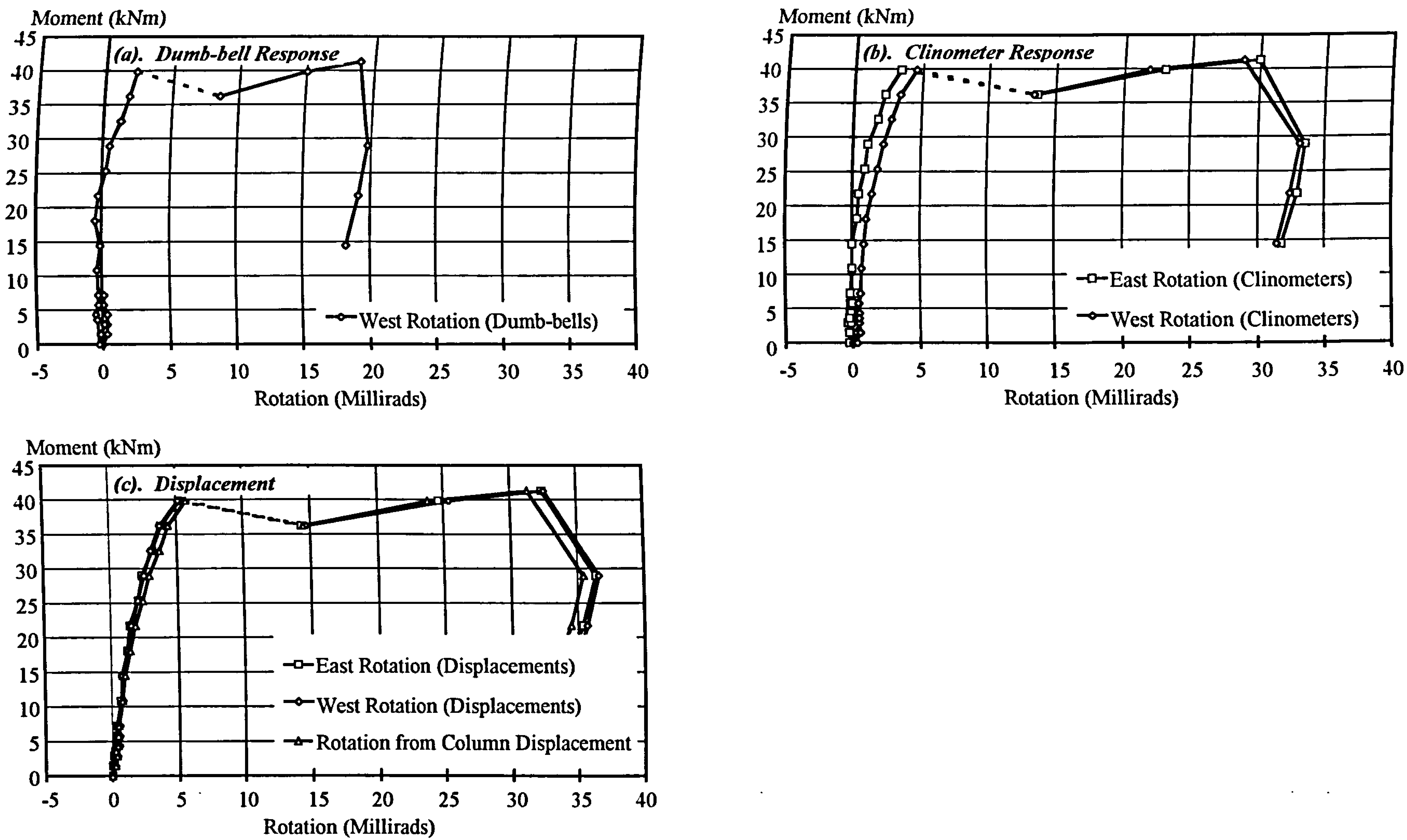


Figure 3.30. Summary of Results from Ambient-Temperature Composite Connection Test (CFEP AMB)

more flexible connection than clinometer devices. There was a close correlation with the response recorded from column displacements.

Similar behaviour was observed regardless of whether displacement transducers were located on the concrete surface or beam flange, although readings taken from the beam flange did suggest a slightly stiffer connection, possibly due to separation at the beam-slab interface. The maximum variation observed was in the region of 1 millirad, and it would be expected that the significance of this would reduce if the slab was tested in an upright position. It is felt that it is acceptable to assess beam rotations from displacement readings taken from the face of the concrete slab where necessary, although it remains preferable to use direct rotations where possible. Assessment of displacement readings along the length of the beam once more suggests that the beam was subject to a negligible degree of curvature, which is supported by the fact that cracking was not found along the length of the beam. There was no sign of slip in the composite connection, possibly due to the its being fabricated in an upright position, subsequent to observations from the bare-steel ambient-temperature connection test.

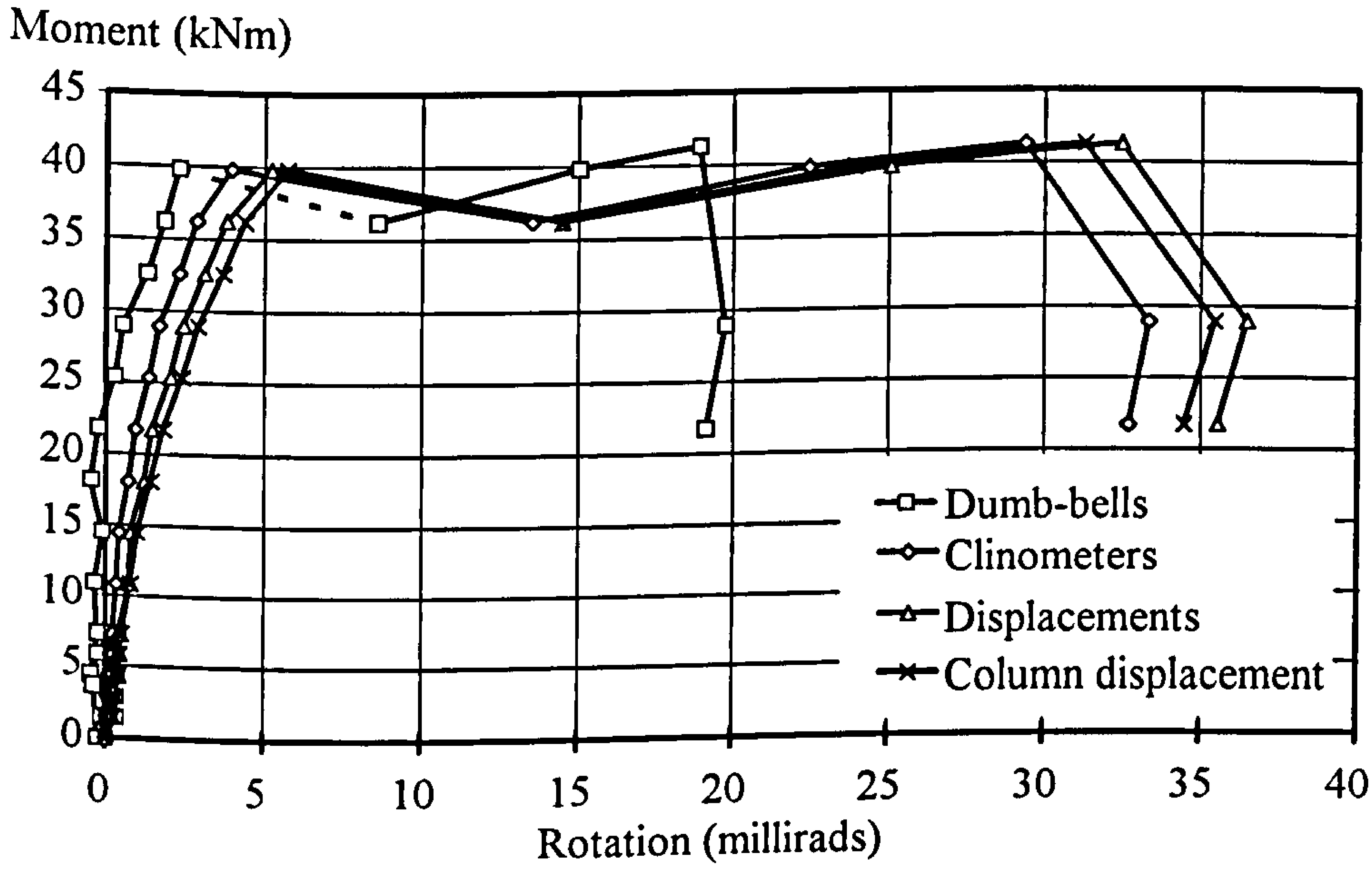


Figure 3.31. Comparison of Ambient-Temperature Rotation Devices

Rotation readings from the various forms of rotation device are compared in Fig. 3.31. It can be seen that there is a greater scatter between results from different rotation devices than was experienced in the ambient-temperature bare-steel connection test. The greatest deviation is observed for dumb-bell devices, possibly due to the increased lever arm to them, necessitated by the obstruction caused by the concrete slab. Results from displacement readings taken from positions along the each of the beams, and those obtained from column displacements, compare well. There is also a close correlation between results obtained by clinometer devices and displacement transducers.

Ambient-temperature moment-rotation response for both the bare-steel and composite connections are compared in Fig. 3.32, based on clinometer devices. As can be seen, the capacity of the composite connection is greatly enhanced at low levels of rotation, although its ultimate capacity was in the region of 40kNm, comparing closely with that experienced for the bare-steel connection, as can be seen more clearly in Fig. 3.5. Although the stiffnesses of the bare-steel and composite connections appear to compare closely, an initial tangent stiffness of approximately 44×10^9Nmm/radian was recorded for the composite connection, compared to 17×10^9Nmm/radian for the bare-steel connection.

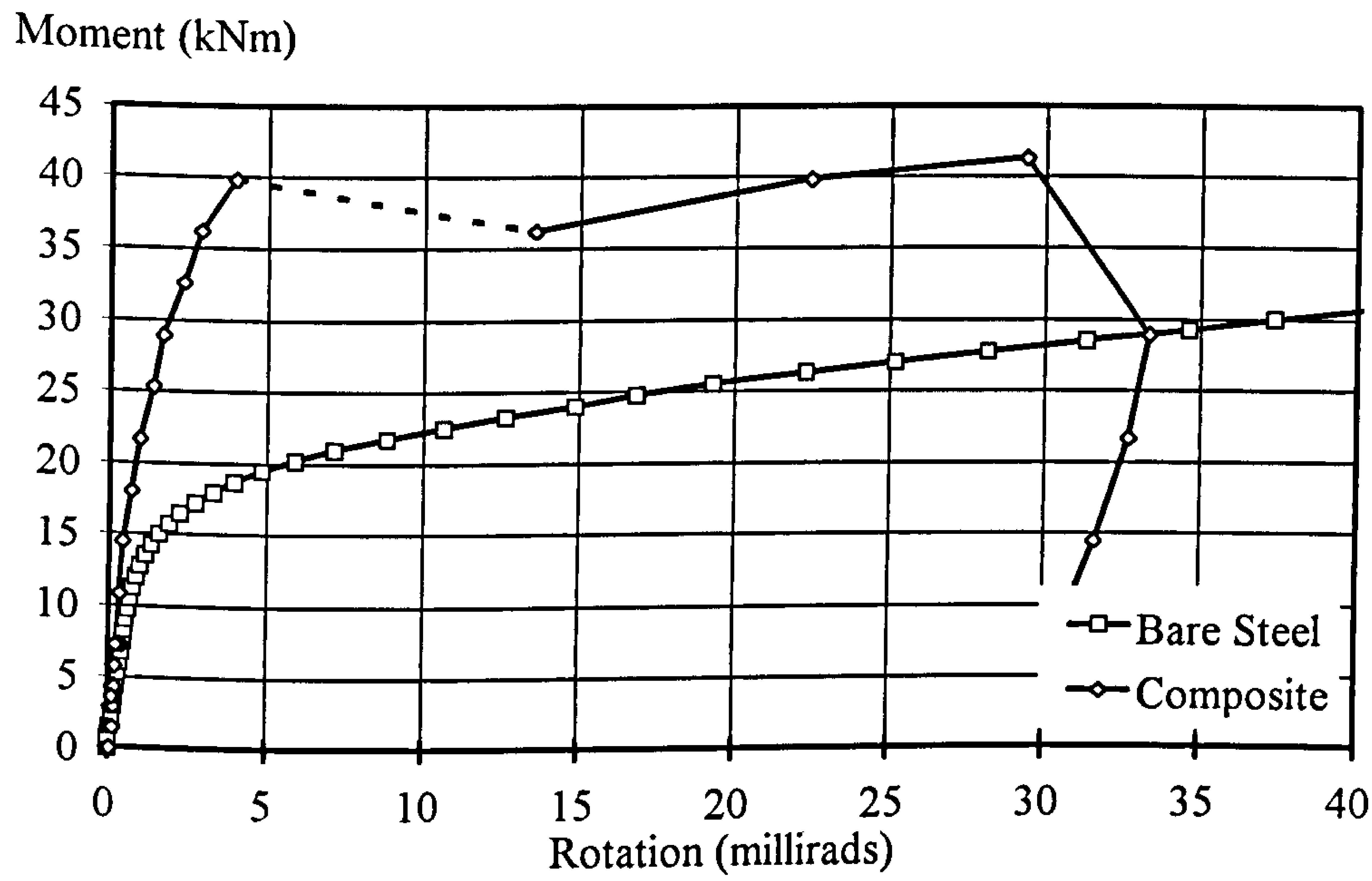


Figure 3.32. Comparison of Bare-Steel and Composite Connection Response

3.3.2. Elevated-Temperature Tests

Testing was conducted under constant moment with increasing temperatures, as with the bare-steel connection tests. The increased levels of loading required for the composite tests necessitated the use of a hydraulic jacking system to apply moments to the connections. Beams were loaded at the same position as previously, with a system of Macalloy bars passing through the strong floor. These were loaded by an arrangement of two hydraulic jacks, reacting against the strong floor, and applying load to each beam individually. A manual control system was adopted, allowing fine tuning of the level of force applied to each beam. The level of load applied to the beams was once more monitored by load cells, but a ball-seating was adopted for the composite tests to remove the previous difficulties in assessing load levels at increased levels of rotation.

To represent a true heating regime, where the connection is heated from below, a ceramic blanket was secured to the top face of the slab, so as to reduce the surface temperature to a reasonable level, and avoid adverse heating of the reinforcing mesh. Insulation was once more provided to the beams and column remote from the connection. The top face of the flange was not protected close to the connection, but instead voids were left exposed, resulting in variations in the temperature distribution along the length of the beams, as is typical of modern constructional procedures.

3.3.2.1. Instrumentation

Instrumentation was as for the bare-steel connection tests, with the incorporation of additional thermocouples to monitor slab surface and reinforcement temperatures. Reinforcement temperature was assessed by securing a thermocouple at the location of the reinforcing mesh, although it was not possible to record an internal reinforcement temperature. As described above, voids were left unprotected close to the connection, with the unprotected top flange temperature being monitored at these locations. No temperatures were recorded at locations where the top flange was protected by the concrete slab.

Silica rods were once more used to record displacements along the length of the beams. These were secured to the top face of the concrete slab where necessary using a high temperature cement, although due to the size of the slab only two of the rods along the length of each beam were actually resting on the slab, with the remainder being attached to the top flange of the beam.

3.3.2.2. Results

As previously described, a series of three elevated-temperature tests was conducted under constant moment with increasing temperature, to describe the moment-rotation characteristics for the composite connection across a realistic range of temperatures. Individual tests are described below.

3.3.2.2.1. Composite Connection Fire Test 1 (CFEP 15)

The first elevated-temperature composite connection test was conducted at a moment of approximately 15kNm. This load level was selected to provide information about the degradation of connection stiffness, although a higher load level was adopted than for the bare-steel connection in order to reduce the influence of the inaccuracies associated with the experimental arrangement. The connection was capable of resisting temperatures of almost 800°C, followed by a plateau in the temperature-rotation response. A more flexible response was observed at low temperatures than for the bare-steel connection, possibly due to the stiffness of the connection being controlled by the relatively flexible column web in the compression zone, at a far greater temperature than that of the reinforcing mesh in the tension zone. Due to the flexibility of the column it would be anticipated that, whilst the composite connection would provide enhanced stiffness and capacity compared to the bare-steel connection at ambient-temperatures, the stiffness of the connection would degrade with temperature at a comparable rate. Ultimate capacity would be expected to degrade more slowly with increase in temperature. Results for the first elevated-temperature composite connection test are summarised in Fig 3.33.

As with the ambient-temperature composite connection, it was found that the deformation of the connection was more closely concentrated in the compression zone, due to the relative flexibility of the column web and increased compressive force. The failure mechanism for the composite connection at elevated-temperatures is illustrated in Fig. 3.34. It may be seen that there is greater deformation of the column web and flanges in the

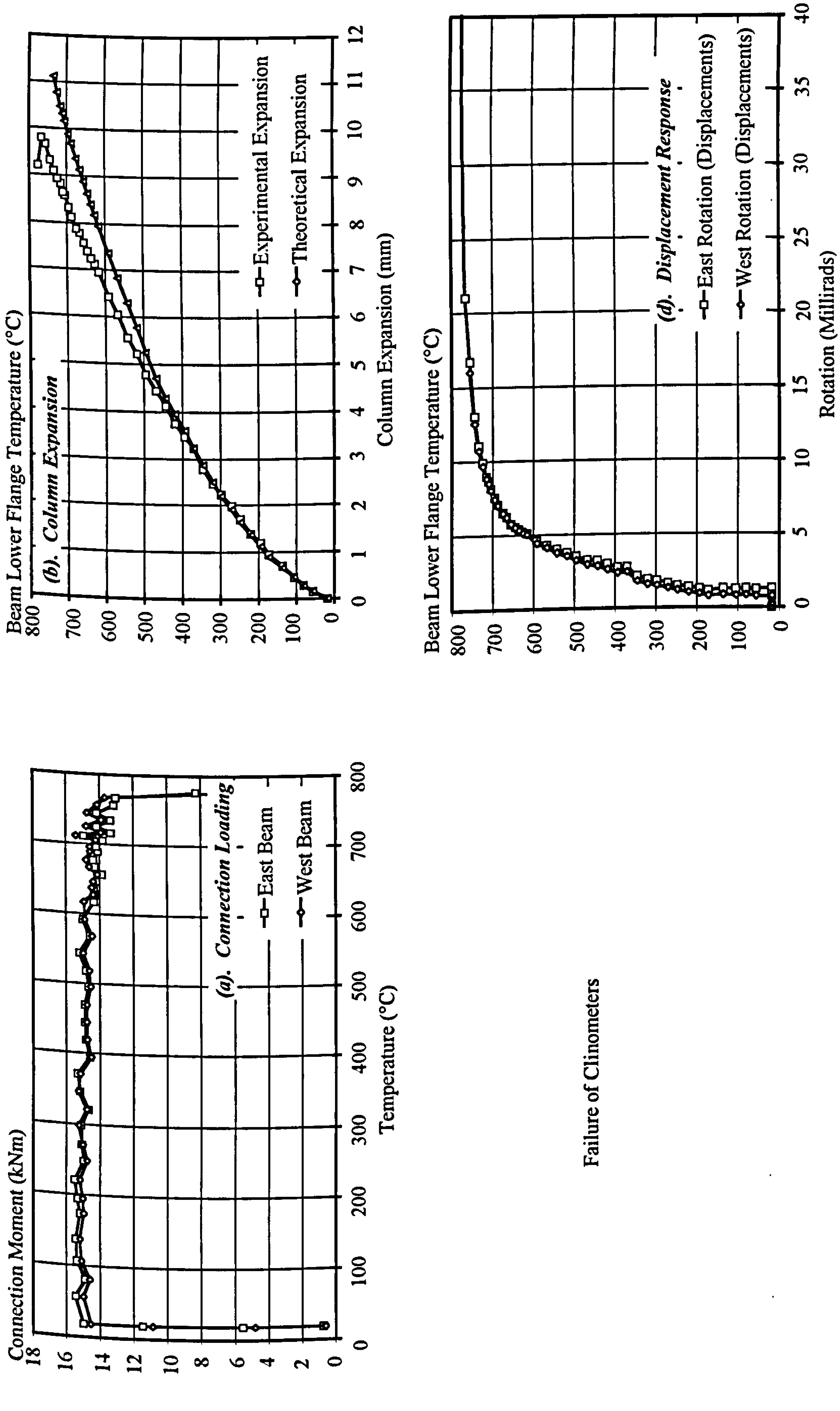


Figure 3.33. Summary of Results from Composite Connection Fire Test 1 (CFEP 15)

compression zone than was experienced at ambient-temperatures, due to the stiffness of the compression zone degrading at a greater rate than that of the tension zone. As previously described, crack patterns for the composite slab are detailed in Fig. 3. 29. A similar form of cracking was observed to that in the ambient-temperature test, although it was not possible to assess the progression of the crack pattern as there was no access to the furnace throughout testing. Once more predominant cracking propagated from the column flanges towards the edges of the slab, although in the case of the elevated-temperature test further cracks were observed at intermediate points along the length of the beams, suggesting the possibility of bending of the beams along their length. Examination of the specimen subsequent to testing suggested that all reinforcement maintained intact, as anticipated due to the increased flexibility of the compression zone.

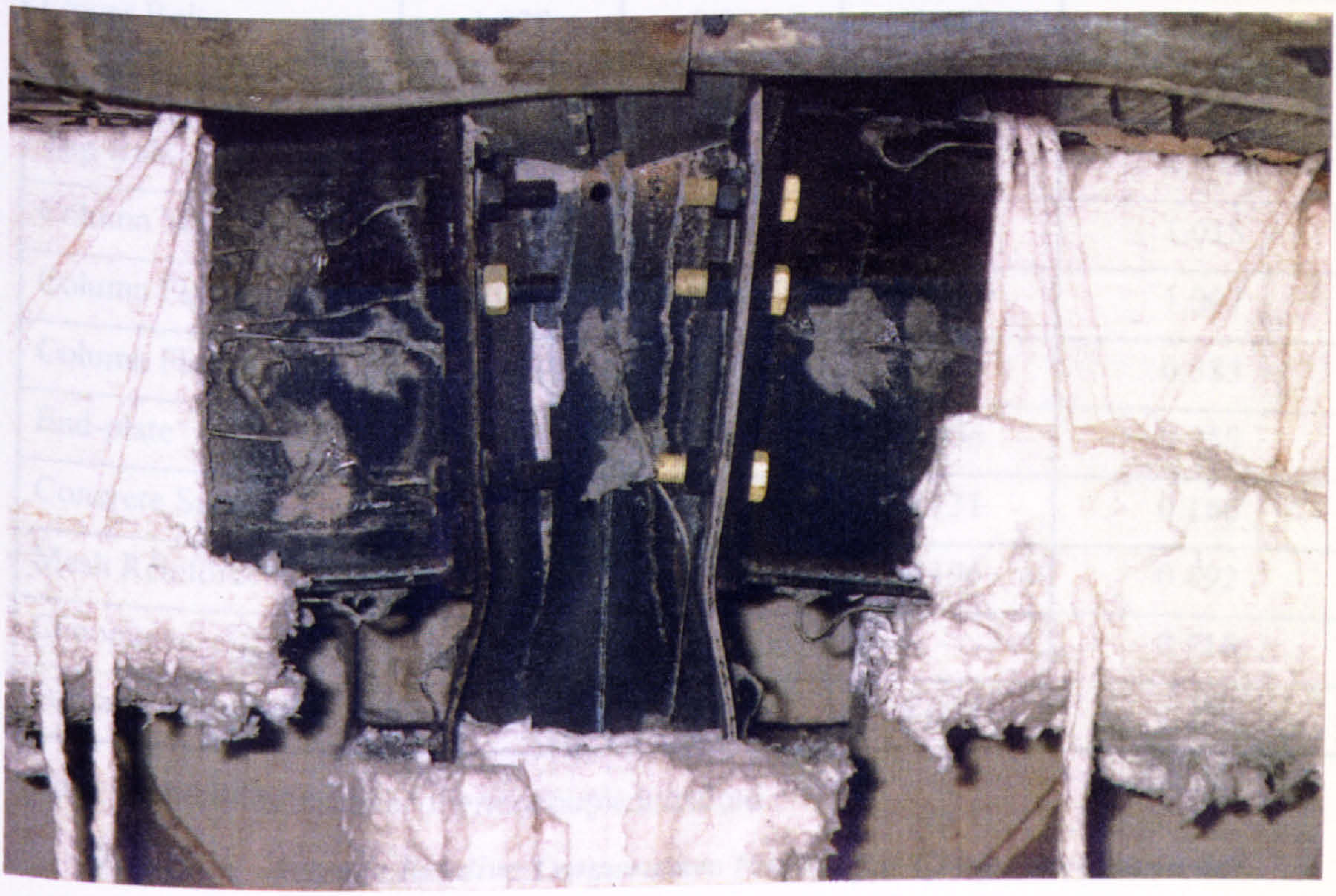


Figure 3.34. Elevated-Temperature Composite Connection Failure Mechanism

Temperature profiles for the arrangement are detailed in Table 3.4 for this and all subsequent elevated-temperature composite connection tests, with the beam lower flange temperature once more being selected as the reference. It may be seen that a similar form of temperature profile was observed to that for the bare-steel connection, although an increase in temperature was observed for the top flange of the beam, being approximately 90% of the lower flange temperature, due to thermocouples being located in the unprotected voids between troughs in the decking. Reinforcing mesh temperature was maintained at approximately 19% of the beam lower flange temperature, with the top face of the concrete slab being at a similar temperature. This indicates that the use of a ceramic blanket to protect the surface of the slab (due to the form of heating not being solely from below, as in real fire scenarios) was capable of reducing the slab temperature to a suitable value. Once more a consistent temperature profile was observed throughout testing and between tests[74].

Location:	CFEP 15:	CFEP 25:	CFEP 32:	Average:
Beam Lower Flange	1.000	1.000	1.000	1.000
Beam Centre Web	0.973	0.971	0.944	0.963
Beam Top Flange	0.906	0.892	0.869	0.889
Beam Lower Flange *	0.326	0.335	0.326	0.329
Beam Top Flange *	0.314	0.386	0.480	0.393
Lower Bolt	1.028	0.994	0.981	1.001
Middle Bolt	0.962	0.969	0.926	0.952
Top Bolt	0.943	-	-	0.943
Column Web	1.002	1.061	0.982	1.015
Column Flange	0.986	1.081	0.955	1.007
Column Flange *	0.393	0.380	0.378	0.383
End-plate	0.983	0.937	0.956	0.959
Concrete Surface	0.183	0.184	0.131	0.166
Mesh Reinforcement	0.188	-	0.196	0.192
Clinometer	0.116	-	-	0.116
Furnace Atmosphere	0.801	0.778	0.695	0.758

Note: * identifies insulated thermocouple locations.

Table 3.4. Average Relative Temperature Profiles for Composite Connection

There was some difficulty in controlling load levels compared to the use of gravity loading, as the hydraulic jacks used for the composite connection tests were independently controlled by a manual pressure valve. However, it may be seen from the summary of results shown that there was a close correlation between moments applied to the connections throughout testing, with the average moment being approximately 14.7kNm, comparing closely with the specified value of 15kNm. The pattern of loading became more erratic towards the end of testing due to difficulties associated with the hydraulic jacks' maintaining control of the rate of deflection, which was necessitated by the high rate of rotation experienced at these temperatures.

Predicted and actual rates of column expansion compare well, up to the point where there was once more a reversal of displacements at high temperatures, possibly due to the degree of deformation experienced in the column web in the compression zone.

Rotations from clinometer devices were disregarded as they produced erratic results, necessitating reliance on displacement readings. It may be seen that there was an indiscernible difference between results obtained for East and West beams, providing a degree of validation of the accuracy of results recorded by displacement transducers. Assessment of displacement readings along the lengths of the beams indicated that there was insignificant deformation of the beams, despite the observed crack pattern. It is possible that the extent of deformation was such that it became undetectable from displacement readings due to inherent inaccuracies. Hence, any possible deformation of the beam has been disregarded. Displacement readings taken from the face of the slab compared well with those recorded from the upper face of the beam flange, with the exception of the displacement transducer closest to the face of the column flange. For both East and West rotations the inner displacement transducers suggest a connection of greater flexibility, although the rotations were observed to converge at high temperatures. Displacement readings closest to the column were disregarded when determining the average rotation for East and West beams. Average rotations recorded from displacement readings are shown in Fig. 3.35.

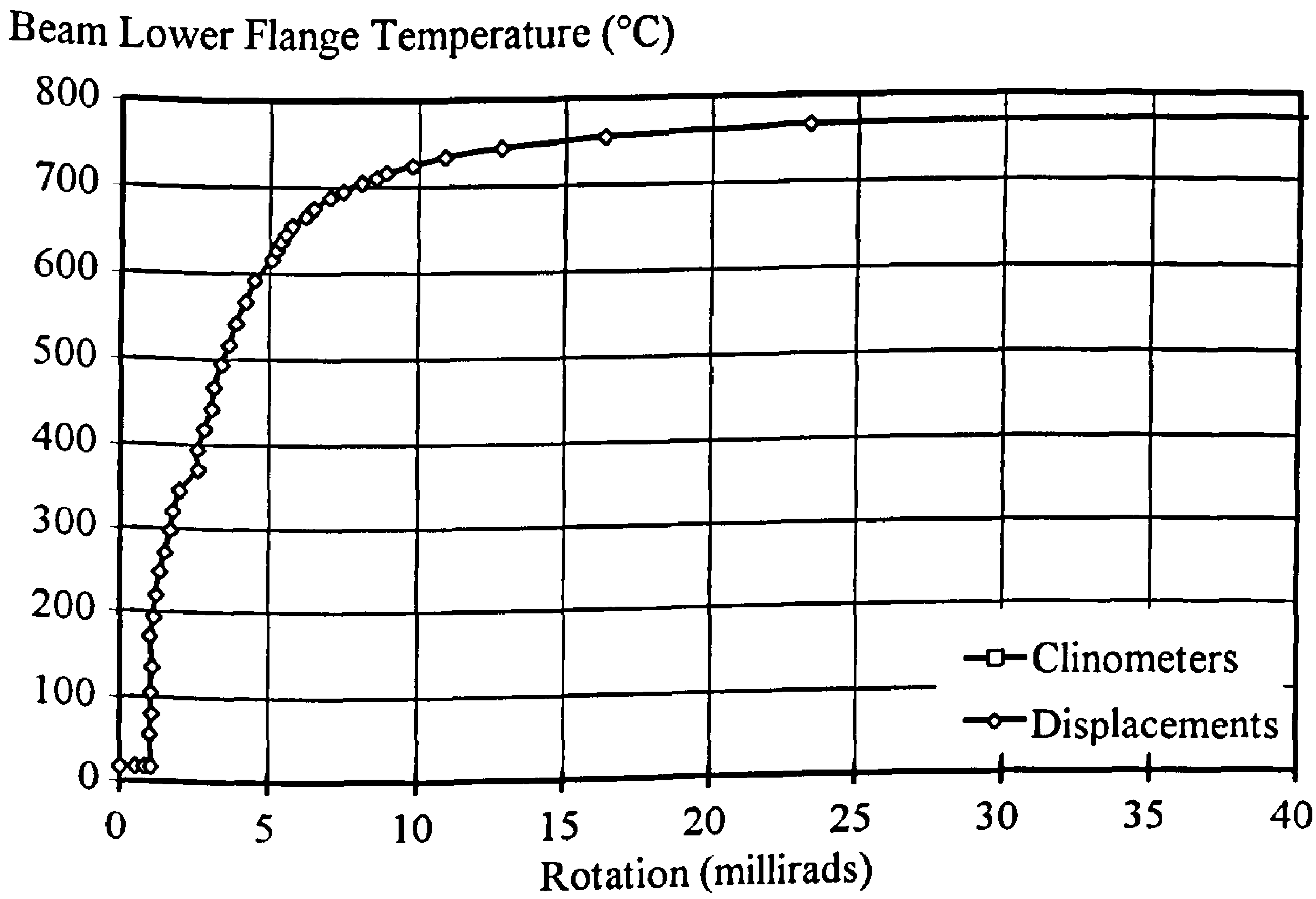


Figure 3.35. Response Recorded by Displacement Readings from Test CFEP 15

3.3.2.2.2. Composite Connection Fire Test 2 (CFEP 25)

The second elevated-temperature composite connection test was conducted under an enhanced moment of 25kNm. Response of the connection was similar to that reported for the first elevated-temperature composite connection test, although the connection was only able to sustain temperatures approaching 700°C. Temperature distribution across the connection compared well with that from test CFEP 15. Failure of the connection was similar to that observed previously, with considerable deformation of the column, concentrated in the compression zone. Cracking of the slab is illustrated in Fig. 3.29, with the pattern of cracking along the length of each beam once more becoming more intensified, despite displacement readings indicating no detectable curvature of the beam along its length. However, as with the first composite connection test, displacement readings close to the column suggested a connection of significantly reduced stiffness.

Testing was terminated at low levels of rotation, as the loading arrangement became unstable due to the effects of lateral-torsional buckling. The influence of small inaccuracies in the location of the load will become amplified as levels of load are increased, and as such it is advisable that the ends of the beams, close to the point of loading, are restrained. This phenomenon was not experienced in the case of the bare-steel tests as no ball seating was incorporated, and hence restraint would have been provided by contact of the beam upper flange with the square hollow section used to apply load to the beams.

Results from the second elevated-temperature composite connection test are summarised in Fig. 3.37. A fairly consistent pattern of loading was maintained until the end of the test, with an average moment of 25.7kNm being applied to the connection.

There was a degree of variation in the levels of rotation recorded for East and West connections by clinometer devices, possibly due to rotation of the test arrangement. However, rotations obtained from displacement readings compared closely with each other, shedding doubt on the actual response. Average results from both displacement readings and clinometer devices are compared in Fig. 3.36. It may be seen that displacement readings predicted a stiffer response than corresponding readings of direct rotation. It is suggested that this may be attributable to inaccuracies associated with the assessment of the extent of column expansion, and the possibility of the separation of concrete at the beam-slab interface. Once more there was a close correlation between predicted and actual column expansion, although predicted values do somewhat overestimate the actual response. This may be due to the fact that theoretical values are based on column temperatures below the level of the slab, and that due to the size of the composite slab in relation to the furnace, temperatures of the column above the slab were somewhat lower than those assumed.

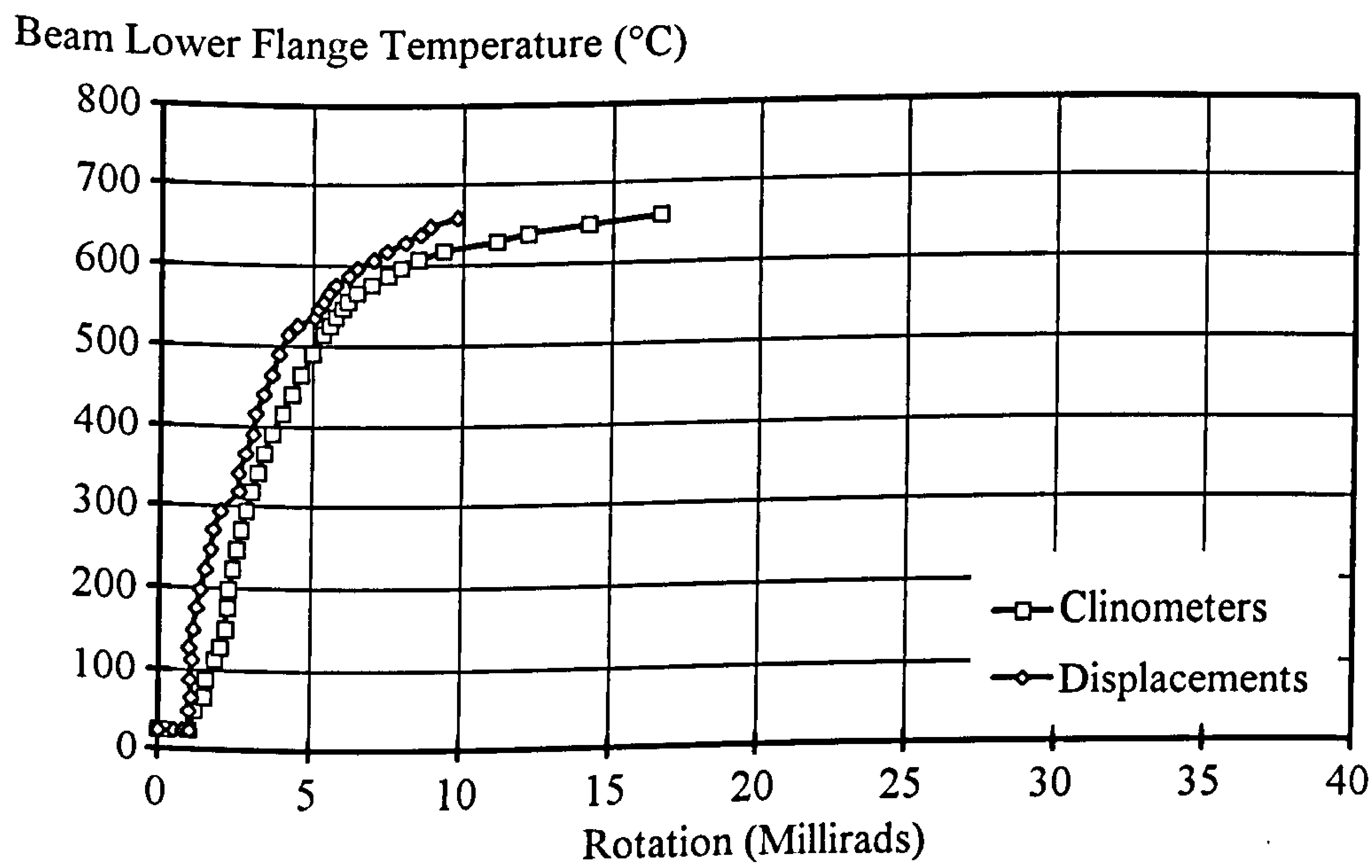


Figure 3.36. Comparison of Results from Test CFEP 25

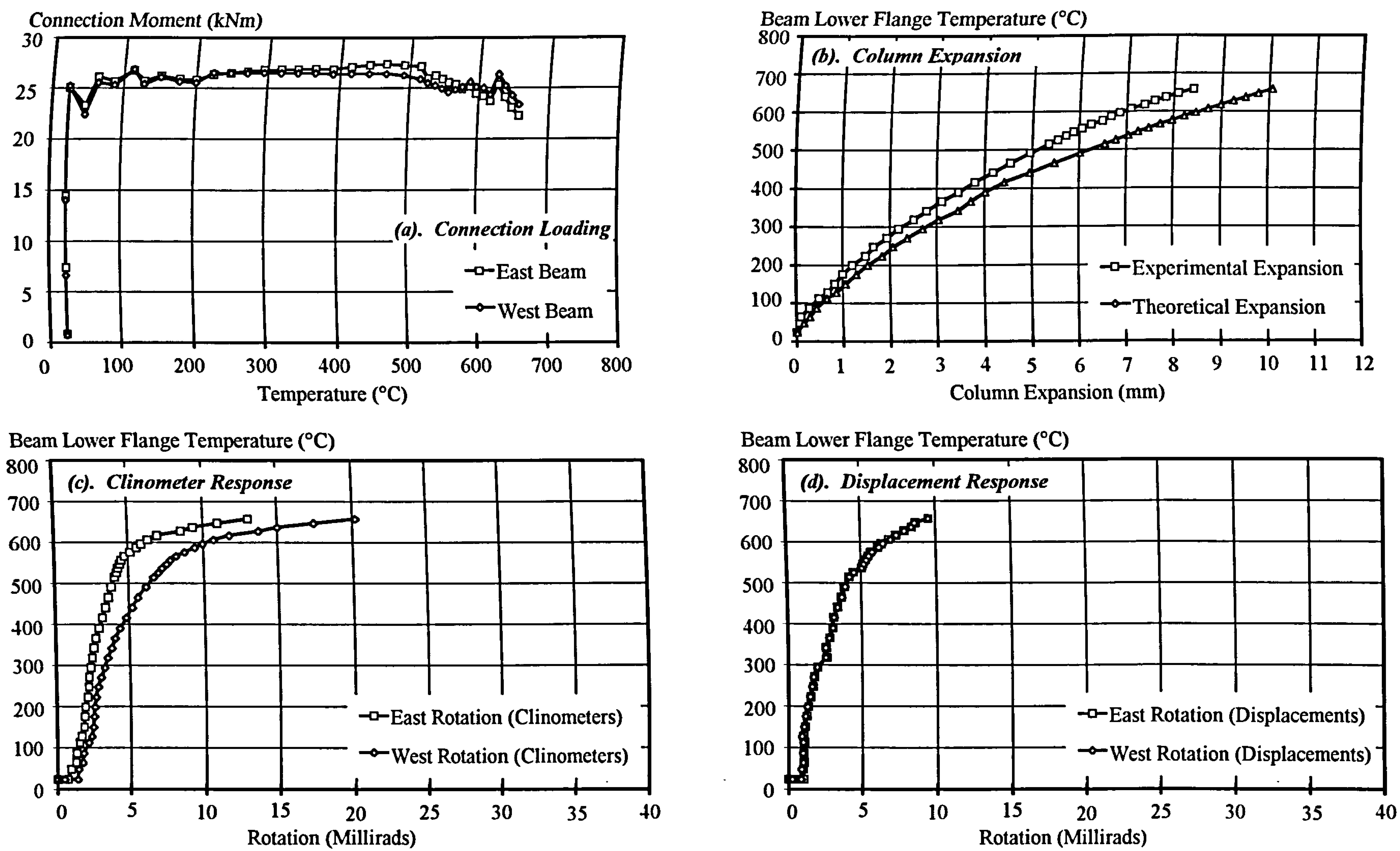


Figure 3.37. Summary of Results from Composite Connection Fire Test 2 (CFEP 25)

3.3.2.3.3. Composite Connection Fire Test 3 (CFEP 32)

The final elevated-temperature composite connection test was conducted under a nominal moment of 32kNm, and the results are summarised in Fig. 3.39. As can be seen, a fairly consistent pattern of loading was maintained throughout testing, with the average moment applied being approximately 31.1kNm.

Failure and the temperature distribution of the connection were similar to those observed previously, with there once more being no visible failure of the reinforcement in the tension zone, due to the increased flexibility of the column web at elevated-temperatures. Crack patterns for the slab may be seen in Fig. 3.29, with the intensity of cracking once more increasing, despite displacement readings indicating negligible curvature of the beams along their length.

There is a degree of variation between rotations recorded for North and South beams by both clinometer devices and the displacement readings. However, both devices indicate that the South connection underwent greater rotation, suggesting the possibility of rotation of the test arrangement. As may be seen, the clinometer readings indicate a stiffer connection than corresponding displacement readings. Indeed, the recorded rotations from clinometer devices actually suggest an enhancement in the response compared to test CFEP 25, despite the increased load level, although there is a reduction in the recorded failure temperature. Responses predicted by both displacement readings and clinometer devices are compared in Fig. 3.38.

Theoretical values for column expansion somewhat underestimate those actually recorded, probably due to the reduced temperature of the upper section of column.

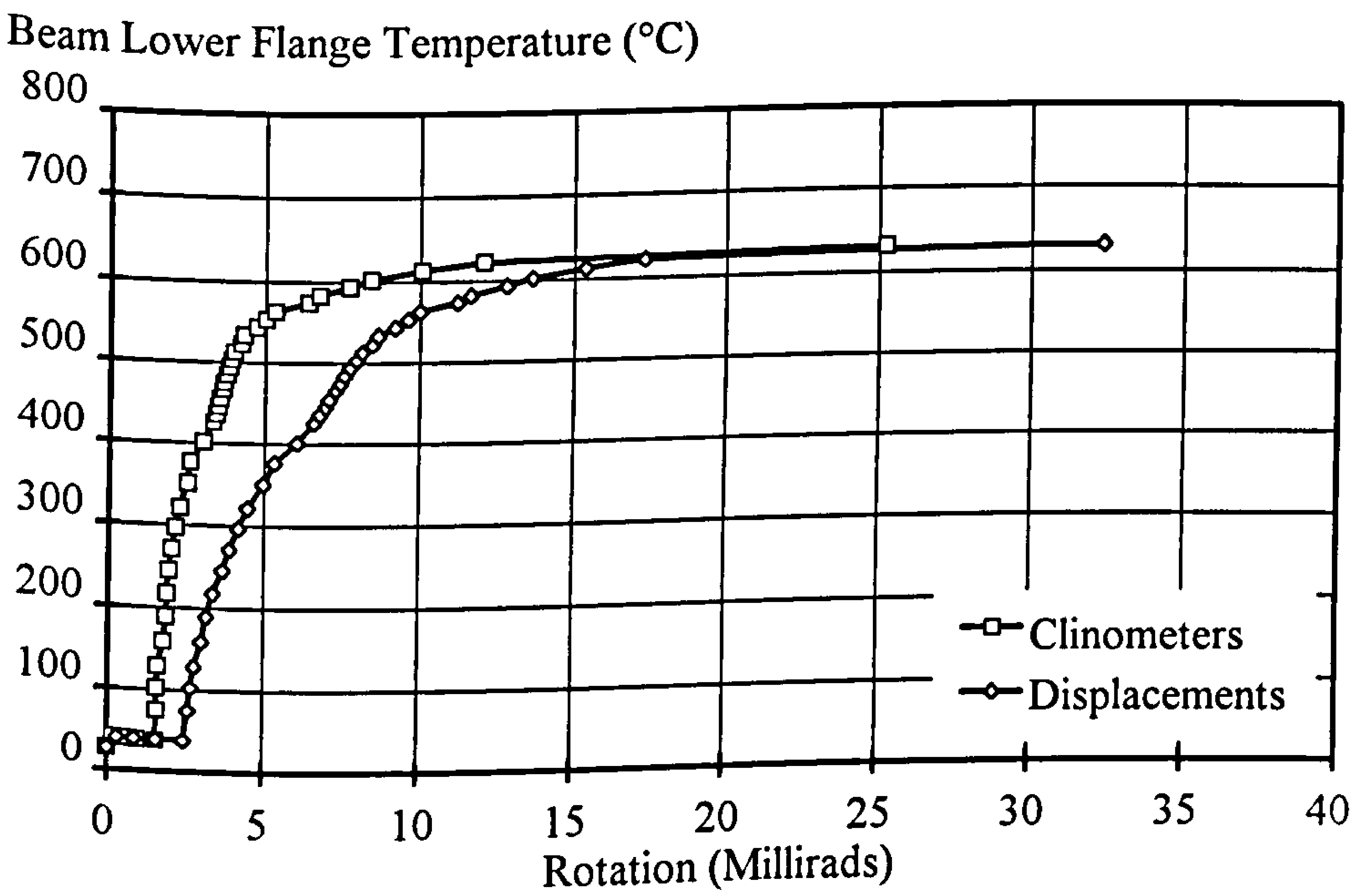


Figure 3.38. Comparison of Results from Test CFEP 32

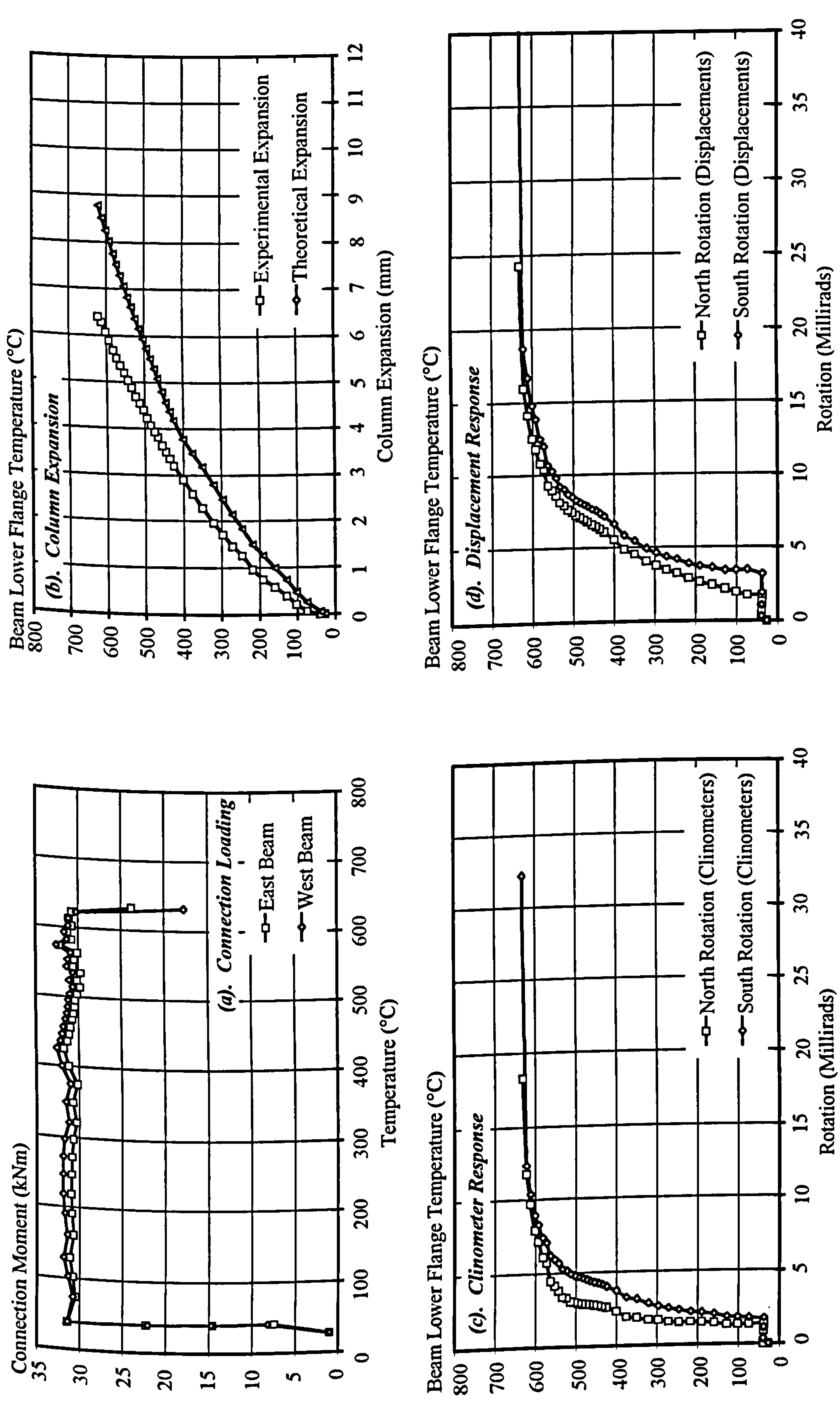


Figure 3.39. Summary of Results from Composite Connection Fire Test 3 (CFEP 32)

3.3.3. Comparison of Results from Elevated-Temperature Composite Tests

As may be seen from the results presented above for elevated-temperature composite connection tests, there was a greater variation between responses recorded by various forms of rotation device than was experienced in the case of the bare-steel connection tests, complicating the assessment of connection response with increasing temperatures.

For the first fire test it was necessary to base rotations on displacement readings, due to the failure of clinometer devices. Although this does not provide direct readings of rotation, there was a close correlation between results recorded for East and West connections, providing reassurance about the results obtained. In the second elevated-temperature test displacement readings and clinometer devices are seen to show a reasonable correlation. It should be remembered that the composite connection results are plotted to a greater scale than corresponding bare-steel results, due to the reduced ductility of the connection, and so any error is emphasised. It is suggested that the rotations from the second composite test should be based on the clinometer devices, as these provide direct readings of rotation. In the third fire test clinometer devices and displacement readings predicted a similar response, both suggesting greater rotation of the South connection. However, it may be seen that the clinometer devices indicated a connection of greater stiffness than was observed in the second fire test. It is therefore proposed that results are initially based on displacement readings. Temperature-rotation responses from all three elevated-temperature composite connection tests are summarised in Fig. 3.40.

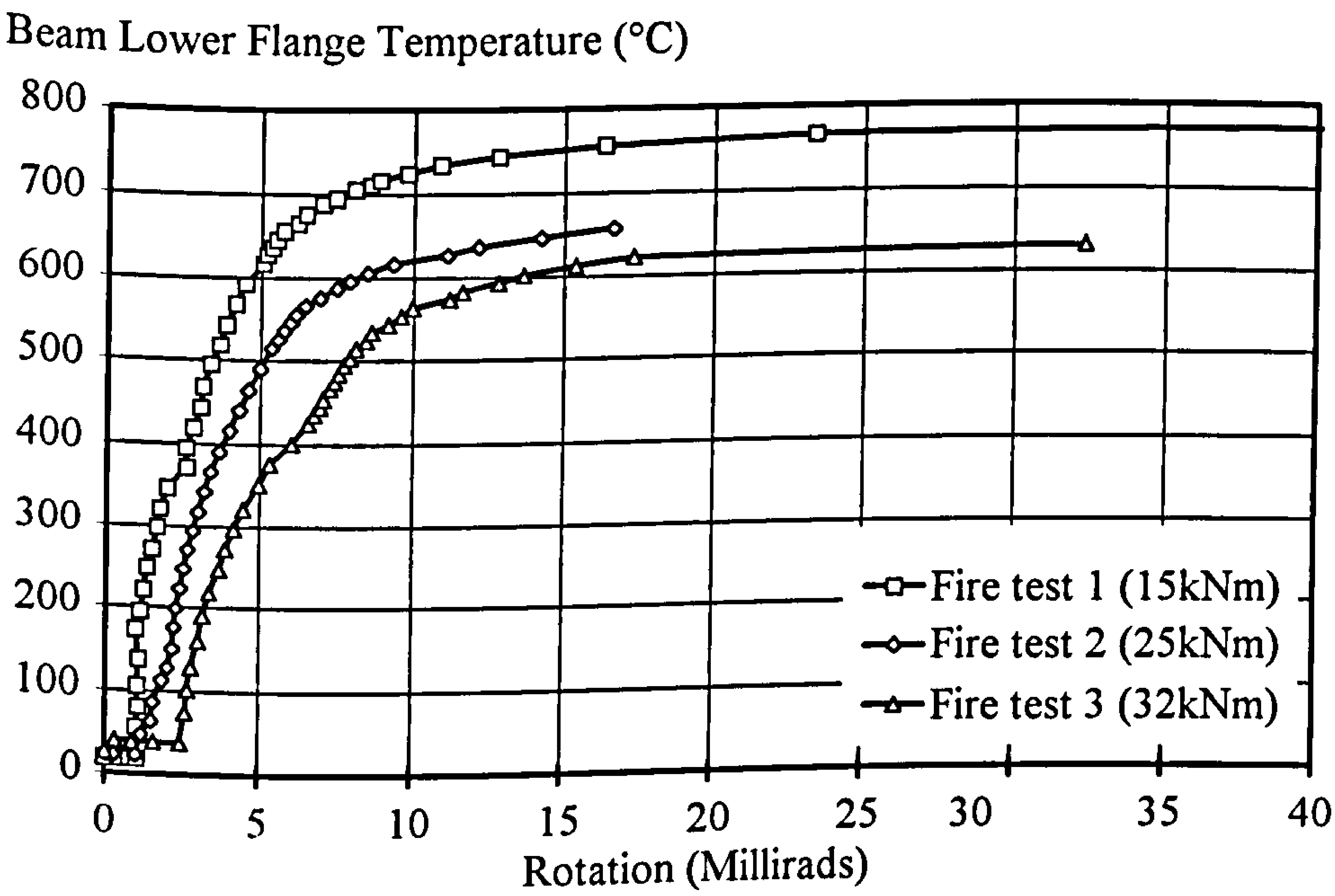


Figure 3.40. Elevated-Temperature Composite Connection Response

It may be seen that there is a significant difference between the connection response in the first fire test and those for the second and third fire tests. This is due to the capacity of composite connections degrading at a lower rate with increase in temperature than the bare-steel connection, due to the flexibility of the connection. Hence results from the first fire test will be contained almost exclusively within the range of linearity, up to temperatures approaching 800°C. Overall results from the series of tests compare well, demonstrating a consistent degradation in the performance of the connection with temperature.

Ambient-temperature results obtained whilst loading specimens within the elevated-temperature test arrangement are compared with the ambient-temperature moment-rotation response in Fig. 3.41. As with the bare-steel connection, it may be seen that the elevated-temperature test arrangement results in a more flexible connection than the corresponding ambient-temperature test. Test CFEP 25 is an exception to this observation, and actually suggests a greater stiffness than the ambient-temperature test. However, it may be seen from Fig. 3.40 that results recorded for the connection at low temperatures seem to suggest a stiffer response than at higher temperatures. If reference is made to Fig. 3.37, this is explained by the fact that the connection was subject to lower levels of load than desired up to temperatures of approximately 200°C, due to initial difficulties in maintaining consistent loading.

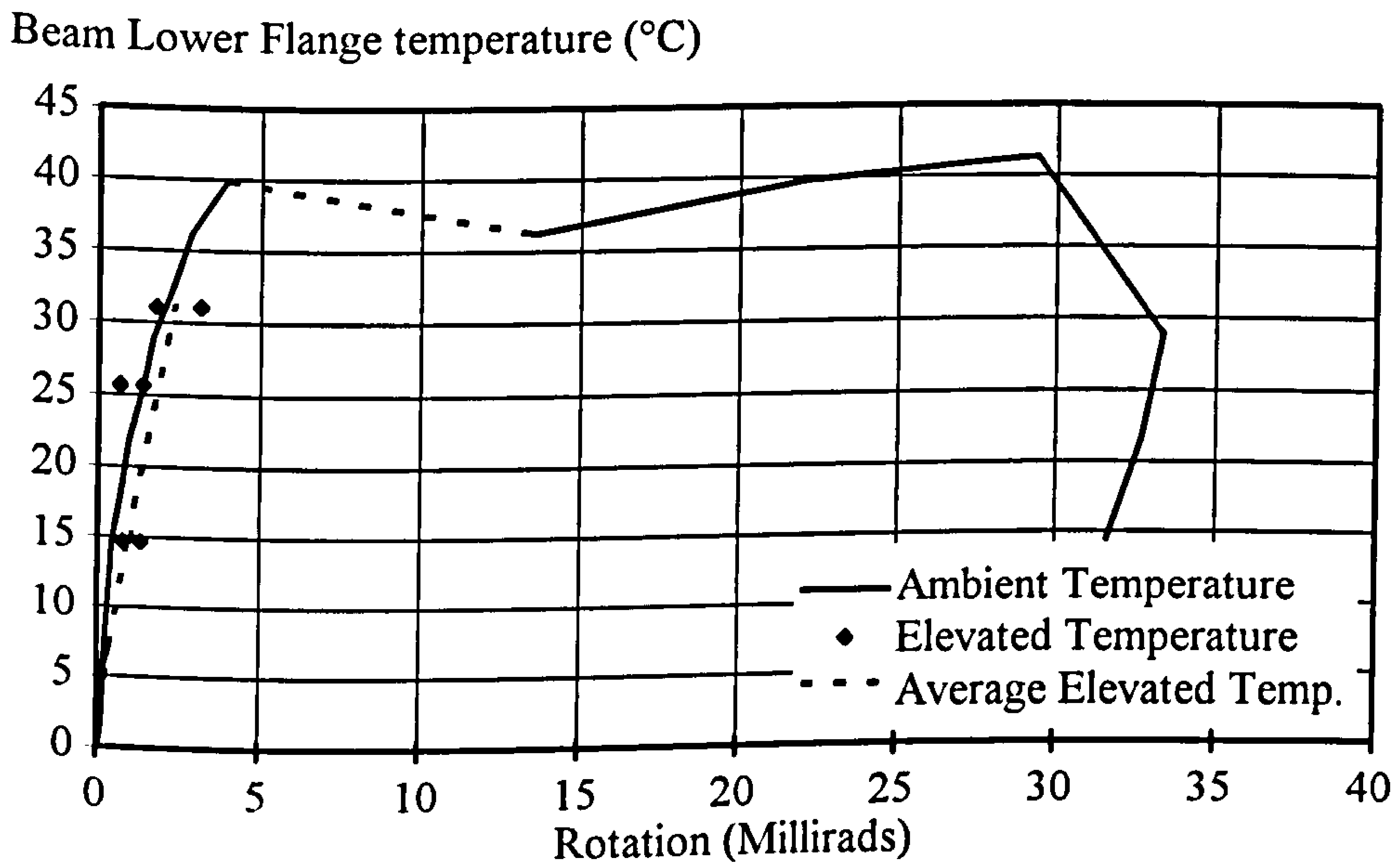


Figure 3.41. Response with Specimen Located in Furnace at Ambient-Temperature Compared to Elevated-Temperature Composite Connection Test Results

Elevated-temperature tests suggest an ambient-temperature tangent stiffness of approximately 14.2×10^9 Nmm/radian, although this will be an underestimate of the actual stiffness as it is based on a moment of approximately 15kNm at the connection. The secant stiffness was assessed to be at a somewhat reduced value of 11.6×10^9 Nmm/radian.

A consistent form of temperature profile was maintained between elevated-temperature composite connection tests, as detailed in Table 3.4. The temperature profile was seen to be similar to that recorded for the bare-steel tests, with the obvious exception of the beam upper flange, whose temperature was higher in the composite connection test as voids were left exposed. It was also observed that there was an increase of approximately 10% over the protected steel temperature. Atmospheric temperature was recorded as approximately 15% higher than in the bare-steel tests. This was not expected, as the corresponding thermocouple was located above the concrete slab, and it was anticipated that the obstruction created would result in a reduction in temperatures for the upper portion of the furnace.

Failure of the connection in all composite connection tests was similar to that observed for the bare-steel connection, with deformation restricted mainly to the column section. However, in the case of the composite connection, deformation was concentrated more in the compression zone, with this becoming more pronounced in the elevated-temperature tests. This was due to the stiffness of the compression zone reducing at a far greater rate than the tension zone, due to the relative temperature of the column section compared to the reinforcing mesh. In none of the elevated-temperature tests was there visible failure of the reinforcing mesh, because of the relative flexibility of the compression zone at elevated-temperatures. Crack patterns are consistent for all tests, although the intensity of cracking along the length of the beams is seen to intensify with increasing load, suggesting the possibility of deformation of the beams, although this was not supported by displacement readings at intermediate points along the length of each beam. In all tests cracking was seen to be almost perpendicular to the beams, indicating that limited shear lag was taking place across the width of the composite slab[75].

3.4. DEGRADATION OF CONNECTION CHARACTERISTICS

The tests that have been carried out in the present project are the first systematic series aimed at quantifying the degradation of connection resistance as temperature increases. It is clearly unrealistic to expect that many such tests can be anticipated in the future, and it is essential that simple, conservative principles be set down for acceptable fire engineering design assumptions. This is aimed at allowing degradation of the extensive fund of ambient-temperature data which now exists, and providing information for the development of simple connection models.

3.4.1. Degradation of Bare-Steel Connection characteristics

The initial stiffness S_j of a connection is directly related to the elastic moduli of the connecting materials, with the overall rotational-stiffness of the connection being dominated by the lower of the stiffnesses of the tension or compression zones. The resultant overall connection stiffness may be defined:

$$S_j^{-1} = S_t^{-1} + S_c^{-1} \qquad \text{Eq. 3.1.}$$

Where S_t and S_c relate to the stiffnesses of the tension and compression zones correspondingly.

For the bare-steel arrangement tested, the stiffnesses of the tension and compression zones would be expected to decrease at similar rates, as significant deformation of the column web in the compression zone and the column flange in the tension zone was observed. However, as the column web was recorded as approximately 15% hotter than the connection as a whole, as detailed in Table 3.2, this has been selected as the reference temperature from which to study the degradation of connection stiffness. The experimental rate of decay of stiffness was based on the first two tests conducted.

Predicted degradation of connection stiffness, based on strain levels of 0.5%, 0.1% and a level of strain contained within the proportional limit, according to the recommendations presented in EC3, are compared with experimental observations in Fig. 3.42. As described in Chapter 2, a linear-elliptical stress-strain curve is adopted in EC3: Part 1.2[8], with assessment of the degradation of material properties being complicated by the determination of a suitable level of strain. It was suggested in Chapter 2 that the Elastic Modulus should be degraded based on a level of strain contained within the limit of proportionality. It may be seen from Fig. 3.42 that this results in a reasonable approximation of the observed rate of degradation of the bare-steel connection, providing a conservative representation of the response for temperatures in excess of 200°C. As would be anticipated, a strain of 0.5% greatly underestimates the rate of degradation of the connection stiffness, with this level of strain being more representative of the rate of decay of steel capacity[48].

The capacity of a connection would be expected to degrade with temperature according to the degradation of ultimate stress for the critical element of the connection, at the relevant temperature. For the flush end-plate connection tested, it was observed that both the column web and column flange were subject to considerable deformation prior to the plastification of the connection, and hence the column web temperature has once more been selected as reference. The rate of degradation of connection capacity was based on a rotation of 70 millirads, corresponding with the maximum level of rotation in test BFEP 15, and the plateau in rotation-temperature response for all tests. Experimentally observed degradation is compared with that predicted based on levels of strain of 2.0%, 1.0%, 0.5% and 0.2% according to the recommendations of EC3: Part 1.2 in Fig. 3.42.

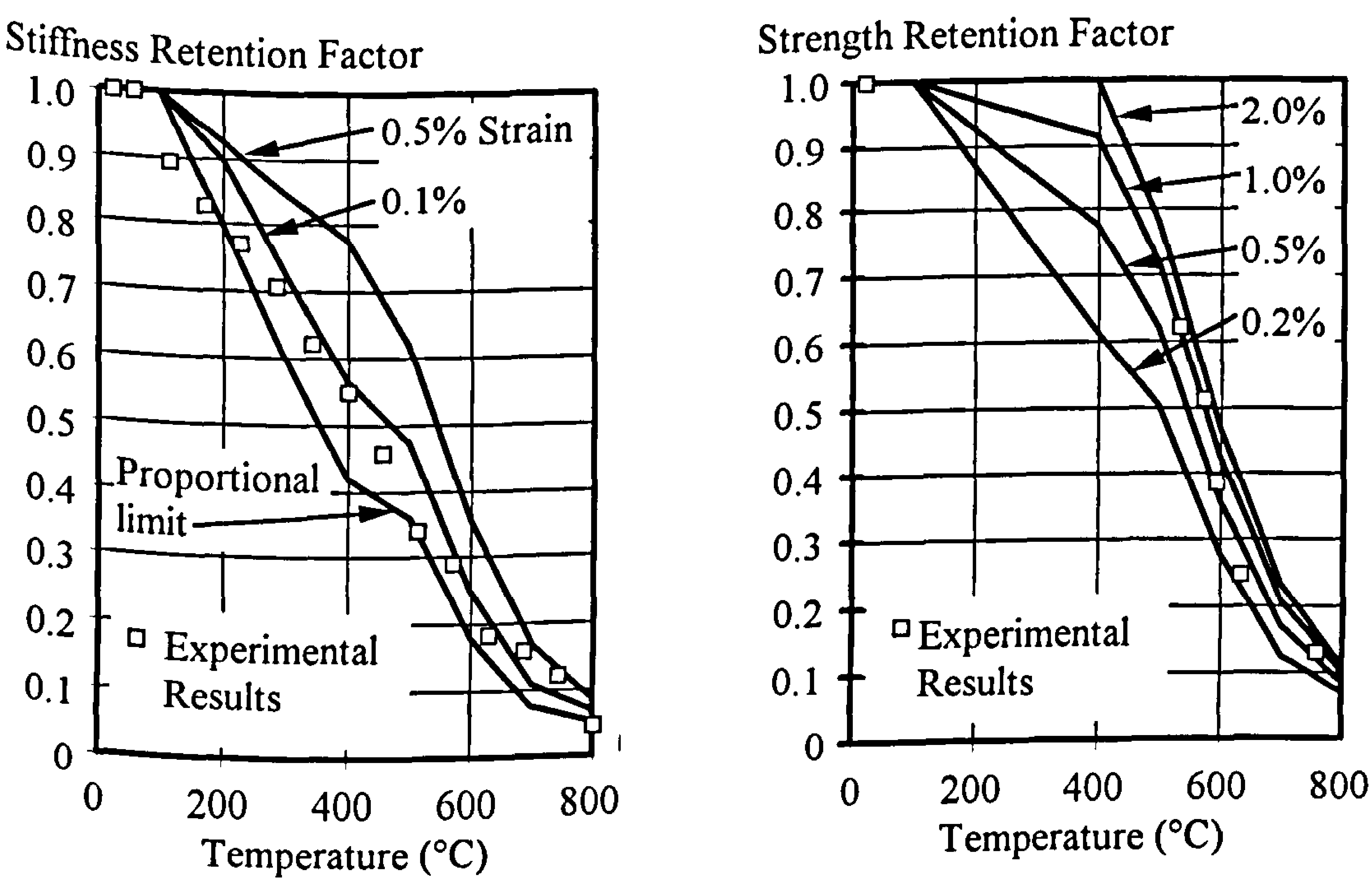


Figure 3.42. Degradation of Bare-Steel Connection with Temperature

It may be seen that a strain of 2%, corresponding to the effective yield stress in EC3: Part 1.2, underestimates the rate of degradation of the connection capacity. A strain of 2% was adopted in EC3, based on a series of elevated-temperature tests conducted by British Steel which concluded that levels of strain obtained within typical members are far in excess of the 0.5% value suggested by ECCS[48]. However, the results presented above suggest that the degradation of connection capacity is more accurately represented based on a level of strain in the range of 0.5% to 1.0%. This is possibly due to the fact that connected elements will not yet have attained full capacity, and so a level of strain of 0.5% is suggested to provide a generally conservative representation of the rate of degradation for the bare-steel connection tested.

3.4.2. Degradation of Composite Connection Characteristics

Degradation of composite connection characteristics is complicated by the influence of reinforcement which stays at a considerably lower temperature than the exposed steel, and this must be incorporated when assessing the rate of degradation.

For the composite flush end-plate connection tested, considerable flexibility of the column section in the compression zone was observed, and this would be expected to dominate the degradation of connection stiffness. As such, it is suggested that the stiffness of the composite connection may be degraded as though it were a bare-steel connection, with no account being taken of the influence of the reinforcing mesh. The observed rate of degradation is compared in Fig. 3.43 with that predicted according to EC3, assuming levels of strain of 0.5%, 0.1%, and a level of strain contained within the limit of proportionality.

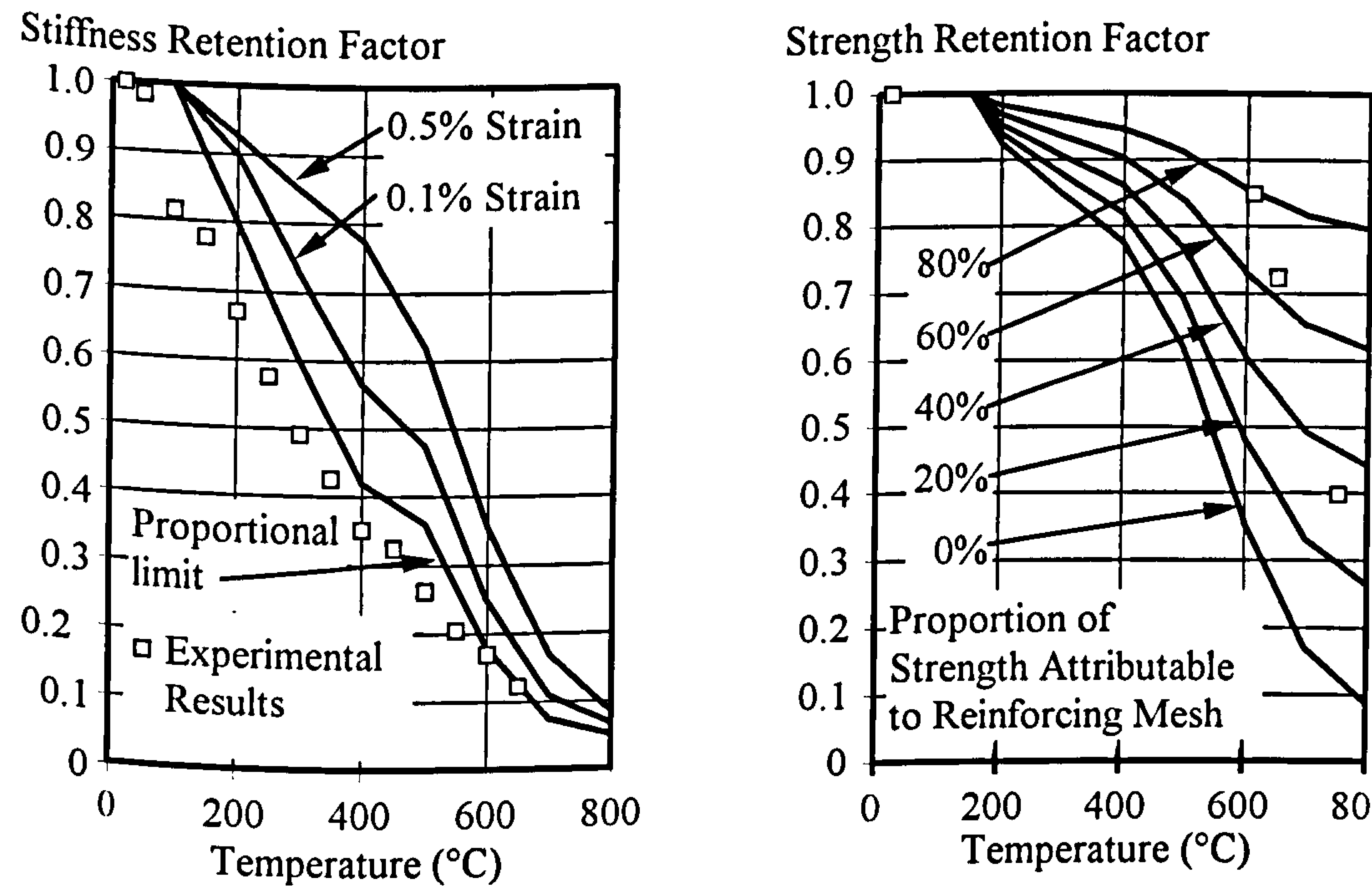


Figure 3.43. Degradation of Composite Connection

It may be seen that the composite connection stiffness degraded at a rate greater than that of the bare-steel connection, and that theoretical rates of degradation underestimate those actually observed. This may possibly be due to increased forces in the compression zone, due to the enhanced capacity of the tension zone.

In the consideration of overall connection capacity a number of authors have previously assumed that the resultant capacity may be obtained by summing the capacity of the bare-steel connection and that arising from the resistance of the reinforcement within the composite slab, resulting in the moment capacity of a composite connection M_{cj} being defined as:

$$M_{cj} = M_j + M_r \qquad \text{Eq. 3.2.}$$

Where M_j and M_r are the levels of moment attributable to the bare-steel connection and reinforcement respectively. The use of such an equation would result in a significant enhancement in connection capacity at increasing temperatures due to the reinforcement remaining at a reduced temperature.

The use of the above equation is somewhat simplified, and assumes that the capacity of the tension zone controls (i.e. the connection will not fail through crushing of the beam flange or column web in the compression zone). Whilst this is often true for connections at ambient-temperatures, with increasing temperatures the capacity of the compression zone will degrade at a higher rate than the tension zone. However, assessment of the relative rates of degradation of the tension and compression zones, and the influence this has on overall connection response is complex. As such the degradation of composite connection capacity has initially been assessed based on a range of proportions of overall capacity attributable to the bare-steel connection and to the reinforcing mesh, with these being degraded individually on the basis of their relative temperatures and material properties.

Predictions are presented for the degradation of composite connection capacity in Fig. 3.43, based on a range of percentages of overall moment capacity attributable to the reinforcing mesh at ambient-temperature. An approximate value of 45% of the overall connection capacity is suggested to derive from the reinforcing mesh, based on the observed capacity of the bare-steel connection in the region of 17kNm, and the yield strength of the reinforcing mesh, assuming rotation about the lower flange of the connection. This results in a conservative approximation of the actual response for temperatures approaching 700°C. For increasing temperatures the modelled degradation fails to follow the rapid reduction in capacity recorded experimentally.

It may be seen from Fig. 3.43 that the general form of curve obtained based on the above recommendations does not follow the response observed experimentally, with experimental results suggesting a lower rate of degradation of capacity for temperatures up to 600°C, becoming more pronounced at higher temperatures. This may possibly be due to the relative stiffness of the column web decreasing with temperature at such a rate that it eventually controls the capacity of the connection. This corresponds with the observed failure of the connection in elevated-temperature tests, in which there was considerable deformation of the column web in the tension zone without resulting in failure of the reinforcing mesh. The model described assumes rotation about the lower flange and clearly, due to the flexibility of the column web, this would not be the case. As temperatures increase, the centre of rotation of the connection would move towards the tension zone, resulting in a lower level of moment resistance, accelerating connection failure.

3.4.3. Observed Degradation in Previous Elevated-Temperature Connection Tests

As described in Chapter 1, a limited number of tests have previously been conducted to investigate the response of semi-rigid beam-to-column connections at elevated-temperatures. Tests conducted by Lawson[44] considered a range of connection types representative of those commonly adopted. However, as only a single test was conducted for each connection, under constant moment with increasing temperatures, the extent of information available is limited.

The results presented by Lawson have been analysed by El-Rimawi[76], to postulate moment-rotation characteristics for flush end-plate and extended end-plate connections across a range of temperatures. Resulting moment-rotation characteristics are compared in Fig. 3.44, in which the moment-rotation curves were generated based on limited test data and the Ramberg-Osgood form of curve-fit. It may be seen from the moment-rotation curves presented that load levels adopted in testing were contained within the non-linear range of response, and so the results are not directly related to the degradation of connection stiffness.

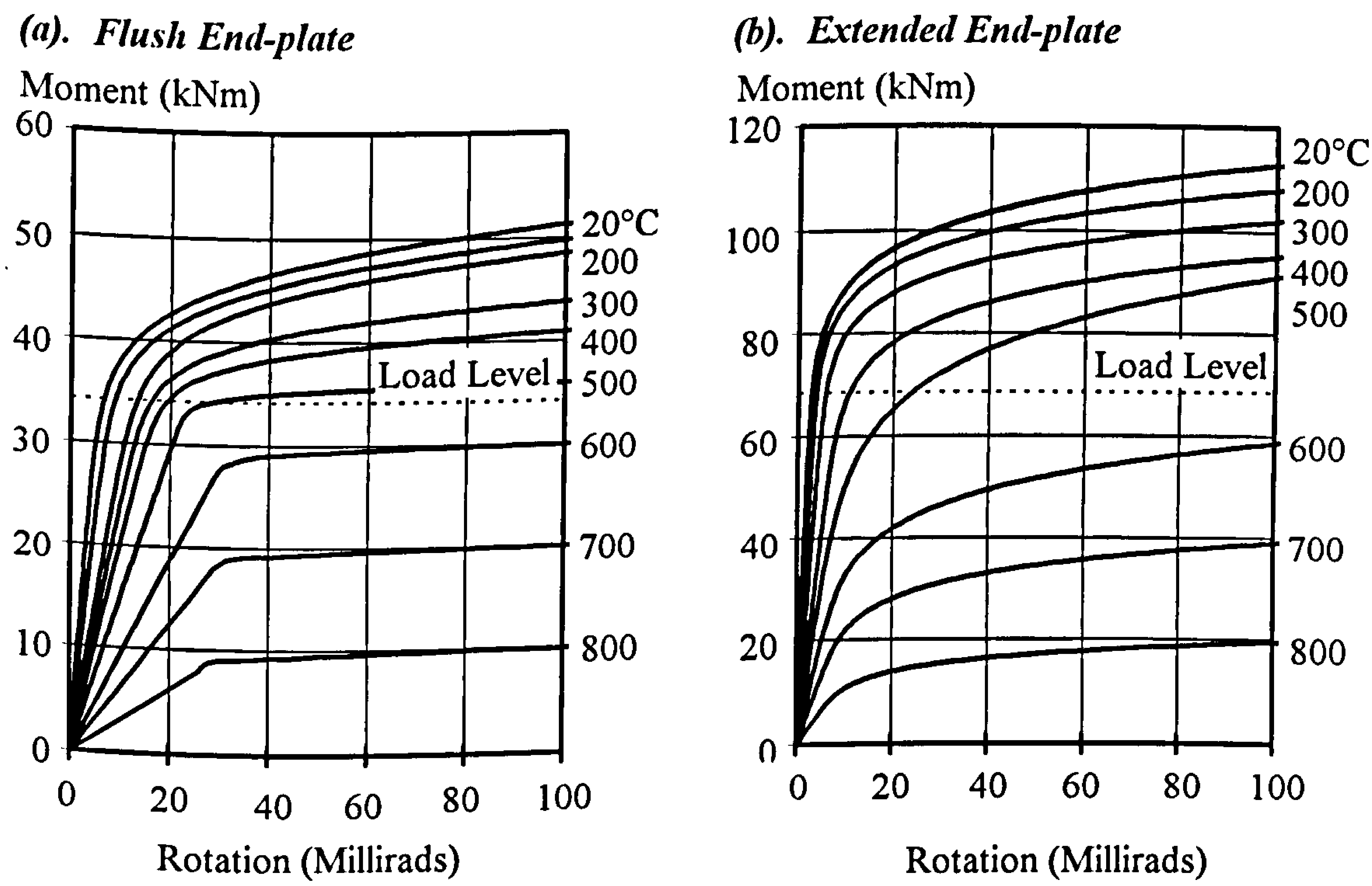


Figure 3.44. Postulated Elevated-Temperature Moment-Rotation Characteristics[44]

An assessment of the rate of degradation of stiffness using the curves postulated by El-Rimawi for both flush and extended end-plate connections is presented in Fig. 3.45(a). It may be seen that, for both types of connection, theoretical rates of degradation based on the assumptions presented above greatly underestimate those observed. However, this is possibly due to the fact that experimental values over-estimate the rate of degradation due to the level of load at which testing was conducted, and the limited quantity of experimental data available. This theory is supported by the fact that results from the extended end-plate test compare better with the anticipated rate of degradation than the flush end-plate connection, and it may be seen from Fig. 3.44 that Lawson's tests were contained more or less within the elastic range of connection response up to temperatures of approximately 400°C.

Observed rates of degradation of connection capacity are presented in Fig. 3.45(b) based on the response of the bare-steel flush and extended end-plate connections tested by Lawson. It may be seen that there is a reasonable correlation between the response observed by Lawson and the flush end-plate connection described above, with a strain of 0.5% representing a conservative approximation in most cases. However the results presented based on the tests should be treated with care, as the actual capacity of the connections at ambient-temperatures was unknown, and was estimated based on the capacity of the bolts in the tension zone, with the connection being designed to sustain this level of moment. Experience of connection response suggests that this approximate technique of determining connection capacity can deviate considerably from the true response. Temperatures adopted in the analysis of the degradation of connection capacity were those for the top bolt in the tension zone (exposed in the case of extended end-plate connections) as this was designated as the critical element, although no details were presented regarding the true failure mechanism of the connections.

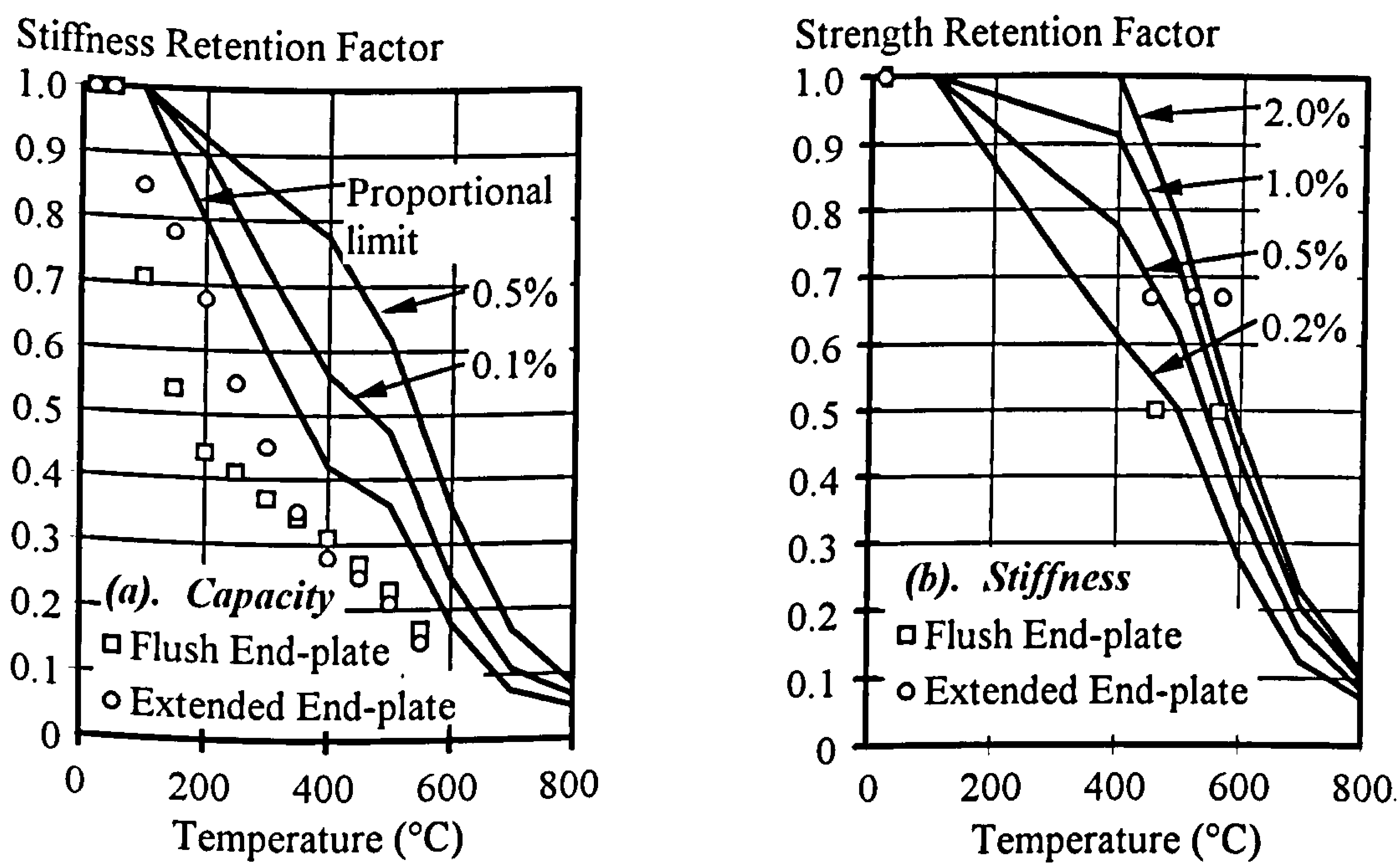


Figure 3.45. Degradation of Connection Characteristics from Tests by Lawson

3.4.4. Comments on the Observed Rates of Degradation

The rates of degradation have been studied for both the bare-steel and composite full depth end-plate tested. It was observed that for the bare-steel connection reasonable approximations of rates of degradation of stiffness and capacity were possible based on levels of strain respectively contained within the proportional limit and of 0.5%, with rates of degradation based on the actual failure mechanism of the connection and the corresponding temperature of the critical element.

For the composite connection stiffness degraded at a rate similar to that for the bare-steel connection, due to its dependence on the flexibility of the column web in the compression zone. However, an assessment based on the recommendations given resulted in an un-conservative approximation of the actual response, possibly due to the increased level of force in the compression zone. Assessment of the degradation of composite connection capacity was complicated by the influence of reinforcing mesh which remains cool. Attempts to assess the proportions of the overall connection response attributable to the bare-steel connection and the reinforcing mesh, and degradation of these, resulted in a form of degradation different from that observed experimentally. This may be due to movement of the neutral axis as testing progressed, with the behaviour of the compression zone eventually controlling the capacity of the connection. A more accurate assessment of the degradation of composite connection response might be achieved for an arrangement in which the flexibility of the compression zone has a smaller influence, for example in situations where the column web is stiffened in the compression zone.

Attempts were made to study the rate of degradation for elevated-temperature bare-steel extended and flush end-plate connection tests conducted by Lawson. These generally support the recommendations presented above, although it is not possible to present strong conclusions, due to the limited number of tests conducted and quantity of data produced.

3.5. COMMENTS

A series of tests has been conducted investigating the influence of elevated-temperatures on the response of a flush end-plate connection, as both bare-steel and composite with a concrete slab. Testing was restricted to two connection types due to the quantity of tests required to define accurately the response of a single connection across a range of temperatures.

Failure of both the bare-steel and composite connections was observed to be dominated by the comparatively flexible column section. In the case of the ambient-temperature composite connection test, failure of the inner reinforcement was observed, although this was not experienced in the case of the elevated-temperature tests due to the increased flexibility of the column web in the compression zone, at a significantly higher temperature than the reinforcement in the tension zone. Due to the observed failure of the inner reinforcement at ambient-temperatures, there was little enhancement in capacity in the case of the composite connection.

Stiffness and capacity were observed to decrease for both connections with increasing temperature. Stiffness degraded at a similar rate for both the bare-steel and composite connections, due to the relative flexibility of the column web in the compression zone. It was observed that the capacity of the composite connection degraded at a lower rate than that of the bare-steel connection, due once again to the influence of the cool reinforcing mesh in the tension zone.

Initial assessment of the rates of degradation of both connection stiffness and capacity suggests that a reasonable approximation may be made of the degradation of the bare-steel connection, based on an understanding of the mechanisms of the connection response and a knowledge of elevated-temperature material properties for the connected elements. However, assessment of composite connections is complicated by the influence of reinforcement at a reduced temperature, and due to the flexibility of the column section in the arrangement tested this results in a rate of degradation which is complex to quantify.

Clearly the results presented are limited in their applicability, and it is essential that further testing is carried out in order to assess the influence of different connection types and member sizes.

4. CONNECTION MODELLING AND CURVE - FITTING

4.1. INTRODUCTION

The applicability of experimentally derived connection characteristics is limited by the expense associated with testing and the wide range of connection types commonly adopted. As such there is a real need to consider the ability with which connection characteristics may be generated, or extrapolated from existing data banks[36]; with a view to incorporate connection characteristics within numerical analysis of overall frame response.

A knowledge of the moment-rotation response, or the ability to approximate critical parts thereof, are essential in the analysis of frame behaviour where there is a desire to incorporate the influence of semi-rigid connections. The constituents of connection behaviour that are critical in the analysis of semi-rigid frame response may be simplified as: strength; stiffness; and ductility; although there may be a desire to represent the full moment-rotation response where more sophisticated analysis is to be conducted. Forms of connection modelling range from simple curve-fitting, through to semi-empirical relationships and finite-element analysis, with existing models for both bare-steel and composite connections commonly being classified according to their theoretical basis into four main categories:

1. Mathematical expressions;
2. Simplified analytical models;
3. Mechanical models accounting for major aspects of response;
4. Finite-element analysis.

The various forms of model described are discussed generally below, with their advantages and limitations being considered in the context of both ambient, and elevated-temperature analysis.

4.2. MATHEMATICAL EXPRESSIONS

Mathematical expressions exist primarily as a tool with which to represent experimental data, or numerical simulations, in a form suitable for incorporation within analytical models. Parameters within the model are frequently linked to the physical characteristics of the connection. The equation should ideally represent the curve in terms of key parameters such as initial-stiffness, strain hardening stiffness and moment capacity, and it is desirable that the mathematical expression defining the curve should satisfy the following requirements:

1. The equation should be capable of representing the non-linear moment-rotation characteristics of the connection throughout the entire range of rotation;
2. The equation should always yield a positive slope corresponding with the rotational stiffness of the connection;
3. The curve should pass through the origin.

Nethercot *et. al.*[77] concluded from studies of both frames and individually restrained members that behaviour beyond 50 millirads has little practical significance in the case of ambient-temperature analysis. At elevated-temperatures far greater levels of deflection and hence rotation are permissible, necessitating more extensive data. The form of curve-fit should ideally be capable of limiting the maximum rotation of a connection, and in the case of connections where the beam lower flange comes into contact with the column flange at high levels of rotation (such as the partial depth end-plate) should be capable of following the subsequent increase in connection stiffness. The question of limiting rotations of connections is one which was not addressed in the experimentation detailed in Chapter 3. However, due to the increased ductility of connections with increasing temperatures it would be anticipated that typical arrangements would be capable of withstanding significant rotations.

Initial attempts to model experimental work by Baker[78] and Rathburn[79] date back to the 1930's. Due to computational limitations at the time a single straight line corresponding to the initial tangent-stiffness of the connection was selected to define connection behaviour, leading to the notion of the semi-rigid connection factor *Z*, which may be directly introduced within slope-deflection equations or moment redistribution.

The applicability of linear modelling of connection characteristics is restricted to connections where the level of rotation is expected to remain within the elastic range of response. As described, whilst this may be satisfactory for ambient-temperature studies, particularly of connections which are designed as 'rigid', in the case of elevated-temperature analysis and the analysis of flexible connections, it may be anticipated that the connection would enter the plastic range of response at low levels of moment. This is highlighted in Fig. 4.1. where the ambient-temperature moment-rotation curve for the bare-steel flush end-plate connection tested is compared with various forms of linear curve-fit. It may be seen that for a moment approaching 20 kNm, the use of a purely linear form of curve-fit predicts a rotation of 10 millirads, compared with the experimentally observed value of approximately 60 millirads. As such it is suggested that

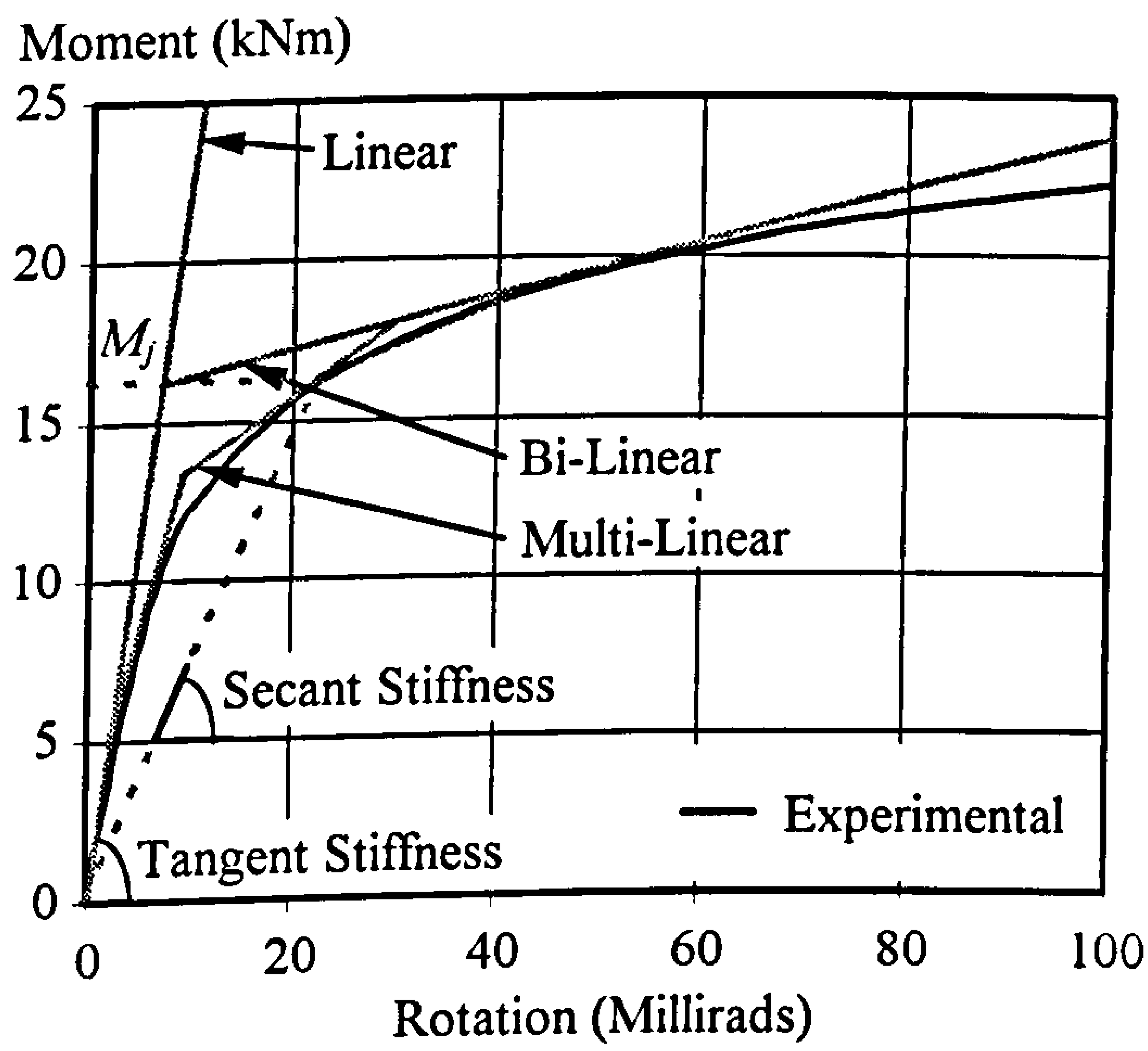


Figure 4.1. Linear Forms of Curve-Fit

the use of linear curve-fitting is of limited applicability in the analysis of elevated-temperature frame response with nominally semi-rigid connections.

It was not until the 1970's that further attempts were made to refine the representation of connection characteristics. Bi-linear curve fit techniques were introduced by Lionberger and Weever[80] and Romstad and Subramanian[81] which recognised the reduced stiffness of connections at high levels of rotation. Bi-linear forms of curve-fit typically consist of a linear portion following the initial tangent-stiffness, which is intersected by a line of reduced stiffness, being tangential to the reduced plastic-stiffness of the connection. It is debatable as to whether the initial tangent-stiffness should be adopted, or the reduced secant-stiffness. The secant-stiffness may be defined as a linear stiffness between the origin and the level of rotation at which the fully non-linear moment-rotation curve is intercepted by the design moment capacity. This results in a conservative form of curve-fit, lying wholly below the true response as shown in Fig. 4.1, making its use more applicable in the case of structural design. In the recently revised Annex J of EC3[41] the secant-stiffness has been adopted as opposed to a tangent-stiffness, where the stiffness is assumed to intercept the true moment-rotation curve at a level of moment corresponding with two-thirds of the connection capacity. This is followed by a reduced stiffness in the strain-hardening range of response, being half that of the secant-stiffness, extending up to the plastic limit. Similarly, a elastic-perfectly plastic response may be adopted neglecting the influence of strain-hardening. Care should be taken when using bi-linear forms of curve-fit as the assumption of a constant plastic-stiffness may result in an un-conservative assessment of moment capacity at high levels of rotation.

Moncartz and Gerstle[82] recognising the limitations of bi-linear forms of curve-fit to follow the rounded knee between the ranges of elastic and plastic response, and proposed that an additional linear slope should be incorporated between the elastic limit and yield moment as shown in Fig. 4.1. Connection models have been further refined due to developments in computational capabilities, with multi-linear models being presented by Poggi and Zandonini[83] to overcome the obvious limitations of bi-linear curve modelling.

At a similar time to the introduction of bi-linear forms of curve-fit, polynomial models were developed by Kennedy[84] and Sommer[85], and somewhat later by Frye and Morris[86], in an attempt to represent the non-linear nature of moment-rotation curves. Whilst this form of curve-fit is capable of more closely representing the true non-linear response, this method may sometimes yield a negative connection stiffness, which is unacceptable.

B-spline techniques were suggested by Jones *et al*[87] to avoid the possibility of negative slopes, where continuity was forced for the first and second derivatives at the intersections of experimental data. Although this form of curve-fit can closely follow the form of connection-response, a large quantity of experimental data is required to achieve an acceptable fit.

An alternative to the polynomial form of curve-fit was presented by Ramberg and Osgood[88] in the 1940's to define the non-linear nature of stress-strain curves in terms of three simple parameters. The expression has subsequently been extended by Ang and

Morris[89] and El-Rimawi[76] to describe moment-rotation characteristics. When applied to moment-rotation curves the model has the advantage of always yielding a positive slope, corresponding with the tangent-stiffness of the connection. The modified version of the Ramberg-Osgood equation states that:

$$\phi_c = \frac{M_c}{A} + 0.01\left\{\frac{M_c}{B}\right\}^n \qquad \text{Eq. 4.1.}$$

Where ϕ_c is the connection rotation,
M_c is the corresponding level of moment,
and A, B and n are temperature dependent factors.

Application of the Ramberg-Osgood from of curve-fit to elevated-temperature connection data yields the advantage that the equation may be degraded for increasing temperatures by modification of the terms A and B controlling the stiffness and capacity of the connection respectively. It is this feature along with the facility of the form of curve-fit to satisfy the criteria detailed above which has led to the incorporation of the Ramberg-Osgood equation within a number of existing models of elevated-temperature frame behaviour[22,76].

The Ramberg-Osgood curve-fit is typically applied to experimental data based on the least-squares method of solution. However, it was found that when a limited quantity of test data is available a more accurate fit was achieved through an iterative process of visual inspection and refinement. The modified Ramberg-Osgood equation has been applied to the experimental data for both the bare-steel and composite connections tested. Resultant moment rotation-curves are shown in Fig. 4.2 below, and associated parameters are detailed in Table 4.1. It may be seen from the parameters described in Table 4.1 that the term n defining the shape function of the moment-rotation curve remains constant for both

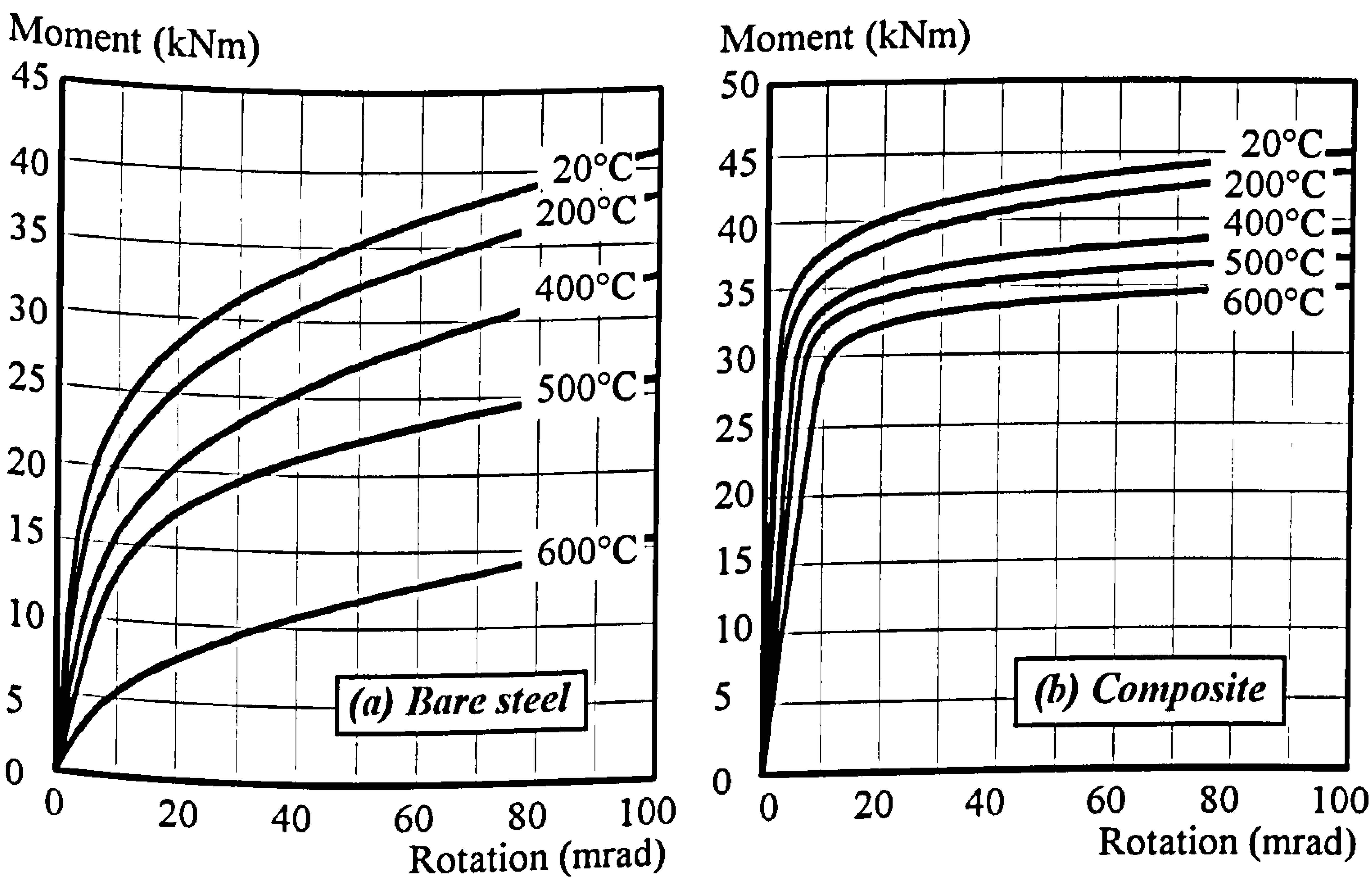


Figure 4.2. Ramberg-Osgood Curve-Fit for Flush End-Plate Connection Tested

the bare-steel and composite connection for increasing temperatures.

Plots of the associated tangent-stiffness (as adopted in numerical modelling) demonstrated that as the shape function remained almost constant with increasing temperatures, the influence of temperature on tangent-stiffness was more accurately modelled based on a constant value of n, with the terms A and B decreasing with temperature. Initial attempts at incorporating varying values of n was seen to result in values of tangent-stiffness which did not necessarily degrade with increasing temperature (over isolated sections), clearly not correlating with the response implied from the recorded moment-rotation characteristics. Where a more visible variation of the shape of the moment-rotation curve was observed for increasing temperatures it would not be envisaged that the incorporation of varying values of n would adversely influence the overall response.

Temperature	*A*	*B*	*n*
20°C	*5.400*	*6.100*	*4.800*
100°C	*4.978*	*6.000*	"
200°C	*4.293*	*5.800*	"
300°C	*3.468*	*5.300*	"
400°C	*2.548*	*4.950*	"
500°C	*1.614*	*4.100*	"
600°C	*0.885*	*2.400*	"

Temperature	*A*	*B*	*n*
20°C	*15.304*	*24.166*	*14.743*
100°C	*15.304*	*24.166*	"
200°C	*13.758*	*23.393*	"
300°C	*11.111*	*22.592*	"
400°C	*8.647*	*21.532*	"
500°C	*7.254*	*19.500*	"
600°C	*3.811*	*16.530*	"

Table 4.1. Ramberg-Osgood Parameters for the Bare-Steel and Composite Flush End-Plate Connections Tested

A multi-parameter, exponential model, proposed by Lui and Chen[90] requiring four or more parameters to effectively describe the connection characteristics has been successfully used in a number of studies by Lui and Chen.

4.3. SIMPLIFIED ANALYTICAL MODELS

Simplified analytical models are based on the prediction of the key parameters within the connection response, such as initial-stiffness and moment capacity, and fitting a skeleton curve through these points. The derivation of these parameters requires a knowledge of the mechanical and geometrical properties of the joint, and may be obtained either from experimental studies or simple analytical modelling, typically restricted to the critical component of the connection. For this reason simplified analytical models are typically restricted to more flexible arrangements where deformation may be easily attributed to an isolated element.

A number of authors have considered the response of key components within connection response for various types of semi-rigid connection. It has been usual to conduct an initial series of tests to identify the major sources of deformation, and then to perform a purely elastic analysis of these based on basic concepts of structural analysis, with a plastic mechanism being assumed to obtain the ultimate capacity. Predictions may then be verified against test data, and expressed in the form of a curve-fit linking the response of the critical components to simplified mathematical terms.

Lothers[91] described an elastic model for the analysis of the initial flexibility of double web cleat connections. This ignoring all forms of deformation other than bending of the cleats, but proved capable of predicting with reasonable accuracy the initial-stiffness of a series of test by Rathburn[79].

Lewitt[92] later developed a formulae for the initial elastic and final plastic phases of the load deformation behaviour of double web-angle segments, concentrating on the response of the angles under tension. The definition of the centre of rotation is essential for such a flexible form of connection, and was defined for the described model on experimental data.

Chen *et. al.*[93,94,95] considered the behaviour of web-cleats, flange-cleats and combined web and flange-cleat connections, utilising a power expression to generate the resultant moment-rotation response. In each of these models the connection was assumed to be to a rigid support, with the elastic and plastic stiffnesses and capacity being assessed by simplified structural idealisations. The resultant expression expressed the response in terms of the initial connection stiffness, plastic connection stiffness and the rotation at which the onset of plasticity may be assumed. A shape factor n was introduced based on experimental data to define the form of the resultant moment-rotation response.

Johnson and Law[96] recognised the influence of connectivity to a 'flexible' column on the response of both bare-steel and composite flush end-plate connections, and developed expressions defining the response of individual connected components. Constituent parts of the connection were superimposed, based on the assumption that the interaction between connected joint components has a negligible influence on the response of the joint of a whole. Joint response was expressed in terms of initial-stiffness and plastic-capacity, with the simplified assumption of a elastic perfectly-plastic form of curve-fit. Whilst verification of the response of component parts of the connection generated a close comparison with experimental data, no studies were conducted to compare the response of a connection as a whole with experimental data.

Yee and Melchers[97] have recently developed a model of a similar form to that described by Johnson and Law[96] for the analysis of bolted end-plate eaves connections, based around a polynomial curve-fit to models defining elastic and plastic stiffness and moment capacity. As with the model developed by Chen *et. al.*[93] a shape factor was introduced based on experimental data to define the non-linear form of moment-rotation response. Plastic-stiffness was defined on the assumption of stain-hardening of connection components or the post-buckling stiffness of the column web in compression. The incorporation of the shape factor c, being dependent on the form of bolted connection and the existence of stiffeners, resulted in a close correlation with test data.

A simplified analytical model has been adopted in Eurocode 3[41] for the analysis of connections, where mechanical models have been adopted to calculate connection capacity, and empirical equations adopted for the description of connection stiffness. The introduction of a codified approach to connection analysis represents a significant step in the incorporation of semi-rigid connection characteristics in design calculations, which had previously been hindered by the complexities associated with developing acceptable connection characteristics.

Composite forms of simplified modelling were introduced by Johnson and Law[96] in 1981. A tri-linear form of curve-fit was adopted to describe the moment-rotation response. Simplified models were used to describe the elastic-stiffness and plastic moment-capacity of the connection, where rotation was assumed to occur about the lower flange of the beam. The tensile resistance of the concrete and shear-lag effects were neglected. Ultimate capacity of the connection was obtained by the simple summation of the capacity of the bare-steel connection and that of reinforcement in the tension zone. Values of the limiting elastic-moment and rotation at which the onset of plasticity may be assumed were defined from test data for differing connection types. Whilst this form of model is suited to flexible forms of connection in which rotation may reasonably be assumed to occur about the lower flange, the neglect of column flange and slab deformation may significantly influence the results obtained.

Aribert[98] has more recently presented a model for flush end-plate type connections with a composite slab based on a series of eight tests. The form of the model adopted is similar to that proposed by Johnson and Law[96]. However, the accuracy of the model is doubtful with errors of up to 100% being observed when compared with experimental data.

4.4. MECHANICAL MODELS

To overcome the obvious limitations of simplified modelling, mechanical models rely on the definition of individual sources of deformation within an arrangement, resulting in an approximation of the response of the connection as a whole.

Mechanical models consist of a set of rigid and deformable elements representing the behaviour of specific components of the joint. Connection response is then obtained by defining the response of the deformable elements, based upon test data, numerical simulations or analytical models, and combining the response of the constituent parts. The accuracy with which mechanical models are capable of accurately predicting connection response is related to the number of elements of deformation incorporated, and for this reason this approach has predominantly been restricted to connections where the number of governing parameters is limited.

Kennedy and Hafez[99] adopted a simple T-stub model to represent the response of partial depth end-plate connections in both the tension and compression zones, where the T-stub response was developed and validated against test data. A trial and error location of the centre of rotation was then adopted to define the moment-rotation response. Comparison against tests conducted by the author demonstrated a close agreement in terms of ultimate capacity, but a rather erratic prediction of the corresponding level of rotation.

Wales and Roscow[100] considered the modelling of double web-cleat connections. The connection was idealised as two rigid bars linked by independent non-linear springs, which simulate segments of the double-web angle. Response of segments subject to either compressive or tensile forces were determined from simple analysis. The angle and column flange are assumed to act in tension along with bolt deformation, whilst compressive forces are resisted solely by the column web. Modelling also incorporated the influence of axial forces. Comparison with a single test by the author generated good results.

The form of model developed by Wales and Roscow has more recently been extended by Richard *et. al.*[101] in the prediction of the response of all forms of cleated connections subject to bending and shear. The force deformation response of double-angle segments was calibrated by curve-fitting against experimental data obtained by the author. Further validation of the model was conducted based on a broader range of test data by others, generating good results in cases where deformation of column components and slip of bolts was negligible. It is however, possible to incorporate these aspects of deformation without modifying the component of the model relating to angle deformation.

Tschemmernegg *et. al.*[102] addressed the problem of column deformation prompted by the increasing trend to leave columns un-stiffened because of the expense of fabrication. The model consisted of an arrangement of springs describing the response of the connection response, and that of the column web shear deformation. A range of tests was conducted firstly on column stubs subject to transverse point loads simulating the load introduction from the beam, and later on whole connection arrangements as both cruciform and cantilever arrangements. A wide range of section sizes was tested allowing the calibration of spring elements describing connection response.

Madas[103] has recently developed a series of spring-stiffness models for a range of connection types as both bare-steel and composite in response to the fact that most existing models are based around a single connection type. Double web-angle, top- and seat-angle and partial welded end-plate connections were considered, where a number of elements such as column and bolt deformation remain transferable between different connection types. The form of model adopted was similar to that described by authors above. Due to the non-uniform deformations along the depth of the concrete slab, this was subdivided into a finite number of layers for an effective width of slab, with deformation of concrete layers being based on the stress-strain relationship for concrete. Flexibility of shear-connectors and the influence of reinforcement was included in the model. A close correlation was observed with existing test data in terms of both the overall form of response and the observed mechanisms of failure.

Based on the form of bare-steel model[102] described above Tschemmernegg[104] recently proposed a revised spring stiffness model for composite connections. The basic form of the model was similar to that for bare-steel connections, with the incorporation of a tension spring to model reinforcement response and a load induction spring to represent the change in loading in the compression zone. The model considers only the column side of response, neglecting the interface-slip between the beam and slab and shear-lag in the composite beam, which may significantly influence connection response.

4.5. FINITE ELEMENT ANALYSIS

Finite element analysis is the most sophisticated form of connection model currently adopted. This form of analysis is capable of generating complex representations of the full non-linear connection response, incorporating the influence of welds and contact zones. However, its application is complex and requires careful construction of the finite element connection representation. These factors along with the computing power necessary to conduct such analysis render this an unsuitable technique for most situations, although it remains a valuable tool for the development and validation of other forms of modelling, and the formulation of recommendations applicable to incorporation within simplified design guides.

Initial attempts at the finite element modelling of connection behaviour at ambient-temperatures date back to the 1970's when Bose[105] considered the response of fully welded beam-to-column connections, where the web was selected as the critical component, and analysed in isolation as a plate strength problem. Patel and Chen[106] subsequently used the general purpose finite element program NONSAP in the two-dimensional modelling of partly welded connections, where the beam was either fully welded to the column flange or simply welded along its flange. Despite the simplification of connection response to a two-dimensional problem through the incorporation of isoparametric elements, a close agreement was observed with test data. More recently Atmaz Sibai and Frey[107] have considered the influence of strain-hardening on column web response in the analysis of one-way un-stiffened welded connections. Though the quantity of finite element analysis investigating the response of welded connections is limited, close agreement has consistently been observed between experimental and numerical data, suggesting that finite element analysis presents a tool of sufficient accuracy to model the response of welded connections.

The numerical modelling of bolted connections is complicated by the influence of complex boundary conditions, including friction, slip and interface contact, all of which interact in a manner that is not yet fully understood, and remains difficult to monitor experimentally. Direct approaches adopted to date in the modelling of bolt influence seem to generate inconsistent results, and consequently simplified methods have been formed to replicate bolt behaviour indirectly. Lipson and Hague[108] considered the response of singe angle connections welded to the column flange and bolted to the beam web, where nodal forces were introduced to simulate bolt forces based on empirical data. Richard *et. al.*[109] considered the response of single web-plate connections, modelling the response of the connection in its entirety, along with the connected beam. An inelastic finite element was developed to simulate bolt behaviour based on a statistical evaluation of tests on single bolts. Patel and Chen[110] adopted a simplified equivalent bar system in the analysis of fully bolted connections consisting of three bars accounting for pre-tension and shear carrying capacity. An improved bar arrangement has recently been proposed by Beaulieu and Picard[111] where a fourth element is introduced to account for interface slip.

Where bolts are required to act in combined shear and tension, the interaction of connected components may influences the response of the connection as a whole due to the effects of contact forces in areas of prying, necessitating the use of a more complex bolt element. Richard *et.al.*[112] applied the same methodology to the analysis of double web-cleat connections as previously used in the analysis of single web-plate connections, where constitutive laws were generated based on experimental data. Close correlation was observed with experimental results, with the additional advantage of a significant reduction of the complexity of the problem at hand compared to the direct modelling of bolts. The use of the technique described by Richards *et.al.* only seems applicable to connections where bolt response may be isolated from overall connection behaviour, and is not wholly applicable to the modelling of end-plate connection where interaction between connected components becomes more significant. Krishnamurthy[113] has developed the most sophisticated representation of this form of connection to date, incorporating the influence of changes in the contact zone between end-plate and an idealised rigid support, and bolt pre-load. Analysis was mainly based on two-dimensional modelling, although three-dimensional models were initially used as a means of calibration. A close correlation was observed with experimental work, and this demonstrated the significance of bolt heads and welds, which it was recommended form essential constituents of finite element modelling of true connection response.

Based on a previously developed ambient-temperature end-plate model[114] Liu developed an elevated-temperature model[115] incorporating material plasticity and deterioration with temperature, non-uniform thermal expansion across a section, and large deformation at high temperatures. The yielding of the structure is followed by the Von Mises yield surface, taking into account plastic flow after the structure has yielded. In addition to the eight noded shell element used to discretize the flanges and web of the beam, column, stiffeners and end-plate, a beam element was introduced to simulate the behaviour of bolts and the contact 'link' between the end-plate and column flange. Verification of the described model was based on two tests of extended end-plate connections by Lawson[44]. A reasonable simulation of connection response was achieved for both connections, and discrepancy between results was suggested to be partly attributable to limited information of temperature distributions and actual stress-strain relationships.

Further work has been conducted by Liu[116] in the development of a finite element model for the form of bare-steel connection described in Chapter 3. The elements were arranged in a form that resembled the exact shape of the structure, with approximately 600 elements being incorporated, the majority of which were concentrated at the direct connection region. Experimentally derived material properties and temperature distributions were used in the modelling of all five tests, assuming a constant level of moment with increasing temperatures. The rotations chosen to be monitored were selected to coincide with the position of the clinometers in experimental work described in Chapter 3. The resultant

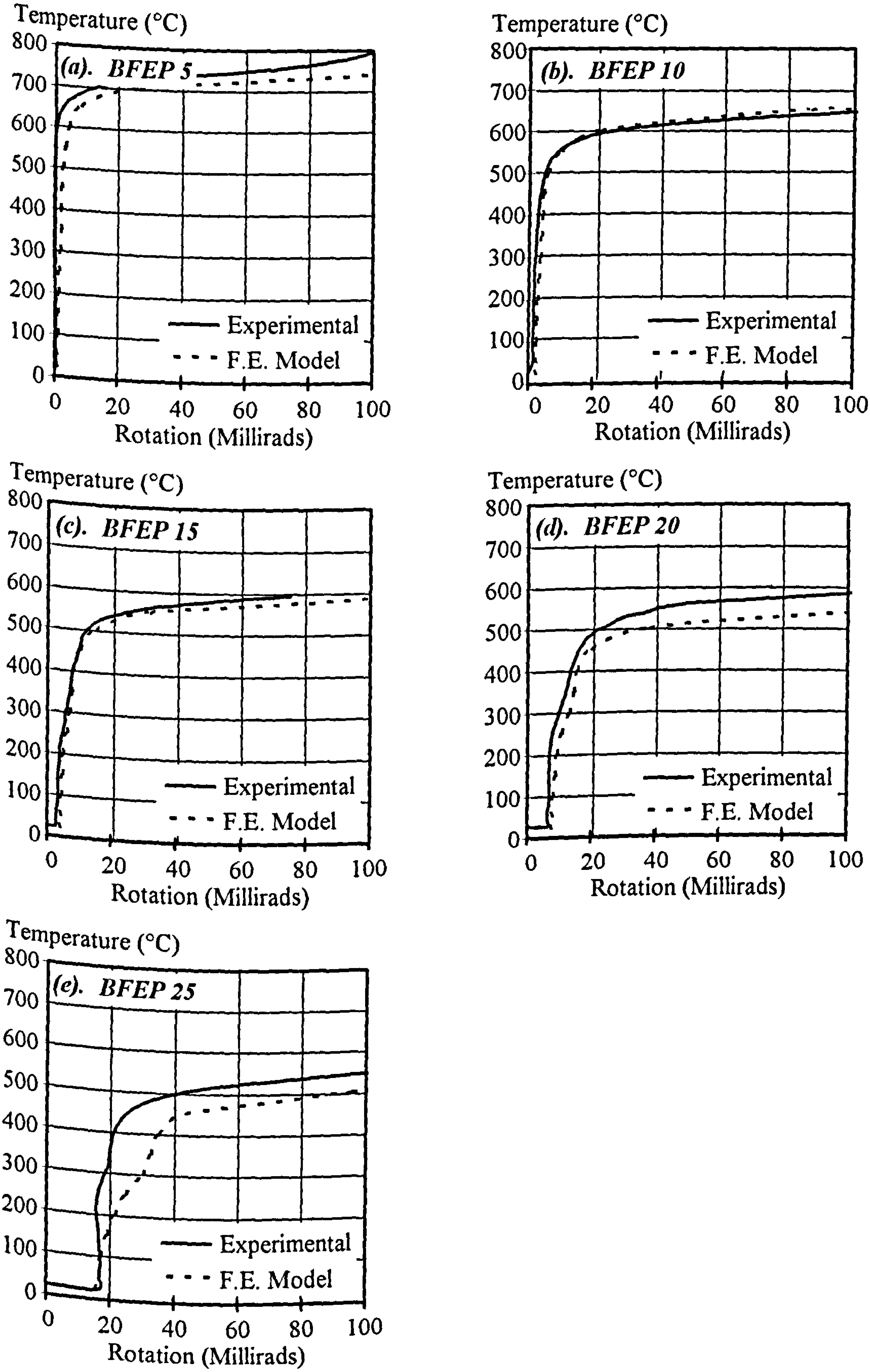


Figure 4.3. Comparison of Finite Element Modelling of Connection Response with Experimental Results

predicted response is compared with that recorded experimentally in Fig. 4.3. It may be seen that predicted response once more compares closely with that observed, particularly at low levels of load. Initial rotations at ambient-temperatures are almost indiscernible from those recorded experimentally, demonstrating the ability of the finite element model to accurately predict ambient temperature connection response. For levels of moment greater than 20kNm the model predicts a greater rate of degradation than that recorded. However, the predicted rate of degradation may be seen to be closer at lower levels of moment. The general form of behaviour is followed by the model, and it may be that errors in the predicted rate of degradation are attributable to the difference in the adopted material properties and those which truly existed. Unfortunately the expense of material testing obviated the derivation of elevated-temperature material properties from experimentation.

The analysis of composite connections by numerical methods is greatly complicated by the natural variability of the concrete component, the influence of shear-lag and the existence of slip at the beam-slab interface. Early attempts at the finite element modelling of composite connection response by Echeta[117] and Leon and Lin[118] neglected interface response between the beam and slab, along with the influence of shear-stud deformation, and there was no advanced modelling of concrete behaviour in the tension zone. Comparison with experimental results indicated the need for refinement.

Davison, Lam and Nethercot[119] adopted finite element modelling to study numerically the response of composite connections using the program SERVAR capable of the incorporation of non-linear connection characteristics at beam-column joints. The software adopted was only capable of dealing with bare-steel joints, and as such a transformed area was adopted to represent the composite condition. The variation in concrete stiffness after cracking and slip at the beam-slab interface was neglected. Good agreement was observed in the comparison with experimental results, with failure loads being almost identical, although there was a greeter variation in the corresponding levels of rotation.

Zandonini[120] adopted the finite element program ABACUS for the modelling of composite connections. Shear stud flexibility was accounted for by a set of non-linear springs, the response of which was based on the constitutive relationship proposed by Aribert[121]. The influence of compression of the column web was incorporated within the model. The ability with which this form of model was capable of accurately predicting connection response was demonstrated by comparison with experimental data.

4.6. CONCLUSIONS

As described a need exists to consider forms of connection model for two fundamental purposes. Firstly it is necessary to incorporate the non-linear form of moment-rotation response observed for connections within numerical models to ascertain the resultant influence on frame behaviour, and secondly due to the expense of testing their is a desire to develop forms of connection model which can accurately predict connection response for the broad range of connection types commonly used.

A number of mathematical expressions exist allowing the curve-fitting of experimental data in a form suitable for incorporation within numerical models. These range from simple linear methods following either the elastic- or secant-stiffness of the connection, through to fully non-linear methods capable of accurately mapping the entire range of response.

Linear methods of curve-fit are only strictly applicable to connections where rotations remain within the elastic range of response. Whilst this may provide an acceptable representation at ambient-temperatures where rotations rarely exceed 50 millirads, with increasing temperatures greater levels of deflection and hence rotation are permissible, with levels of rotation exceeding 100 millirads not being uncommon. Due to the large levels of rotation experienced it is suggested that linear forms of model are not suited to elevated-temperature analysis, and that a form of curve-fit capable of following the plastic range of response should be adopted. A number of authors have recommended the use of both bi-linear and multi-linear expressions in which a piece-wise linear 'curve' is adopted. Based on a bi-linear expression the representation of the curve remains 'coarse', with accuracy increasing along with the number of terms adopted. Concern is once more felt regarding inaccuracies which may arise where an infinite plastic-stiffness is adopted and as such it is proposed that a limiting moment should be imposed for all forms of curve-fit used within elevated-temperature analysis. Fully non-linear forms of expression clearly represent the most accurate representation of connection response. The Ramberg-Osgood form of equation is particularly suited to elevated-temperature analysis, being defined by a single equation always yielding a positive slope corresponding with the tangent-stiffness of the connection, and being simple to degrade for increasing temperatures. The full moment-rotation response for both the bare-steel and composite connections tested as described in Chapter 3 have been represented for a range of temperatures. The resultant influence of varying types of curve-fit has been considered in Chapter 6 based on the finite-element analysis of bare-steel and composite sub-frames subject to increasing temperatures.

Whilst the use of mathematical expressions allows the accurate representation of almost any shape of moment-rotation curve it only serves as a tool with which to represent data obtained from either experimentation or analytical modelling in a form suitable for incorporation within numerical frame analysis. As such a need exists to consider viable techniques for the development of moment-rotation characteristics without the need to resort to testing. Existing forms of connection model suitable for the prediction of connection response have been considered according to their theoretical basis as: simplified analytical models; mechanical models accounting for major aspects of response and finite-element analysis.

Simplified analytical models are based on the prediction of key parameters within the connection response, and the fitting a skeleton curve through these points. However, whilst this form of modelling allows the formulation of approximate moment-rotation curves without the need to resort to testing, there still remains a need for empirical curve-fitting in order to generate the fully non-linear curve, and as such this form of model is only strictly applicable to the form of connection for which it was developed. Whilst extensive data-banks exist documenting connection response at ambient-temperatures, little experimental work has been conducted at elevated-temperatures, and as such this form of model is not wholly applicable at present.

Existing mechanical models have been demonstrated to be capable of providing an accurate representation of connection response for a broad range of connection types. Unlike simplified analytical models the generation of the full moment-rotation response for any given arrangement does not necessitate the use of experimentally generated data, with connection response being formulated from a knowledge of the load-deformation curve of the critical components. As such applicability of the model to differing connections is possible provided there is a knowledge of the response of critical elements. To date the application of spring-stiffness models at elevated-temperatures has not been considered. It is felt that the use of spring-stiffness models compares favourably with other forms of modelling due to the combination of efficiency with the ability to accurately follow the full non-linear range of connection response. The ability with which spring-stiffness models are capable of following elevated-temperature response of both bare-steel and composite flush end-plate connections has been considered further in Chapters 5 and 6.

The use of finite-element forms of connection model provides a powerful tool capable of incorporating the effects of bolt action and contact zones, particularly relevant in the case site-fabricated connections such as the flush end-plate connection. A number of bare-steel and composite models now exist which have been demonstrated to provide an accurate representation of the full range of connection response. Recent work by Liu has extended the scope of finite-element modelling to include the effects of temperature. A comparison with the experimental work described in chapter 3 demonstrated the applicability of the model with increasing temperatures. Whilst the use of finite-element methods of connection modelling provide an invaluable tool for the validation of simplified forms of model (in conjunction with experimental data), the associated complexities and computational requirements preclude its use in design.

5. ELEVATED-TEMPERATURE SPRING STIFFNESS MODEL

5.1. INTRODUCTION

Moment-rotation relationships have been measured for a flush end-plate connection, both as bare-steel and as composite with a slab, across a range of temperatures and these are presented in Chapter 3[71,74]. It is clearly unrealistic to expect that many such tests can be anticipated in the future, and as such it is essential that recommendations be presented based on experimental observations and fundamental structural principles to allow the prediction of connection response at elevated-temperatures.

A number of techniques exist for modelling connection behaviour at ambient-temperatures, as previously summarised by Nethercot and Zandonini[122]. However, elevated-temperature connection models are limited, and to date are based around complex numerical techniques such as that developed by Liu[115] as described in Chapter 4. It is the opinion of the author that whilst sophisticated connection models are necessary to provide an accurate prediction of connection response; in the case of elevated-temperature analysis an acceptable representation of overall frame behaviour may be achieved through the incorporation of approximate connection characteristics, due to the large levels of deformation permissible.

The most commonly adopted techniques for predicting connection response may be classified as simplified analytical models, mechanical models and finite element analysis. As described previously, the component-based model compares favourably with other analytical methods due to its relative ease of application, and its ability to provide a reasonable representation of the full range of connection response, and as such has been selected as the basis for a simplistic model to approximate the response of both bare-steel and composite flush end-plate connections at elevated-temperatures.

5.2. SPRING STIFFNESS MODEL

The spring stiffness model presented has been restricted to the flush end-plate type of connection, as both bare-steel and composite with a concrete slab, as this is felt to be typical of the forms of connection currently adopted due to its ease of fabrication and ability to be contained within the beam depth[46]. Further commentary is provided regarding the modification of analysis when considering partial-depth end-plate connections, often adopted due to the associated reduction in fabrication costs, and corresponding with one of the types of connection used within the Cardington test frame[123].

It is possible to model connection behaviour throughout the entire moment-rotation relationship by assembling the contributions of individual components, representing the connection as a set of rigid and deformable elements. If it is assumed that the interaction between connected components has a negligible effect on the response of components considered in isolation, the response of the connection as a whole may be obtained by superimposing the stiffnesses of individual components in the compression and tension zones.

Modelling the non-linear deformation of connections is a complex procedure, and mechanical connection modelling is generally confined to the critical elements controlling the response of the connection. The accuracy and applicability of the model is enhanced as the number of components taken into consideration increases. This does however call upon an understanding of the behaviour of the individual components, which have to be modelled in isolation. It is then possible to predict variations in failure modes and deformation resulting from changes in geometry, material properties and temperature distributions within the connection. The connection model presented applies to a balanced two-sided connection, in which there is no shear deformation due to out-of-balance moments.

A number of existing ambient-temperature models have simply concentrated on the elastic response due to rotations typically being contained within the range of linear response, with the capacity of the connection being defined by a plastic plateau. However, due to the large levels of deformation, and hence rotation, permissible at elevated-temperatures, and the potentially significant influence of strain hardening, it is desirable to follow the entire moment-rotation response. Due to the complexities associated with fully non-linear modelling, a multi-linear representation is proposed, whereby the initial stiffness continues until the onset of failure caused by plastification of one or more of the connected elements. A strain-hardening stiffness may then be assumed based on revised elemental stiffnesses. This procedure is repeated as further elements enter their strain hardening regions. Bare-steel and composite connection models are considered in isolation below, where elements of the bare-steel model form constituents of the composite model, despite the overall differences in formulation for the two arrangements.

The terms presented describing the stiffness and capacity of the connection are temperature dependent, with the values for Young's modulus, yield strength and ultimate tensile strength varying in accordance with the temperature of the connection. The model is formulated such that individual temperatures may be assigned to elements at a given bolt row. This allows any form of temperature profile to be adopted for the connection, being based either on experimental values or simulations of the temperature profile through the depth of the connection.

5.3. BARE-STEEL SPRING STIFFNESS MODEL

It is proposed that an acceptable representation of elevated-temperature response may be obtained by considering the connection in a manner similar to that adopted within existing ambient-temperature studies, having modified material properties to account for the effects of temperature. This neglects the influence of time-dependent factors such as thermal creep and expansion, but as described the aim of the proposed model is to balance the accuracy of the solution (and hence the complexity of the formulation) with the level of sensitivity necessitated in frame analysis to generate an acceptable prediction of the influence of connection characteristics on overall frame response.

The connection is modelled principally as a two-dimensional problem, although out-of-plane response has been incorporated within the development of axial spring elements.

Rotation of the connection is assumed to occur about the centre-line of the beam lower flange, as is typical of bare-steel connection models. This assumption may result in unconservative solutions if the axis of rotation propagates into the depth of the connection, although studies have demonstrated that the centre of rotation typically remains close to the beam lower flange. The model presented assumes the 'connection' to include the column web panel in the compression zone and the end-plate, column flanges and bolts in the tension zone, but not the column below the web panel or the beam. Individual springs are used to simulate the stiffnesses of the individual components, and may be assumed to follow any pre-defined force-displacement relationship. To simplify the solution process, the stiffness of all components acting in the tension zone are grouped and considered as a single spring of equivalent stiffness.

The idealised representation of the connection is illustrated in Fig. 5.1, where the components contributing towards overall connection stiffness may be summarised as:

Tension zone (K_{eqt}):

1. Bolt stiffness, K_{bt}.
2. End-plate stiffness, K_{ept};
3. Column flange stiffness, K_{cft};

Compression zone:

1. Column web stiffness, K_{cwt}.

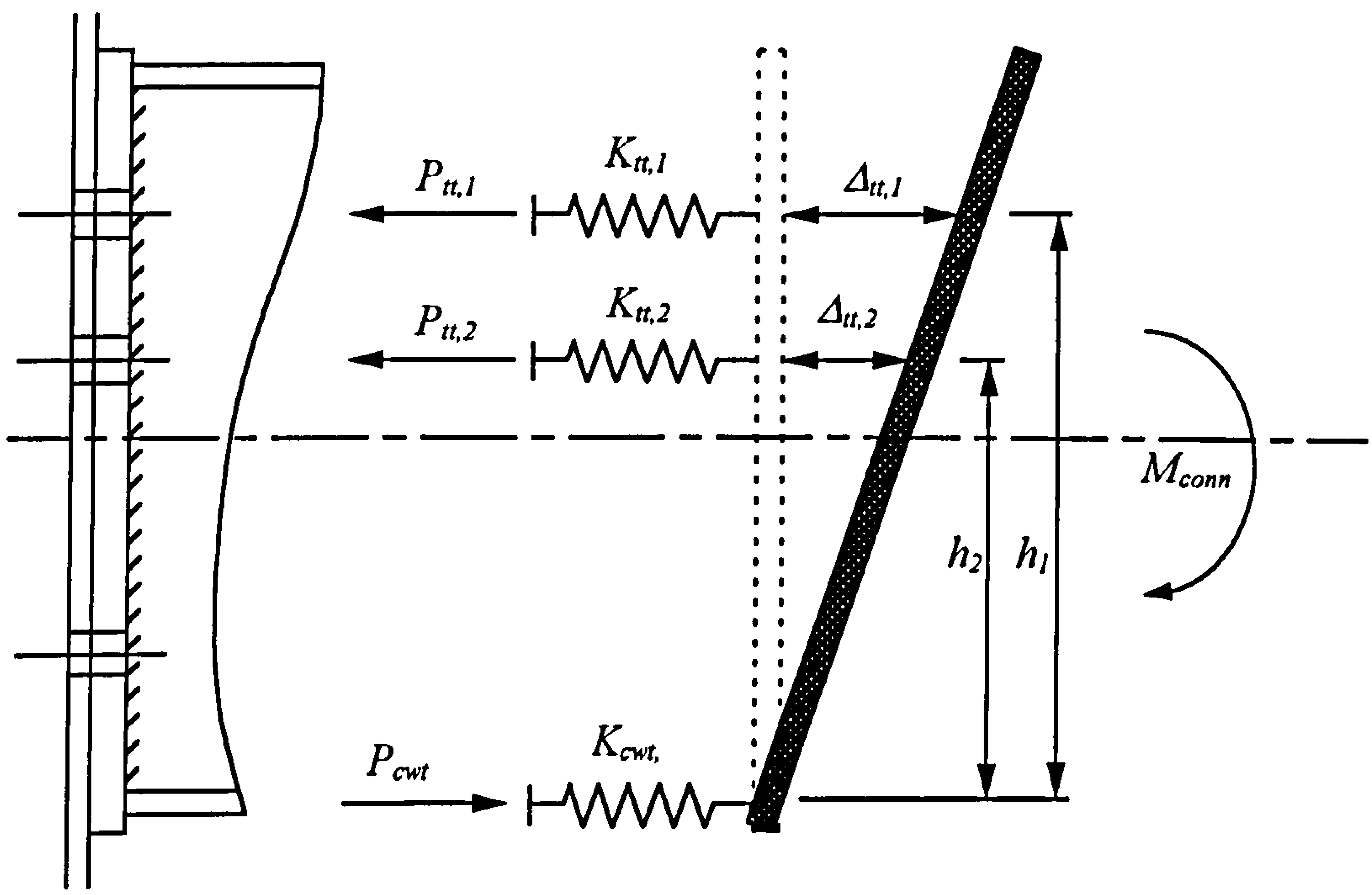


Figure 5.1. Idealised Bare-Steel Spring Stiffness Model

The global rotational stiffness of the connection, S_{jt}, may be calculated for any given moment and temperature based on the stiffness of the elements in the compression zone, K_{cwt}, and the collective stiffness of elements acting in tension, K_{eqt}. Where the column web is stiffened, or in the case of minor axis connections, the stiffness of the connection in the compression zone approaches infinity, and the rotational stiffness may then be assumed to be equivalent to the rotational stiffness of the tension zone of the connection alone, S_{tt}. Hence, the rotational stiffness of the connection as a whole may be described as:

$$S_{jt}^{-1} = S_{tt}^{-1} + S_{ct}^{-1} \qquad \text{Eq. 5.1.}$$

$$S_{jt}^{-1} = \left(K_{eqt}.z^2\right)^{-1} + \left(K_{cwt}.z^2\right)^{-1} \qquad \text{Eq. 5.2.}$$

Where S_{jt} is the rotational stiffness of the bare-steel connection as a whole for a given temperature;

S_{tt} is the rotational stiffness of the connection in the tension zone;

S_{ct} is the rotational stiffness of the connection in the compression zone;

K_{eqt} is the stiffness of the equivalent tension spring;

z is the lever arm to the centre of the tension zone (location of equivalent tension spring).

The deformation of components for a typical bolt row acting in tension are illustrated in Fig. 5.2. Overall stiffness for a bolt row at a given temperature may thus be obtained from the following expression:

$$K_{tt,n}^{-1} = \left(2.K_{ept}\right)^{-1} + \left(2.K_{cft}\right)^{-1} + \left(N_b.K_{bt}\right)^{-1} \qquad \text{Eq. 5.3.}$$

Where $K_{tt,n}$ is the tension zone load-deformation spring stiffness at a given temperature, for the bolt row under consideration;

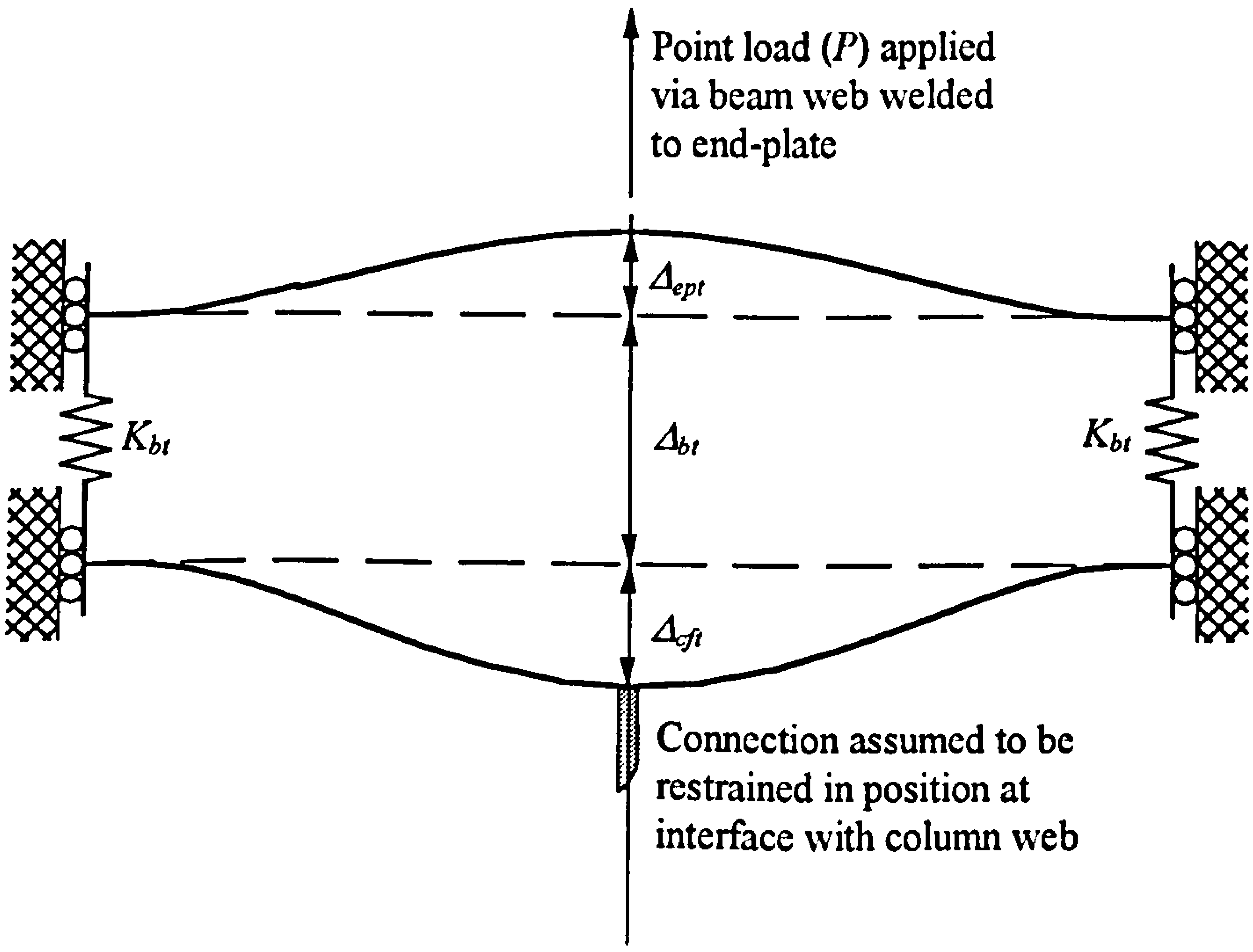


Figure 5.2. Assumed Deformation of Connection in the Tension Zone

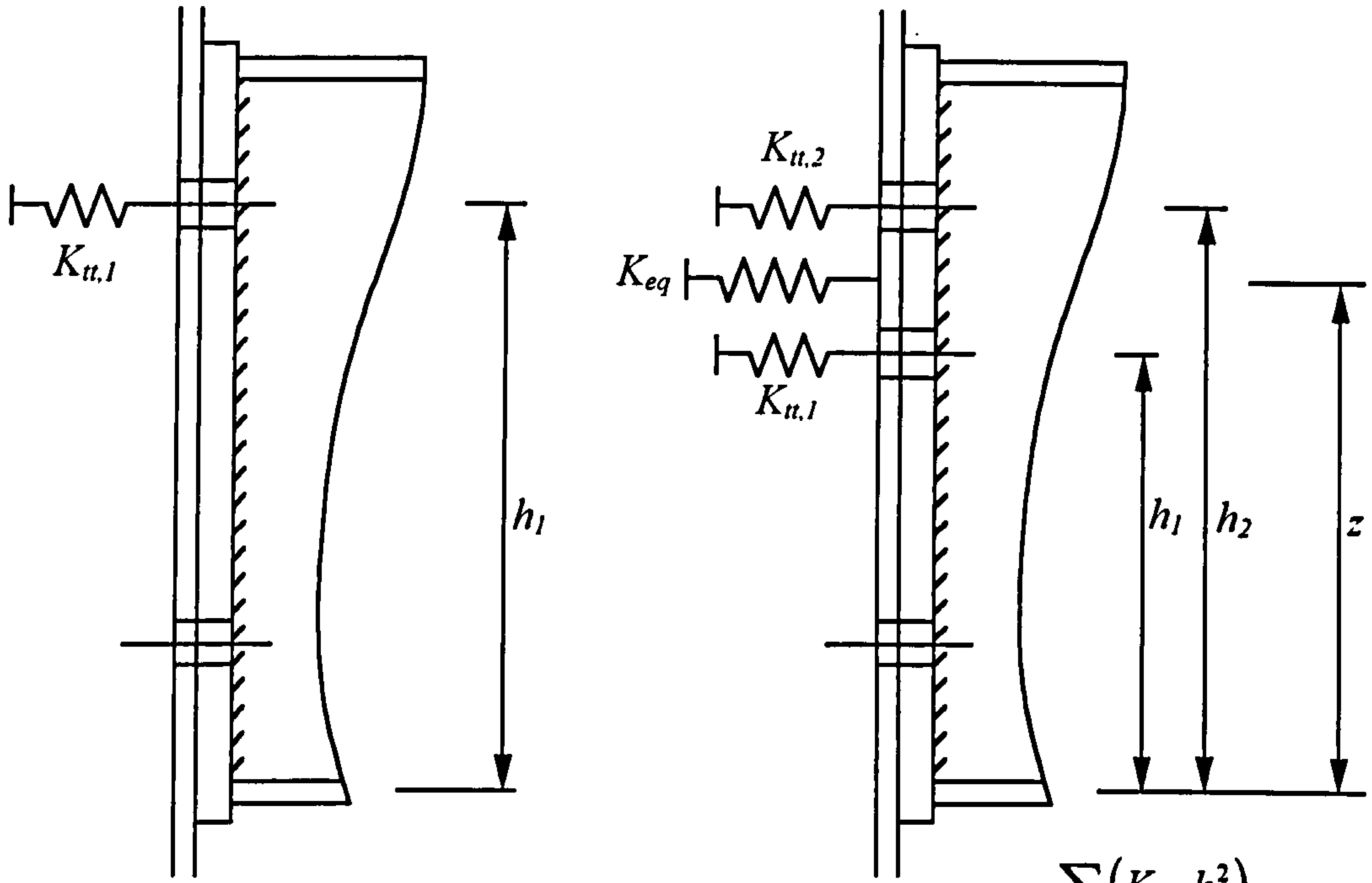
N_b is the number of bolts in tension at a given bolt row.

End-plate connections with more than one bolt row in tension may be represented as a single spring of equivalent stiffness, K_{eqt}, determined from:

$$K_{eqt} = \frac{\sum_n \left(K_{tt,n}.h_n\right)}{z} \qquad \text{Eq. 5.4.}$$

Where h_n is the lever arm between bolt row n and the centre of compression;

For bolted connections with a single bolt row in tension, the bolt row stiffness, $K_{tt,n}$, may be assumed for the equivalent tension zone spring stiffness, and the lever arm may be taken as the distance from the centre of compression to the centre-line of the bolt row acting in tension, as illustrated in Fig. 5.3*(a)*. When considering connections with more than one bolt row in tension, the lever arm z may be determined as illustrated in Fig. 5.3*(b)*:



$$z = h_n \qquad\qquad z = \frac{\sum_n \left(K_{tt,n} h_n^2\right)}{\sum_n \left(K_{tt,n} h_n\right)}$$

Figure 5.3. Determination of Lever Arm to Equivalent Tension Spring

In order to estimate the capacity of the connection it is necessary to determine the capacities of individual elements contained within the model, where the load distribution within the connection may be assessed based on a number of representations as summarised in Fig. 5.4. It is generally accepted that the most realistic representation of bolt forces at low levels of moment is that depicted in *(a)*. As the moment increases towards ultimate, the force distribution tends to change from *(a)* to *(b)*. Experimental observations have indicated that the distribution represented in *(b)* provides an

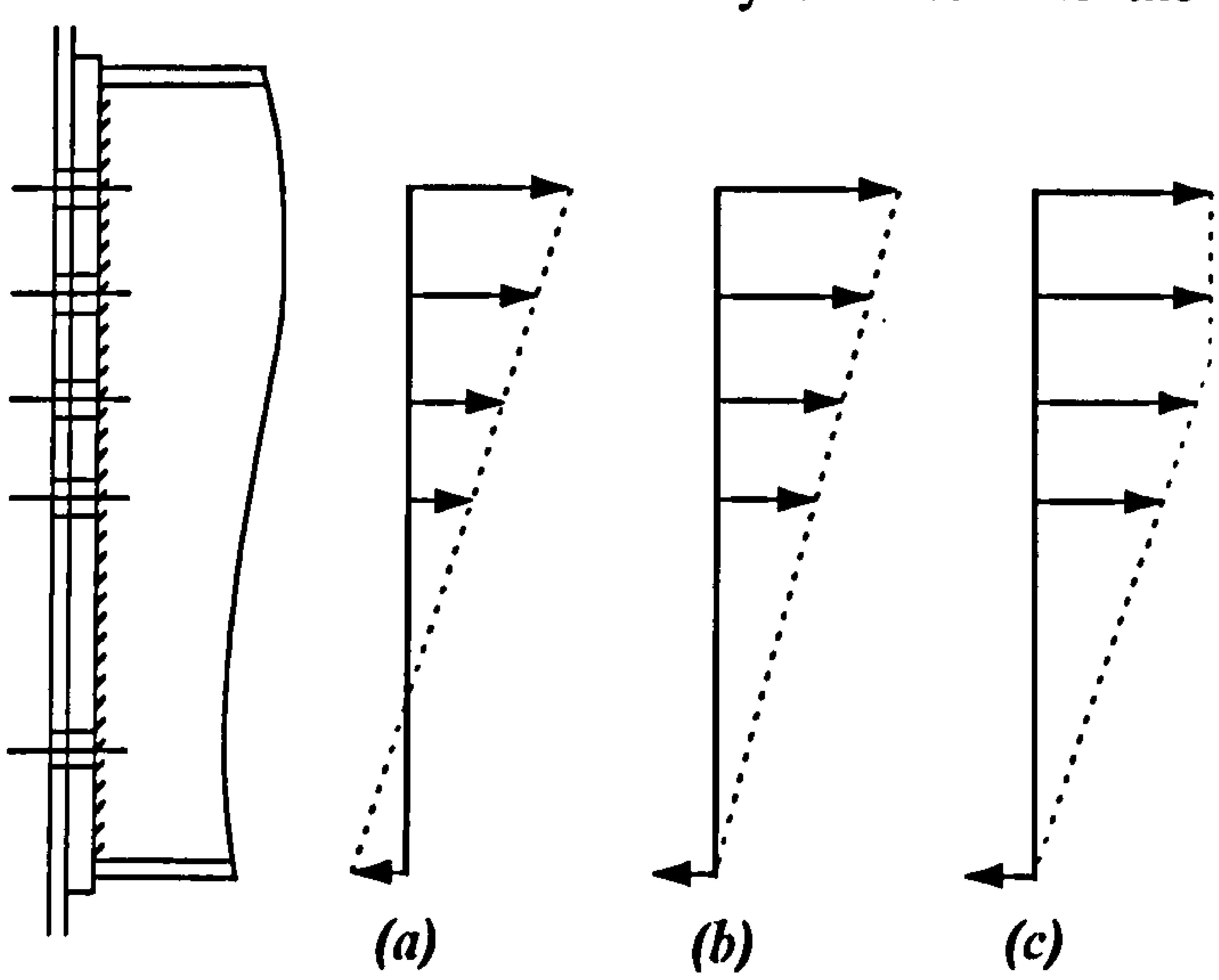


Figure 5.4. Force Distribution Models

acceptable representation of bolt forces within an elastic range. This assumes that the centre of rotation is situated at the stiffest part of the connection, namely where the beam compression flange bears against the column flange, which is stiffened by the column web. However, this assumption is only strictly correct where column web response is not critical but demonstrates a significantly greater stiffness than the tension zone at all times. To represent force distribution up to collapse, a plastic distribution has been adopted within the proposed spring-stiffness model as illustrated in *(c)*. The use of a plastic load distribution assumes that sufficient ductility exists within the connection for the force at any bolt row to be based on the potential resistance and stiffness, not just on the relative lever arm. Hence, it is possible to obtain the force at a given bolt row, P_n, knowing the overall connection rotation and bolt row stiffness:

$$P_n = \phi . K_{eq} . h_n \qquad \text{Eq. 5.5.}$$

To evaluate the stiffness and capacity of the connection, appropriate models such as those described below are required to predict the behaviour of individual components.

5.3.1. Bolt Behaviour

Determination of bolt behaviour is complicated by pre-stress in the bolts and the existence of prying forces. Pre-stress forces within the bolts are beneficial to connection performance as little deformation will occur until the external force exceeds the pre-stress, whilst prying action will result in an increased bolt load, and hence deformation. Grade 8.8 bolts are commonly used in the fabrication of 'simple' connections, and are typically hand-tightened, producing a clamping force considerably less than with high strength friction grip bolts. Although the bolt pre-stress has been suggested as being approximately 50% of the proof load for Grade 8.8 bolts[65], there is considerable variation in the actual level of force applied when tensioned 'on-site', and as such it is unwise to count on this at the design stage. In the tension region of beam-to-column connections the flexibility of the end-plate and column flanges could affect the behaviour of the connecting tension bolts by inducing prying action, and so the interaction between end-plate, bolts and column flanges justifies further consideration.

The problem of prying action was first investigated by Douty and McGuire[124] based on the analysis of an elastic beam, and modified in the light of test results. A number of empirical relationships have since been presented[125,126] but these are only applicable to the specific combinations of bolt and plate material for which they were developed, whilst further analysis by Nair *et. al.*[127], and Struik[128] produced more generally applicable formulae.

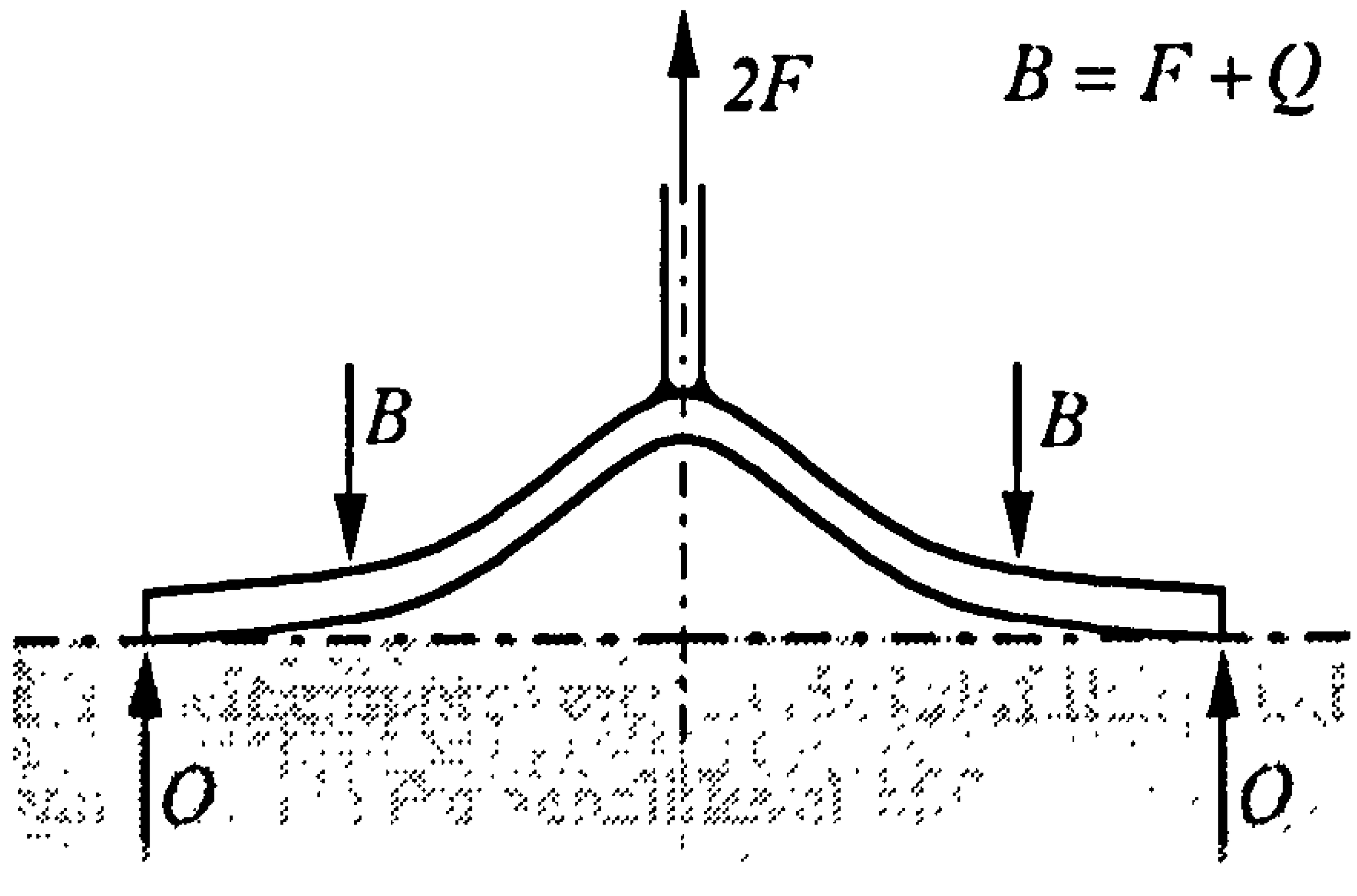


Figure 5.5. Prying Forces in T-Stub

Prying action is difficult to predict as it occurs as a result of the influence of surrounding elements, and is best illustrated by considering a T-stub, as shown in Fig. 5.5. Flexure of the plate subject to a tensile force, *2F*, results in the free edges of the plate being pressed against the supporting plate, with the reactions generated at the point of contact being referred to as prying forces. For equilibrium the total forces in the bolts must therefore equal the applied force plus the prying forces. In the case of a relatively rigid end-plate there is no significant deformation of the plate, and it is possible to ignore flexural action. At relatively low levels of load, separation of the connected components is limited; this continues until the external applied load reaches the level of the bolt pre-stress, at which point the end-plate is assumed to separate entirely, and the bolt force becomes approximately equivalent to the applied load. In the case of flexible end-plates the behaviour is more complex, with flexural deformations within the plate inducing additional prying forces in the bolts, possibly resulting in a reduction in overall connection stiffness and capacity. As the bolt load approaches ultimate capacity, further separation will occur, resulting in a reduction in prying forces. The influence of prying action is far more significant in the case of extended end-plate connections, and it has been suggested to be of little influence in the case of flush end-plates[129]. Similarly, Johnson and Law[96] concluded that a purely analytical determination of the influence of pre-stress and prying action is impracticable, and that their influence must be neglected.

Johnson and Law considered a series of tests conducted by Packer and Morris[130] investigating the influence of T-stubs with thin column flanges, resulting in an arrangement which would be anticipated to generate considerable prying forces. The assumed T-stub arrangement was as shown in Fig. 5.5. The typical relationship between bolt tension, B, and the apparent applied load, $2F$, in a T-stub was assumed to follow the form illustrated in Fig 5.6*(a)*, where WXY represents a joint with no prying action, and K_b and K_p represent the stiffness of the bolts and gripped plate respectively. Any load path in the region WXYZ may exist, but if Q is known, the limiting case of greatest prying action, represented by WZ, can be determined. Surtees and Mann[131] suggested that prying action may generally be assumed to increase the bolt load by approximately 33%, although this value was refined to 25% by Johnson and Law to represent reality more closely, and hence it seems reasonable to assume that Q = 0.25B, with the resultant relationship between applied load and bolt

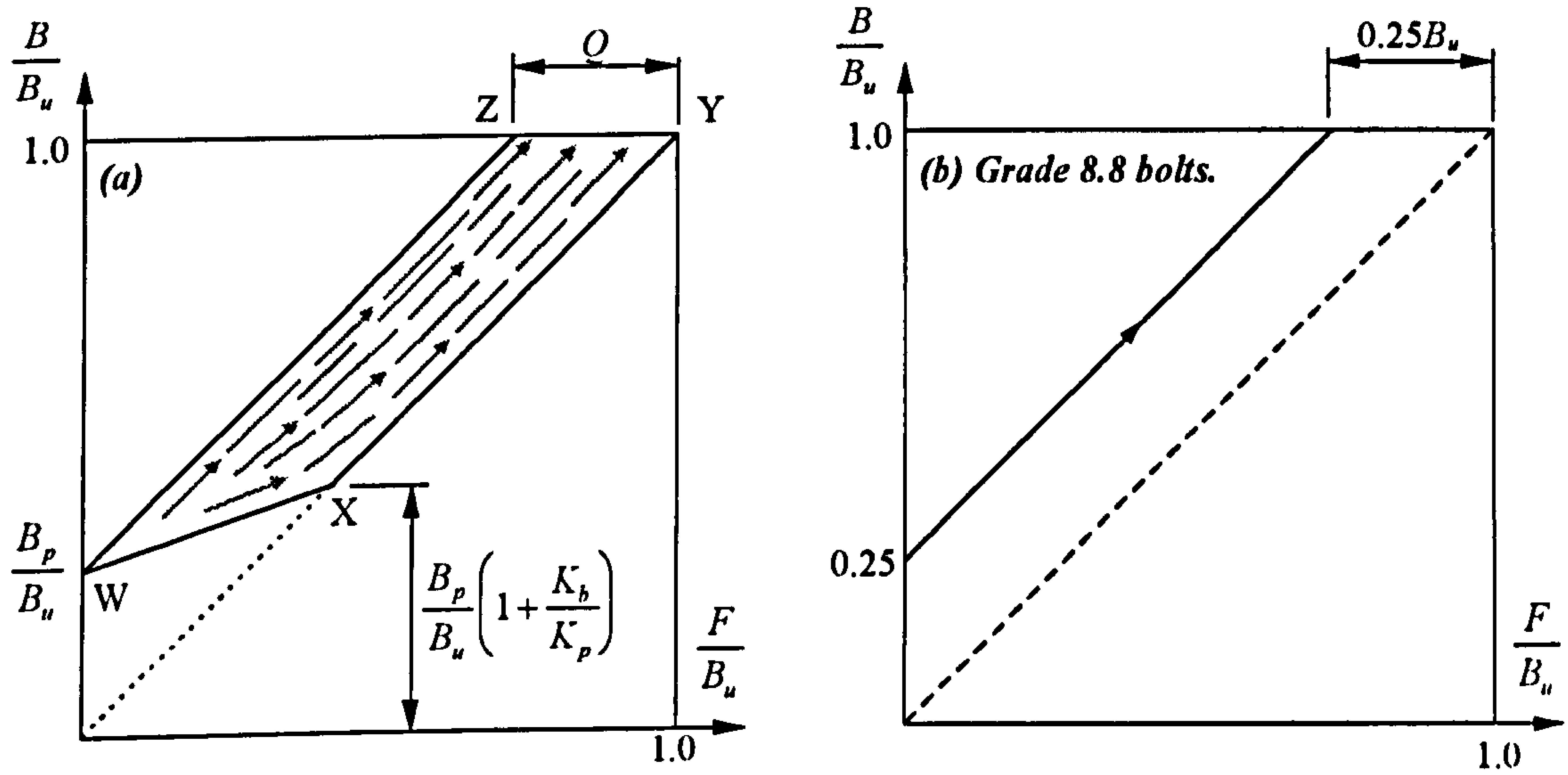


Figure 5.6. Bolt Tension and Force Transmitted by T-Stub

force being shown in Fig. 5.6*(b)*. In the limiting case it may be seen that $dF / dB \cong 1$, suggesting that it is acceptable to neglect the influence of prying action, and simply assess the stiffness of the bolts on Hooke's Law.

As such, the bolts are simply considered to be subjected to direct tensile force in isolation, and assuming the principles of Hooke's law it may be demonstrated that:

$$K_{bt} = \frac{E_{bt}.A_s}{l_b} \qquad \text{Eq. 5.6.}$$

Where E_{bt} is Young's modulus for the bolts at a given temperature;
A_s is the bolt shaft area;
l_b is the bolt elongation length;

Consideration of experimental results indicated that deformation of the bolts was always less than predicted by Eq. 5.6.

Aggerskov[129] suggested that it was not possible to neglect the influence of nut and washer deformation when considering the bolts elongation length, and hence it was proposed that the length of the bolt be taken as equal to the grip length (total thickness of material and washers), plus half the height of the bolt head and nut. Existing test data for a thin-flanged column tested with washers placed under the bolt nuts only suggests that bolts tend to punch their way through the column flanges before the ultimate load is attained, so it seems advisable always to place washers under both the bolt head and nut when considering thin sections:

$$l_b = t_{ep} + t_{cf} + 2.t_w + \left(\frac{t_{bh} + t_{bn}}{2}\right) \qquad \text{Eq. 5.7.}$$

Where t_w is the thickness of the washers;
t_{bh} is the thickness of the bolt head;
t_{bn} is the thickness of the bolt nut.

The force, P_{btp} that causes plastification within the bolts, at a given temperature, may be defined as:

$$P_{btp} = f_{ybt}.N_b.A_s \qquad \text{Eq. 5.8.}$$

Where f_{ybt} is the yield strength of bolts for the given temperature (NB: The strength values given in Table 32 of BS5950[3] have been reduced to make allowance for the influence of prying action).

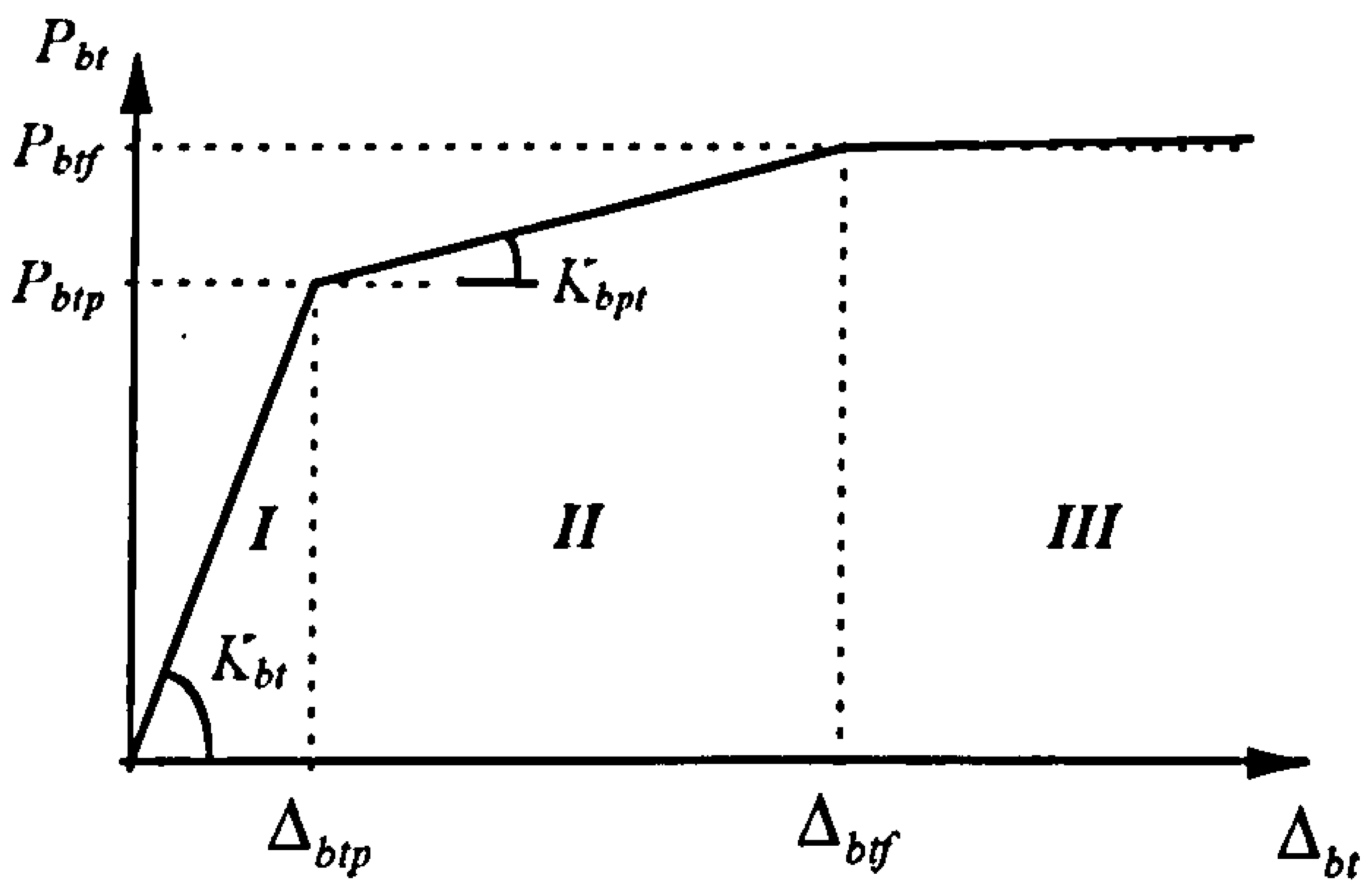
Subsequent to the onset of plasticity a strain hardening stiffness is assumed, and may be expressed as:

$$K_{bpt} = \mu_b K_{bt} \qquad \text{Eq. 5.9.}$$

Where K_{bpt} is the strain hardening spring stiffness of bolts at a given temperature;
μ_b is the strain hardening coefficient for the relevant grade of bolts.

Values for μ_b (Strain-hardening stiffness / Elastic stiffness) may be determined from testing, or based on existing data. A value in the range of 0.019 to 0.024 has recently been suggested by Atamaz Sibai and Frey[107] for mild steel at ambient-temperatures. Due to the lack of available data describing the strain hardening stiffness of bolts, a value of 0.02 has been adopted in the subsequent analysis. It is assumed that the elevated-temperature strain hardening coefficient for steel is the same as at ambient-temperatures, due to lack of accurate material test data.

Ultimate capacity of the bolts may be approximated on the basis of Eq. 5.8, having replaced the term defining the yield strength of the bolts with the ultimate capacity, f_{yut}. Subsequent to failure, the stiffness of the bolts reduces to zero. To avoid computational difficulties, a reduced stiffness may be used where necessary, with a value of K_{bt} / 10000 having been suggested as suitable in EC3[132]. The resulting form of force-deformation response is illustrated below:



I. Elastic Response

$$K_{bt} = \frac{E_{bt}.A_s}{l_b} \qquad P_{btp} = f_{ybt}.N_b.A_s$$

II. Strain Hardening Region

$$K_{bpt} = \mu_b K_{bt} \qquad P_{btf} = f_{ubt}.N_b.A_s$$

III. Plastic Response

$$K_{bft} = K_{bt} / 10{,}000$$

Figure 5.7. Assumed Force - Displacement Relationship

Assessment of the degradation of bolt stiffness and capacity may be based upon the recommendations presented in section 2.4.

5.3.2. Column Flange Behaviour

Due to the influence of the column flanges external to the depth of the connection, the column flange in the tension zone is assumed to act as an infinitely long cantilever plate of constant breadth a, and thickness t_{cf}, subject to an arbitrarily located transverse point load, a distance m from the support; as formulated by Jaramillo[133] and more recently adopted by Johnson and Law[96] and Madas[103] for the purpose of modelling column flange behaviour at ambient-temperatures. The idealisation of the column flange in the tension zone is illustrated in Fig. 5.8, where the subsequent stiffness may be demonstrated to be:

$$K_{cft} = \frac{\pi.D}{\beta.a^2} \qquad \text{Eq. 5.10.}$$

in which:

$$D = \frac{t_{cf}^3.E_{st}}{12.(1-\upsilon^2)} \qquad \text{Eq. 5.11.}$$

Where D is the flexural rigidity of the plate;

β is a dimensionless coefficient;
a is half the column flange width ($= B_c / 2$);
υ is Poisson's ratio ($\cong 0.3$ for steel);
t_{cf} is the column flange thickness;

β is a function of the distance to the centre of the bolt hole from the column web centreline, s (= gauge length / 2), and flange breadth a. A third-order polynomial curve-fit has been applied to representative values of β as defined by:

$$\beta = -0.0542 + 0.4160\left(\frac{s}{a}\right) - 0.7584\left(\frac{s}{a}\right)^2 + 0.9216\left(\frac{s}{a}\right)^3 \qquad \text{Eq. 5.12.}$$

Where the column flange is stiffened in the tension zone, it may be assumed to be infinitely stiff.

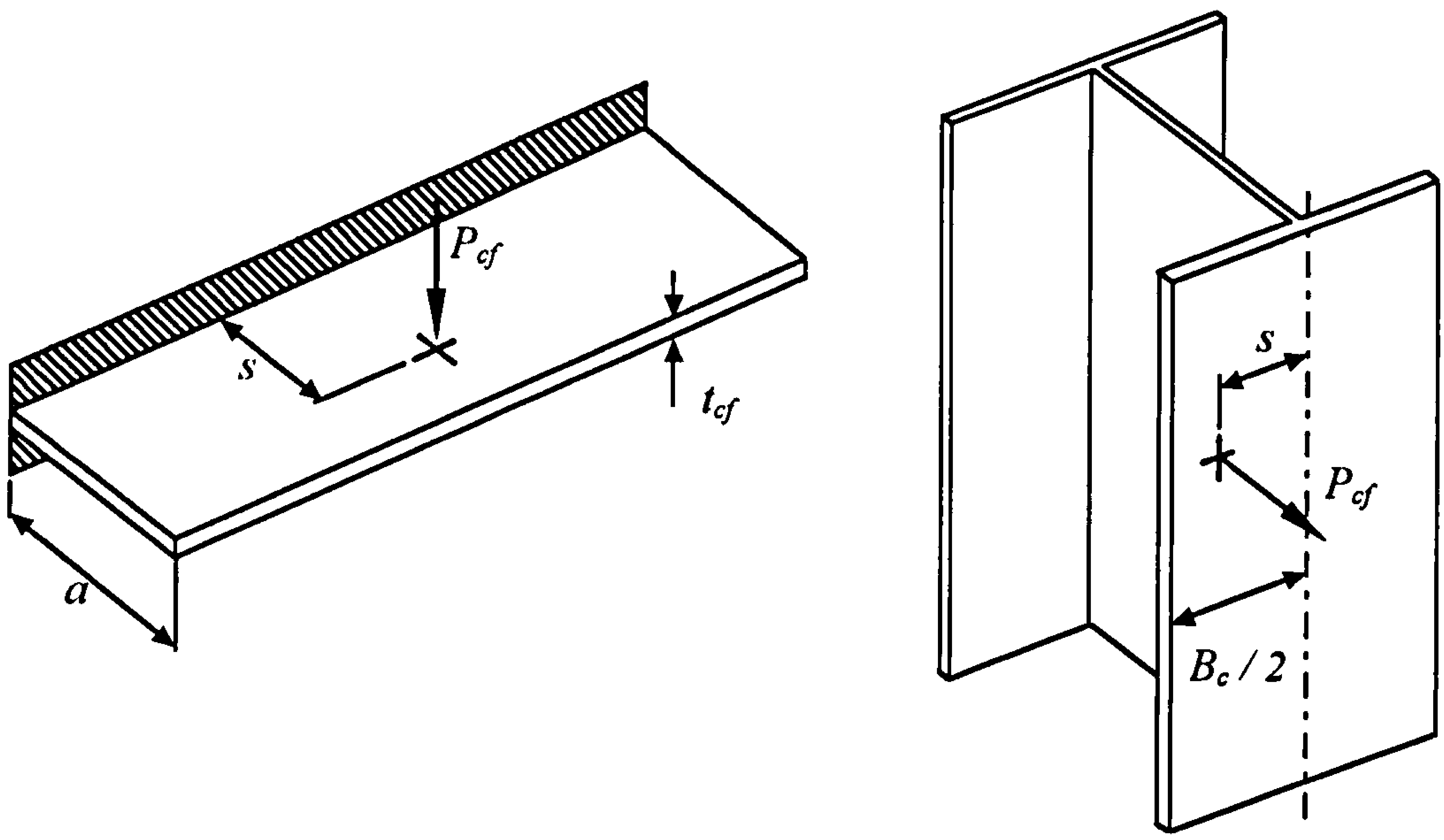


Figure 5.8. Idealised Representation of Column Flange Behaviour

Johnson and Law compared the resultant stiffness obtained from the equation described above with a series of ambient-temperature tests on unstiffened column flanges by Zoetemijer[134] and Packer and Morris[130]. A close agreement existed between theoretical and experimentally observed stiffnesses, with the model always yielding a conservative estimate. This might be anticipated, as the proposed model neglects the influence of prying action and the additional restraint provided by the bolt-heads.

Elastic analysis of the column flanges provides no indication of the ultimate load-carrying capacity, and further analysis has to be conducted for this condition. It is proposed that an elastic-plastic representation be adopted, with the ultimate capacity of the plate being determined on the basis of assumed yield-line patterns. The yield-line method of analysis gives an upper bound to the ultimate load capacity of the plate, the accuracy of which is dependent upon the assumed pattern. However, it is generally accepted that the consideration of a small number of suitable yield-line patterns results in an acceptable prediction of the actual capacity. It is suggested that yield-line patterns should consider the cases of bolt rows acting in isolation and in combination. The capacity of a bolt row, $P_{cft,n}$, may be obtained assuming the column flange to act as an equivalent T-stub of length L_{eff}:

$$P_{cft.n} = \frac{4M_{pt}}{m_1} \qquad \text{Eq. 5.13.}$$

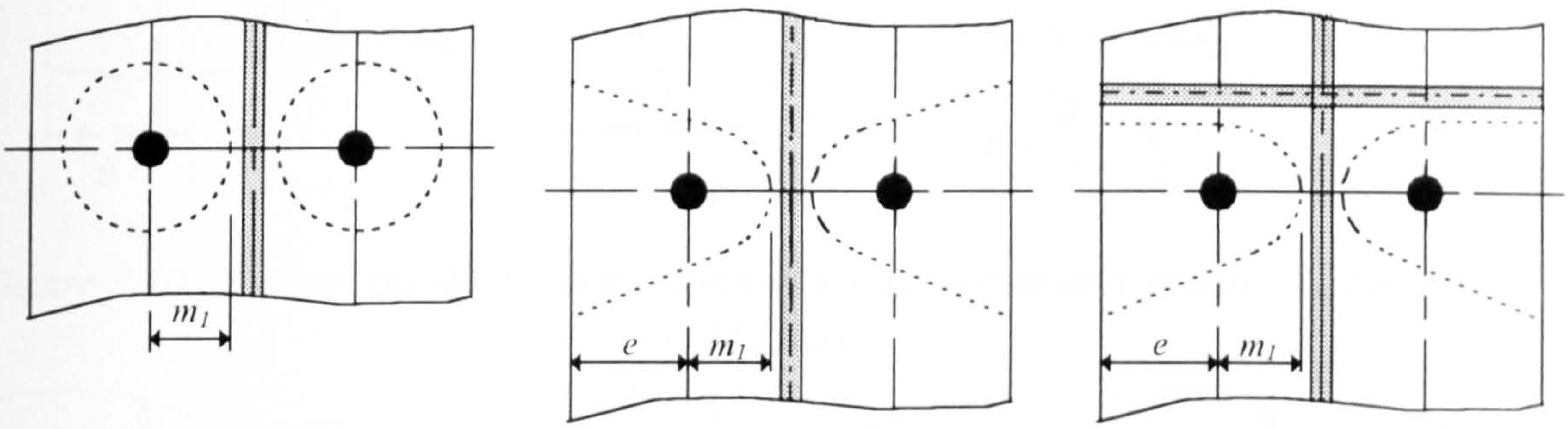
Where m_1 is the distance from bolt centre to 20% into the column root radius, as detailed;

$$M_{pt} = \frac{L_{eff}\, t_{cf}^2 . f_{ycft}}{4} \qquad \text{Eq. 5.14.}$$

(the plastic moment capacity of an equivalent T-stub);

f_{ycft} is the yield strength of the column flanges at a given temperature.

In the case of bolts acting in isolation, the yield-line patterns illustrated in Fig. 5.9 are assumed, based on the standard scenarios of hole yielding, side yielding and side yielding near a stiffener. For the case of a bolt row not influenced by a stiffener to the column web, the effective length should be taken as the minimum of patterns *(i)* and *(ii)*. Where the bolt is located near to a stiffener, the critical of patterns *(ii)* and *(iii)* must be determined, and the effective length be based on the minimum of this value and that obtained from *(i)*.



Pattern (i). *Hole yielding* $L_{eff} = 2\pi m_1$

Pattern (ii). *Side Yielding* $L_{eff} = 4m_1 + 1.25e$

Pattern (iii). *Yielding near stiffener* $L_{eff} = \alpha m_1$

Figure 5.9. Assumed Yield Line Patterns for Column Flanges in Isolation

The influence of stiffeners located close to the yield pattern, as in pattern *(iii)*, has been considered by Zoetermeijer[134], based on the study of an infinitely long plate bounded by two fixed edges and one free edge, loaded with a concentrated force, as illustrated in Fig. 5.10. The various yield line patterns which resulted in the lowest upper bound values are represented by the term α which may be obtained from satisfying the conditional statements presented in Appendix C, having obtained values for λ_1 and λ_2.

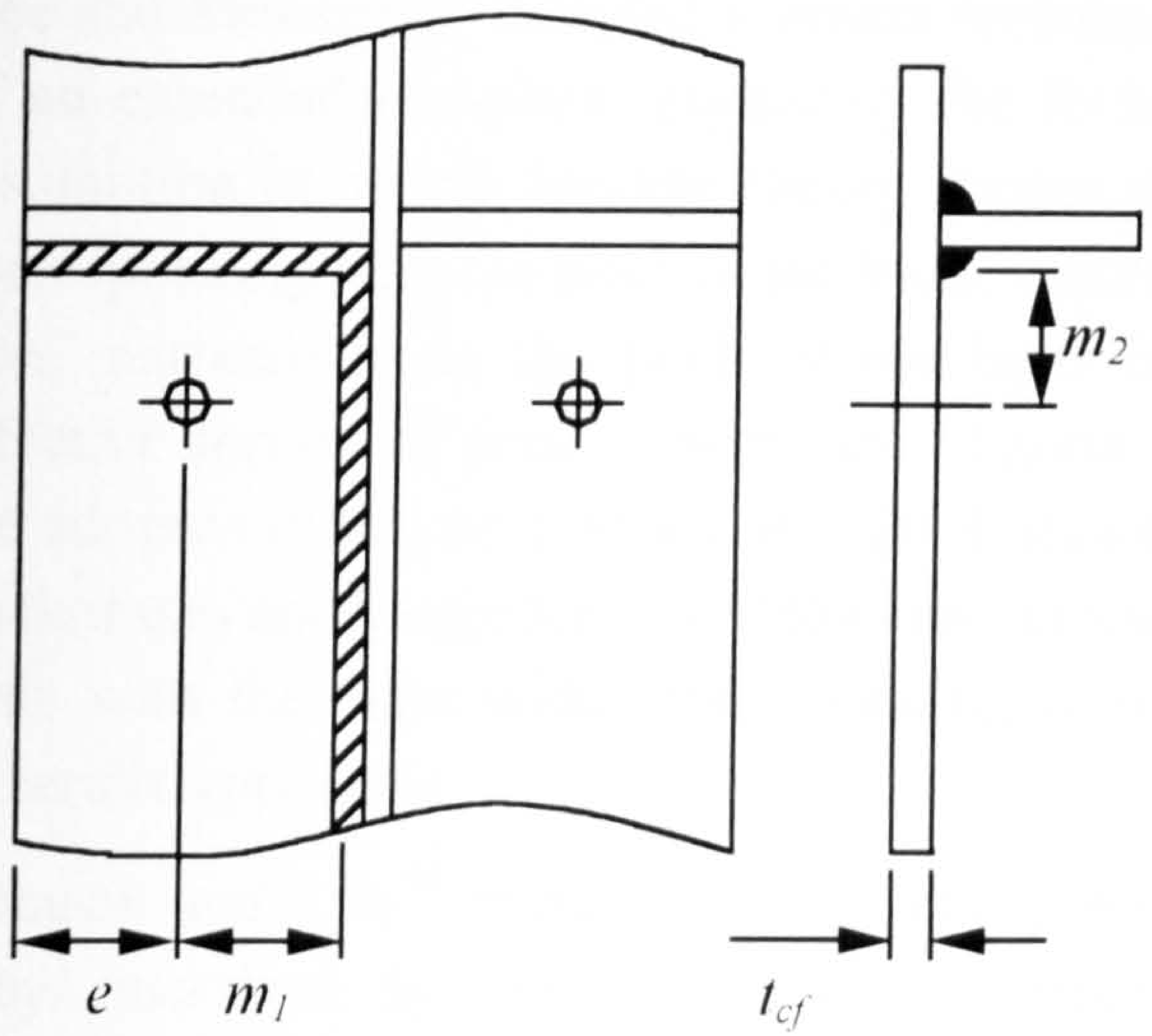
The effective yield line based on failure of a group of bolts acting in combination may be similarly assessed, where typical assumed yield line patterns are shown in Fig. 5.11. Each row may firstly be considered in isolation, and then in combination with successive rows above, so as to ascertain the critical arrangement of yield lines:

$P_{cft,1}$ = *capacity of row 1 alone*

$$P_{cft.2} = \text{Min. of} \begin{bmatrix} \textit{capacity of row 2 alone} \\ (\textit{capacity of rows } 2+1) - P_{cft.1} \end{bmatrix}$$

$$P_{cft.3} = \text{Min. of} \begin{bmatrix} \textit{capacity of row 3 alone} \\ (\textit{capacity of rows } 3+2) - P_{cft.2} \\ (\textit{capacity of rows } 3+2+1) - P_{cft.2} - P_{cft.1} \end{bmatrix}$$

and so forth .....



$$\lambda_1 = \frac{m_1}{m_1 + e}$$

$$\lambda_2 = \frac{m_2}{m_1 + e}$$

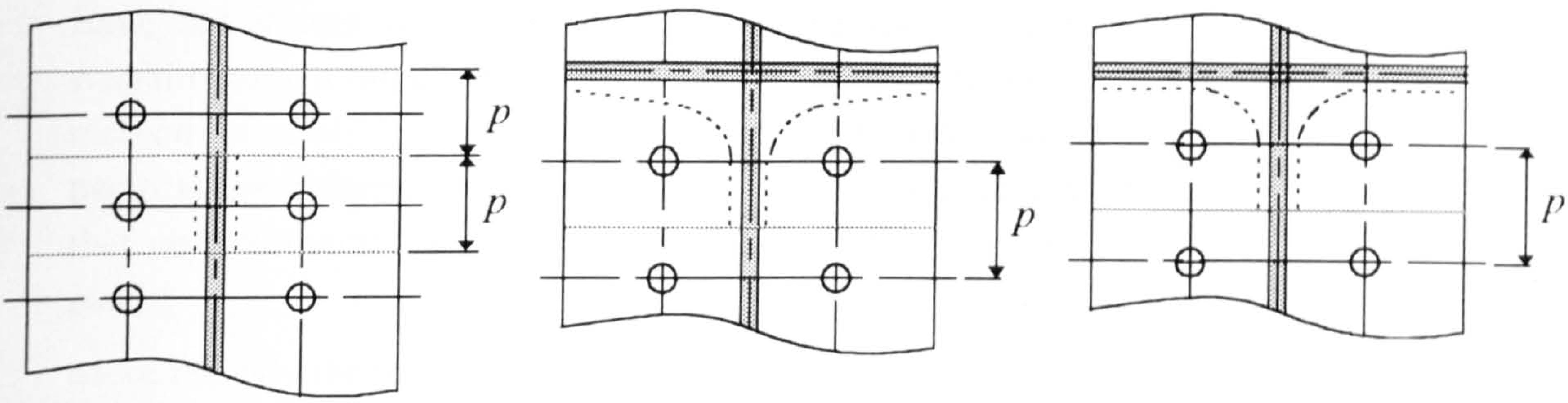
Where

$$m_1 = \frac{g}{2} - \frac{t_{cw}}{2} - 0.8r_c$$

$$m_2 = x - 0.8s_{ws}$$

$$e = \frac{B_c}{2} - \frac{g}{2}$$

Figure 5.10. Factors for the Determination of the Influence of Stiffeners on Length of Yield Lines



Pattern (iv). Intermediate row $L_{eff} = p$

Pattern (v). Outer row along clear edge $L_{eff} = 2m_1 - 0.625e + p/2$

Pattern (vi). Outer row near stiffener $L_{eff} = \alpha m_1 + (2m_1 + 0.625e) + p/2$

Figure 5.11. Assumed Yield Line Patterns for Column Flanges Acting in Combination

Subsequent to the onset of plasticity, a nominal stiffness may be assumed as with the bolts, so as to avoid computational difficulties. The degradation of steel stiffness and capacity may be based on the recommendations presented in Section 2.2.

5.3.3. End-Plate Behaviour

Little consideration has previously been given to the analysis of flush end-plate connections due to their relatively low stiffness compared with extended end-plate connections. Indeed, Douty and McGuire[124] commented that the former were undesirable in plastically designed structures, and probably even in elastically designed structures. As such the response of flush end-plates appears to have been insufficiently addressed within existing spring stiffness models.

A number of authors have previously considered the response of the end-plate based on simple beam theory, with the assumed width of the effective flange corresponding with the pitch of the bolts. This approach has been adopted by Laurie Kennedy and Hafez[99] and more recently by Madas[103] for modelling the response of partial-depth end-plates, whilst Yee and Melchers[135] adopted a similar technique in the consideration of the tension region of an extended end-plate, expanding the formulation to incorporate prying action. The assumption of simple bending theory implies that the plate yields across its entire width, corresponding with the pitch of the bolts, simultaneously. This is clearly not necessarily the case, particularly as the pitch of the bolts increases, and further consideration of the effective section of plate is necessary. Laurie Kennedy and Hafez based the validation of the adopted model on a series of eight T-stub tests covering a practical range of end-plate thicknesses and gauge lengths. However, as the tests conducted considered an isolated bolt row, with the plate width corresponding with an assumed pitch, the results may not be generally applicable.

Johnson and Law[96] considered the full-depth end-plate to be fully restrained by the bolts and to deform as a simple cantilever, with a point load at its free end, as illustrated in Fig. 5.12. The approach adopted is inconsistent with the method of predicting bolt stiffness adopted by Johnson and Law, but it was concluded that a more realistic treatment would require a three-dimensional analysis. The use of such a method of analysing plate stiffness seems unrealistic as it neglects the deformation of the plate at bolt rows, assuming that no deformation will occur across the width of the end-plate.

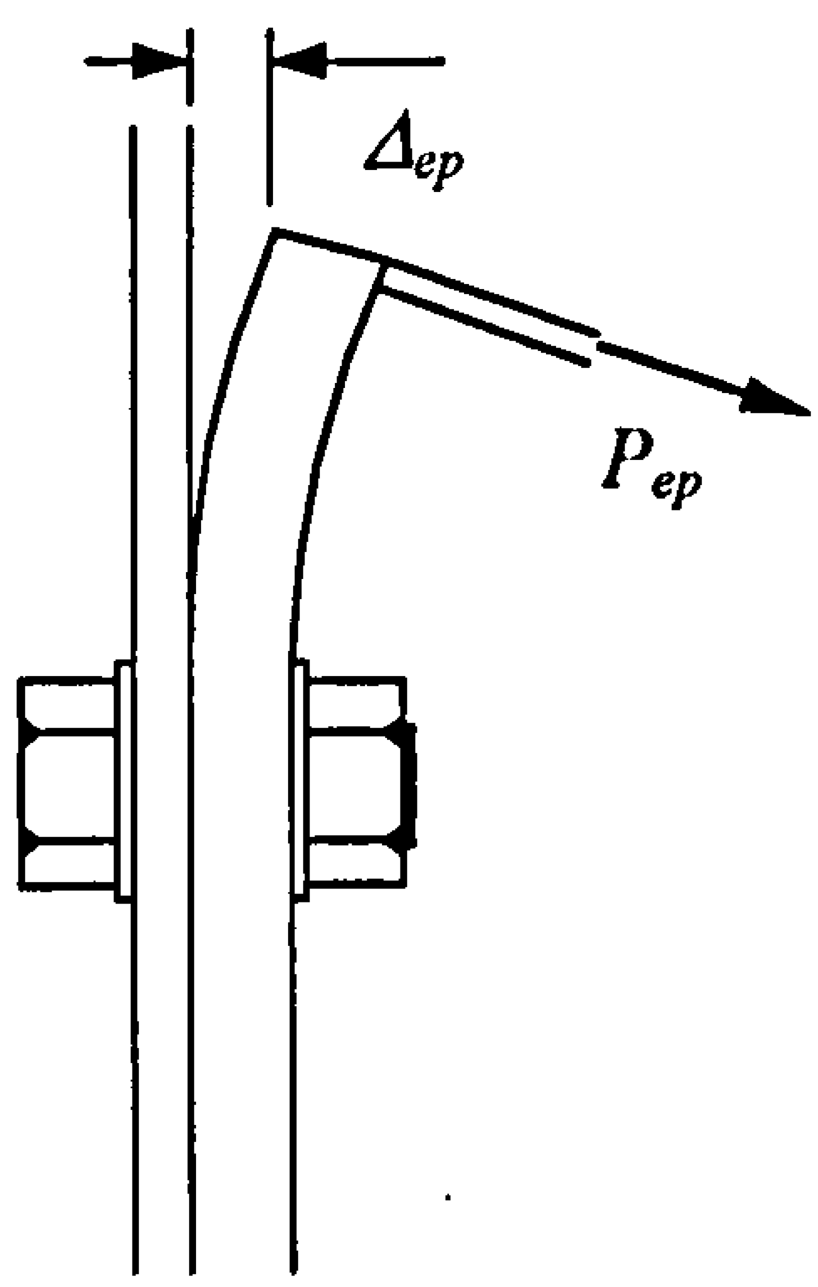


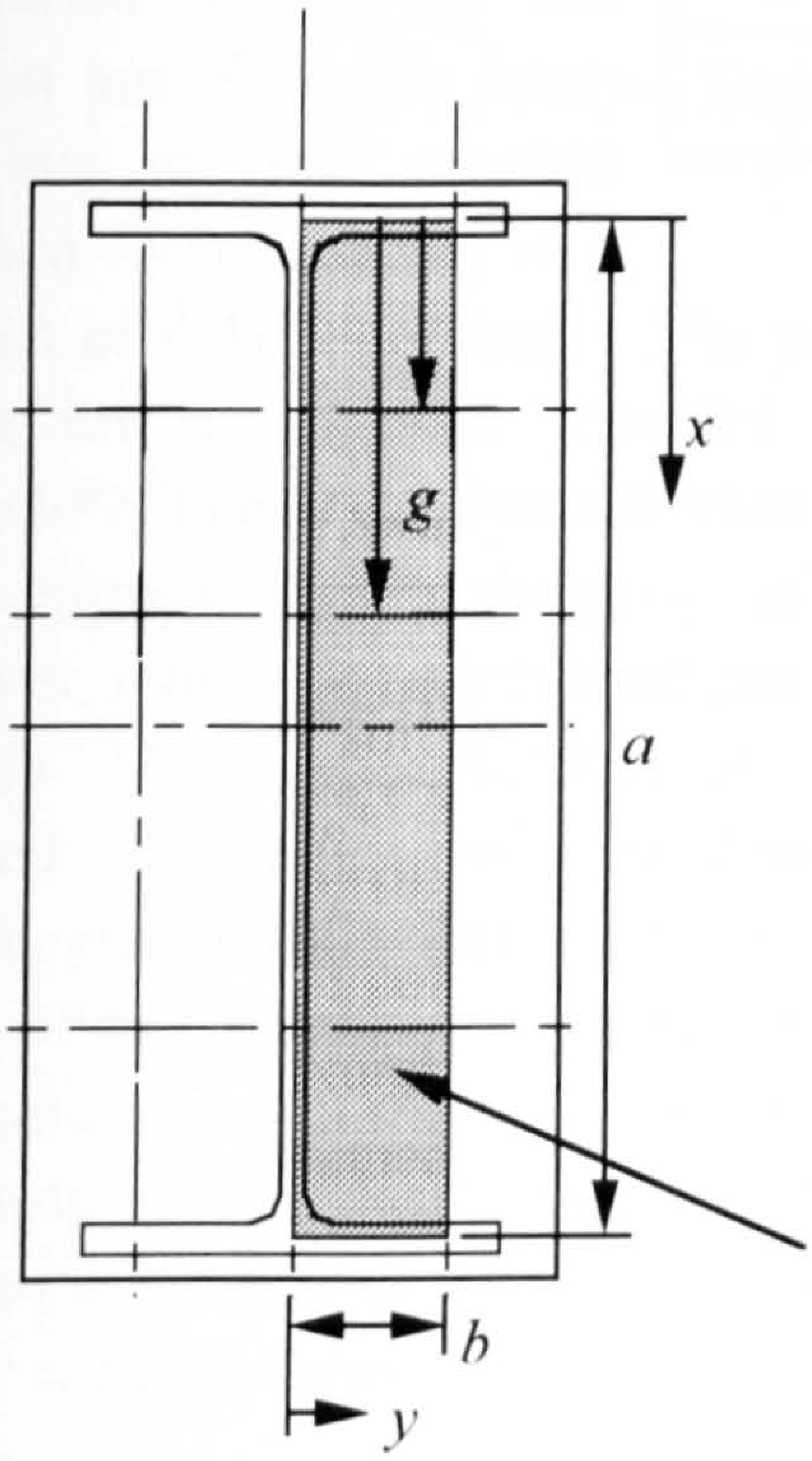
Figure 5.12. End-Plate Deformation

More recently the revised Annex J of EC3[41] suggested that the stiffness of end-plates may be assessed based on assumed yield line arrangements. However, the original draft of EC3[136] proposed an end-plate of far lower stiffness than in the revised draft, and no information has been provided to support this change of approach.

The three-dimensional response of the end-plate has been considered through the application of plate bending theory, so as to account for the influence of restraint provided by welding to the beam flanges. Assessment of the end-plate is described in greater depth in Appendix B, with the area of plate considered and the assumed geometric and boundary conditions being detailed in Fig. 5.13. The deflection at the bolt location, Δ_{ep}, may be shown to be:

$$\Delta_{ep} = \sum_{n=1}^{\infty} \frac{16P\sin^2(n\pi\xi)}{D\pi^4\left\{\frac{3bn^4}{a^3} + \frac{2n^2}{ba} + \frac{a}{b^3}\right\}} \qquad \text{Eq. 5.15.}$$

Where D is the flexural rigidity of the plate (see Eq. 5.11);
P is the assumed point load applied at $y = b$ and $x = g$;
ξ is the relative location of the point load 'x-wise' (= g/a);
n is the number of terms 'x-wise'.



(a) Geometrical Conditions:

$a = D_b - t_{bf}$

b = gauge / 2

Where

D_b is the depth of beam section;

t_{bf} is the thickness of beam flanges;

g is the distance from the centre of the top beam flange to the centre of the bolt row under consideration.

(b) Assumed Boundary Conditions:

At $y = 0$: $\partial_w/\partial_y = 0$, $w = 0$; At $y = b$: $\partial_w/\partial_y = 0$

At $x = 0, a$: $w = 0$

Assumed effective area of end-plate in plate bending analysis.

Figure 5.13. Idealised Representation of End-Plate

The resulting deflected form of the end-plate is shown in Fig. 5.14, with ten terms having been adopted 'x-wise'.

As can be seen from Fig. 5.14, the deflected form seems reasonable, with maximum deflection occurring at the location of the point load, and most non-relevant sine waves having been counteracted. Deflection of the plate soon becomes negligible as one moves away from the point of loading, suggesting that the plate may possibly be considered as a cantilever of infinite length, as with the column flange.

Assessments of the end-plate stiffness, based on each of the techniques described above, are compared in Table 5.1, in which a single side of the end-plate described in Chapter 2 has been considered. As can be seen, there is considerable variation in the calculated stiffness based on the techniques considered, and quite significantly the highest stiffness was obtained through the use of assumed effective yield lines as prescribed in the revised Annex J of EC3, indicating that this may possibly result in an un-conservative solution.

Method of Analysis:	*Stiffness ($x10^6$ N/mm):*
Simple cantilever	0.046
Cantilever of infinite length	0.212
Finite Element Analysis	0.263
Beam theory	0.323
Plate bending	0.419
Yield Lines	0.915

Table 5.1. Assessment of End-Plate Stiffness

Considering analysis of the end-plate based on plate-bending theory, it can be seen that, despite load having been applied as a concentrated point load at the centre of the bolt, there is a considerable degree of restraint provided to rotation at both the bolt location and along the beam web due to the assumed deflected form, resulting in a stiffness of $0.419x10^6$N/mm. The adopted deflected form appears to account to some degree for the restraint provided by the bolt head. A reduction in stiffness to $0.323x10^6$N/mm was observed when analysed based on beam theory, assuming a beam length corresponding to the gauge of the bolts and a plate breadth equal to the bolt pitch. However, it must be remembered that the derived stiffness is a function of the plate breadth adopted. A modified stiffness of $0.233x10^6$N/mm is obtained if the plate breadth is assumed to correspond with the diameter of the bolt head. This seems to suggest that a lesser degree of rotational restraint is provided at bolt locations, and reducing the assumed length of the plate to correspond with the edges of the bolt head results in a significant enhancement in stiffness to $3.327x10^6$N/mm due to the cubic relationship with the assumed beam length. This clearly highlights the sensitivity of the end-plate stiffness to the assumed restraint at the bolt locations. Analysis using finite element techniques, based on solution by flat shell elements[22], resulted in a significant reduction in end-plate stiffness. Whilst

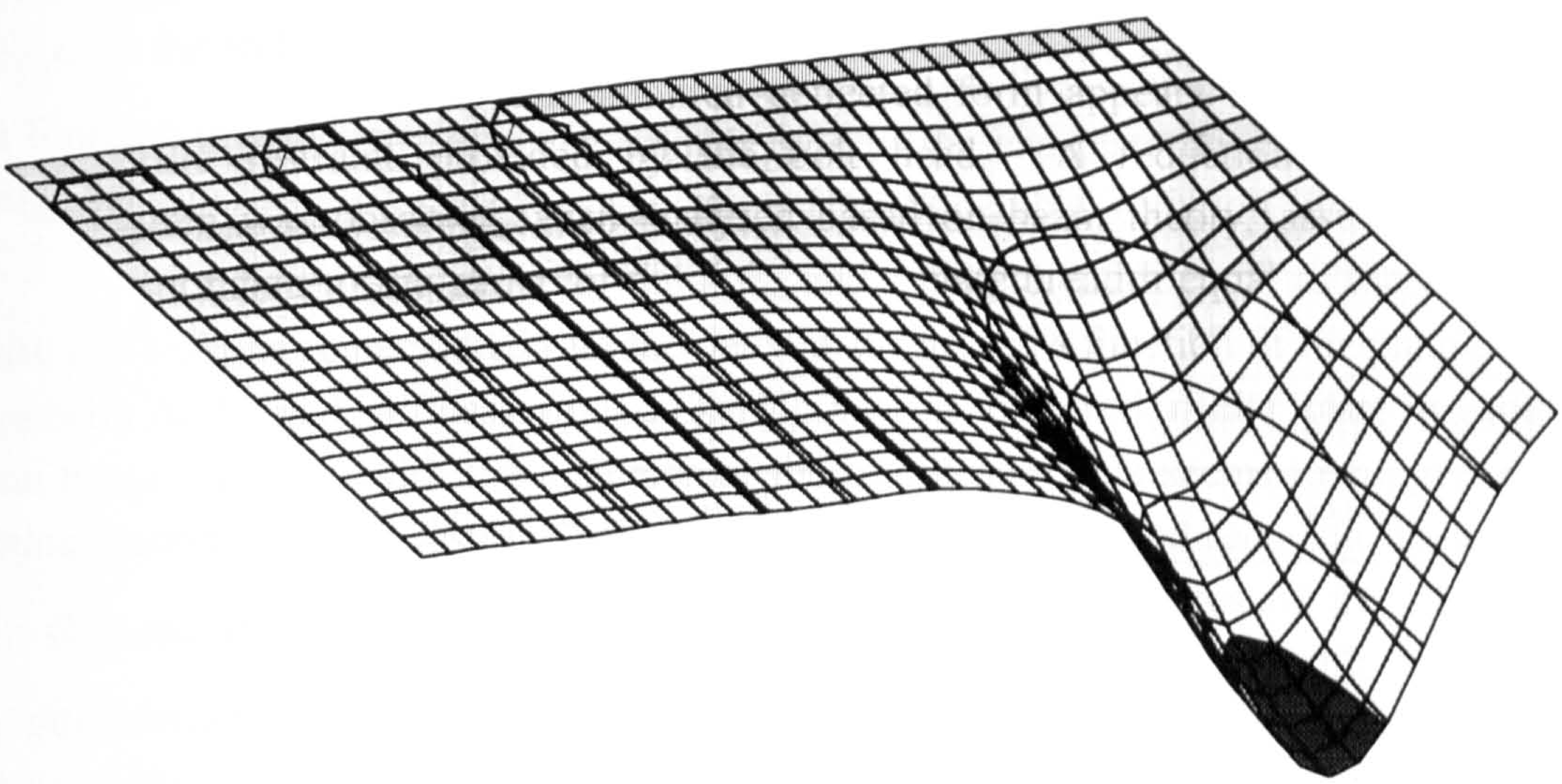


Figure 5.14. Resultant Deflected Shape of End-Plate from Plate Bending Theory

rotation was once more restrained at bolt and beam web locations, consideration of the deflected form indicated that the assumed boundary conditions predict a significantly reduced restraint against rotation compared with that implied from the deformed shape adopted in the plate bending model, possibly due to the use of thin-plate theory for an essentially thick-plate bending problem.

Assessment of end-plate behaviour based on the recommendations of Johnson and Law results in a very low stiffness of 0.046×10^6N/mm. The plate was assumed to be restrained against rotation at the bolt centreline, which may be considered to be an overly-conservative approximation. If the length of the cantilever is reduced to correspond with the edge of the bolt head, the calculated stiffness would increase to 0.146×10^6N/mm, demonstrating the sensitivity of the model to the assumed cantilever length.

It seems reasonable to conclude that there is considerable ambiguity concerning the response of end-plates as considered by a number of authors, with the validity of differing techniques being difficult to assess without the development of further experimental data considering the response of end-plate elements in isolation, for a variety of geometric arrangements. Hence, it is proposed that the stiffness of the end-plate is assessed assuming the plate to act as a cantilever of infinite length, due to this resulting in a conservative approximation, and the existing validation of this model considering column sections subject to tensile forces. Hence, end-plate stiffness is expressed as:

$$K_{ept} = \frac{\pi . D}{\beta . a^2} \qquad \text{Eq. 5.16.}$$

in which:

$$D = \frac{t_{ep}^3 . E_{st}}{12.\left(1 - \upsilon^2\right)} \qquad \text{Eq. 5.17.}$$

Where a is half the end-plate width;

t_{ep} is the end-plate thickness;

β is a function of the distance to the centre of the bolt hole from the column web centreline s (gauge length / 2), and end-plate breadth a, and may be calculated as described in Eq. 5.12.

As with the analysis of the column flange, an elastic-plastic relationship is proposed, where the capacity of the end-plate may be assessed in a manner similar to that described for the column flange. Degradation of steel stiffness and capacity may once more be based on the recommendations presented in Chapter 2 for structural steel.

5.3.4. Column Web Behaviour

When considering stiffened connections, column web deformation in the compression zone becomes negligible, and the element may be assumed to be infinitely stiff. However, there is a tendency nowadays to leave columns unstiffened for reasons of economy. In the case of unstiffened connections, web deformation may have a considerable influence on the overall stiffness, and hence this has been incorporated within the proposed model.

Idealising the compression zone of the column web as a plate of dimensions d_c x b_{eff} subject to a uniform compressive force applied at the centre of compression (assumed to correspond with the centreline of the beam lower flange), as shown in Fig. 5.15., and assuming the plate to obey the principles of Hooke's law, the following expression may be obtained:

$$K_{cwt} = \frac{E_{st}.t_{cw}.b_{eff}}{d_c} \qquad \text{Eq. 5.18.}$$

Where t_{cw} is the thickness of the column web in the compression zone;
d_c is the depth of the column web between fillets;
b_{eff} is the assumed effective width of the column web.

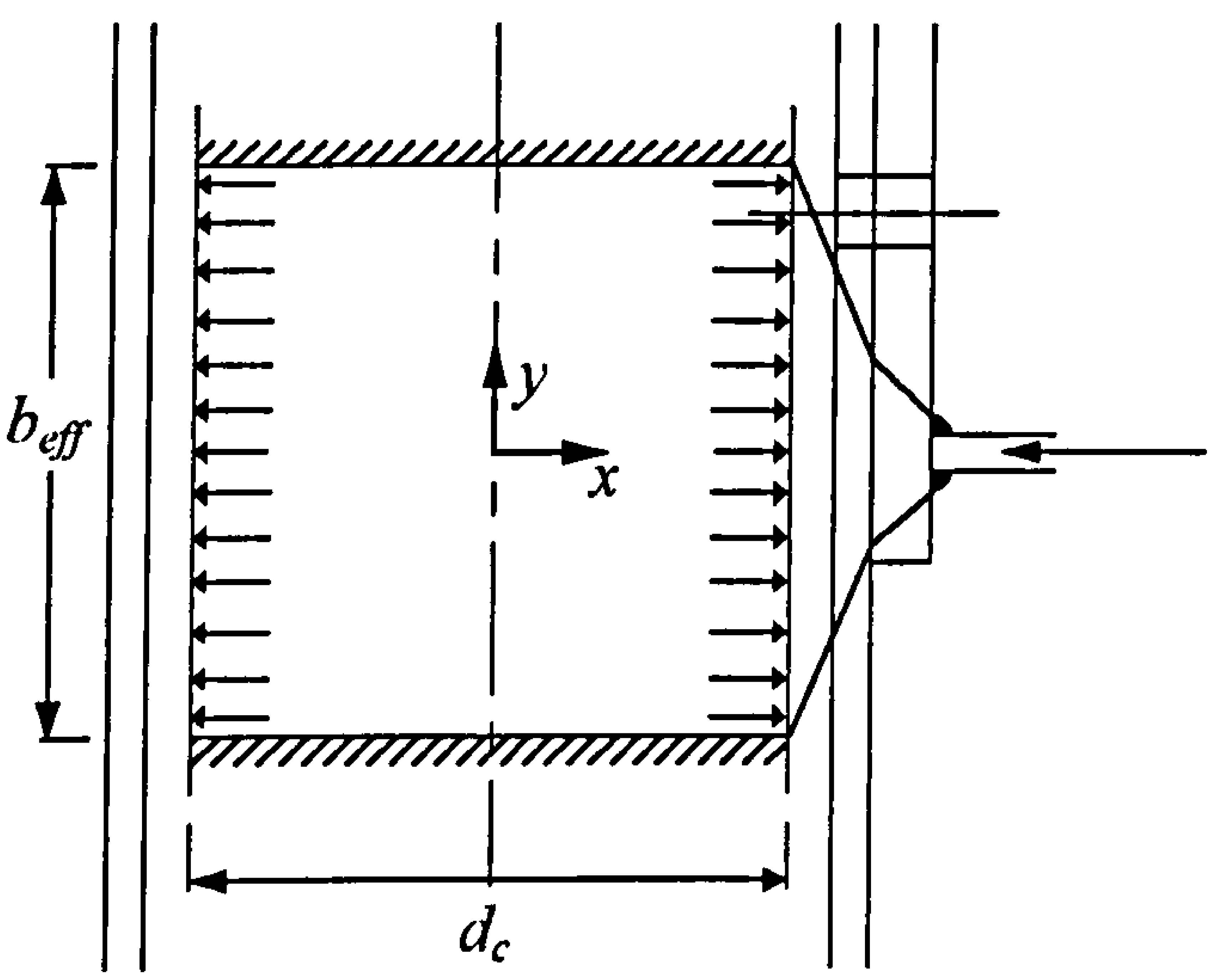


Figure 5.15. Idealised Column Web Behaviour in Compression Zone

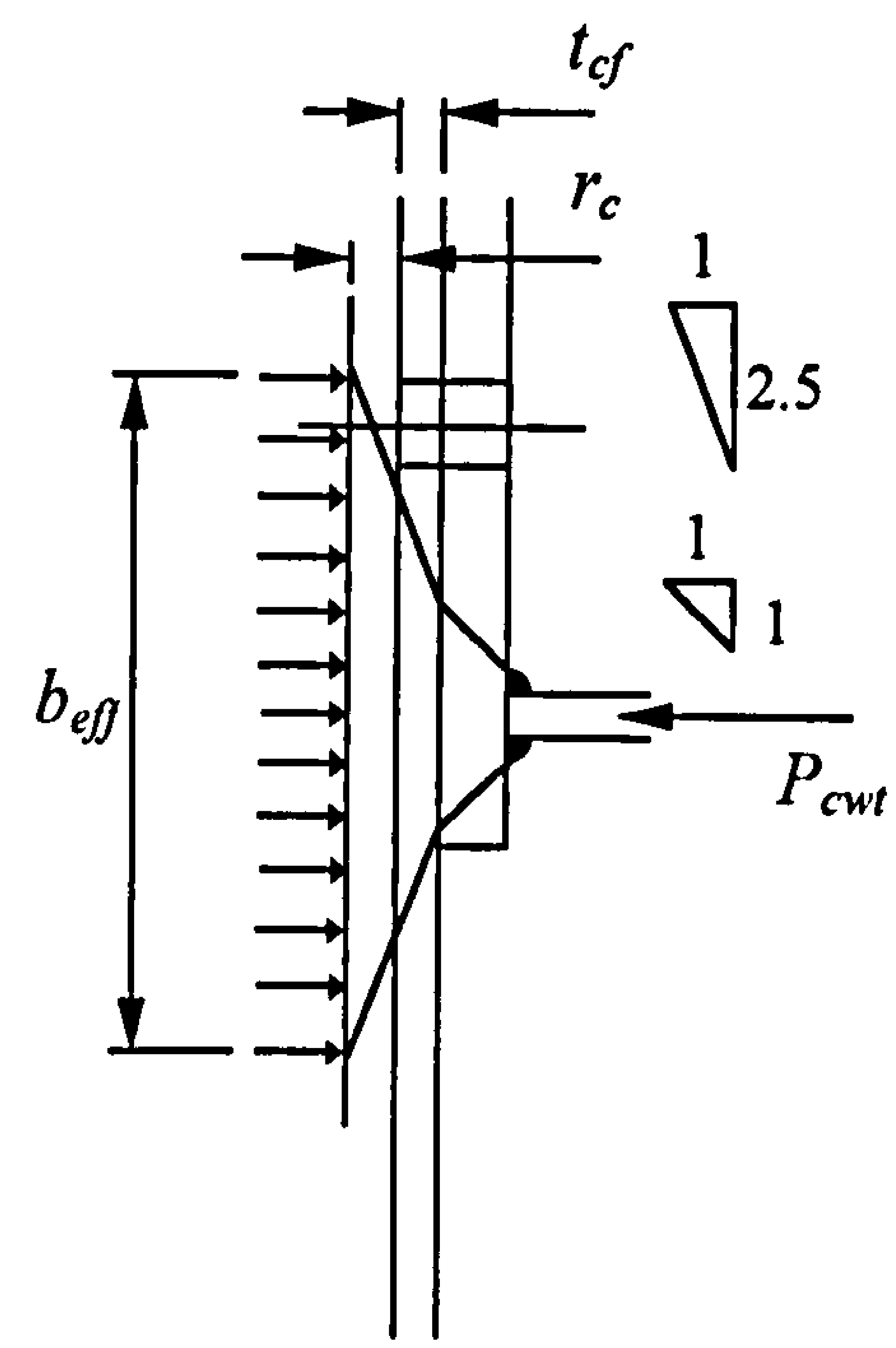


Figure 5.16. Determination of Effective Bearing Width

The effective width of the column web in the compression zone may be determined as described below, based on a stiff bearing resulting in a 1:1 dispersion of forces through the end-plate from the edge of the welds, and a 1:2.5 dispersion of forces through the column flange and root radius, as illustrated in Fig. 5.16. Hence:

$$b_{eff} = t_{bw} + 2.a.\sqrt{2} + 2.t_{ep} + 5.k \qquad \text{Eq. 5.19.}$$

Where t_{bw} is the thickness of the beam web;
a is the weld size;
k is the distance from the outer face of the flange to the web toe of fillet.

$$k = t_{cf} + r_c \qquad \text{Eq. 5.20.}$$

r_c is the column root radius.

The stiffness of the column web in the compression zone is assumed to remain constant until the onset of either crushing or buckling within the depth of the column web. In ordinary rolled I or H sections, crushing resistance generally prevails; but in the case of welded built-up members, members with slender webs, and members of high-strength steel grades, local buckling resistance may become critical. Hence, the critical force, P_{cwpt}, for the column web should be taken as the lesser of the crushing or buckling capacities as described below:

i. Crushing Resistance

Crushing resistance may be assessed assuming the column flange to act as a bearing plate, distributing the compressive force applied at the beam lower flange across a greater length, b_{eff} as defined in Eq. 5.19. Hence, the capacity may be expressed as:

$$P_{ccwt} = f_{ycwt} . t_{cw} . b_{eff} \qquad \text{Eq. 5.21.}$$

Where P_{ccwt} is the force that causes crushing of the column web in the compression zone at a given temperature;

f_{ycwt} is the yield strength of column web in the compression zone at a given temperature;

The above assumption has previously been validated by Chen and Newlin[137], who demonstrated the formulae to be conservative for steel grades up to 690kN/mm^2 based on a series of tests. Aribert[98] similarly considered a series of 23 tests in which crushing failure was observed to be critical, in which a close correlation was observed with the described formulae.

ii. Buckling Resistance

Assessment of buckling resistance in Annex J of EC3[41] considers the web to act as a virtual compression member of effective breadth. However, further studies by Aribert[98] indicated that this appears to be overly-conservative. Hence, the buckling capacity is assessed using empirical relationships relating the critical stress to the yield limit. Based upon the recommendations presented within Chapter K of the AISC[138] specification:

$$P_{bcwt} = 10{,}750 \frac{t_{cw}^{\,3}}{d_c} \sqrt{f_{ycwt}} \qquad \text{Eq. 5.22.}$$

Where P_{bcwt} is the force that causes buckling of the column web in the compression zone at a given temperature;

Comparison of the above relationship once more resulted in a close correlation with experimental results when compared with a series of 60 tests[98].

Walker[139] proposed a technique for predicting the post buckling stiffness of flat square plates based on perturbations about the bifurcation load, using a McLaurin series expansion to analyse shells in the post-buckling range of loading. This technique was applied to obtain the buckled behaviour of simply supported plates under compression along two opposite edges, and has more recently been adopted by Yee and Melchers[135] to describe the post-buckled behaviour of column webs in the compression zones of bare-steel connections. By idealising the column web as a simply supported plate subject to a uniform compression force, the following expression may be shown to relate the buckled stiffness to the flat plate stiffness:

$$\frac{PostBucklingStiffness}{FlatPlateStiffness} = \frac{1}{2.45 + 0.585\left(\frac{P_{cwt}}{P_{cwpt}} - 1\right)}$$ Eq. 5.23.

Where P_{cwt} is the force applied to the column web.

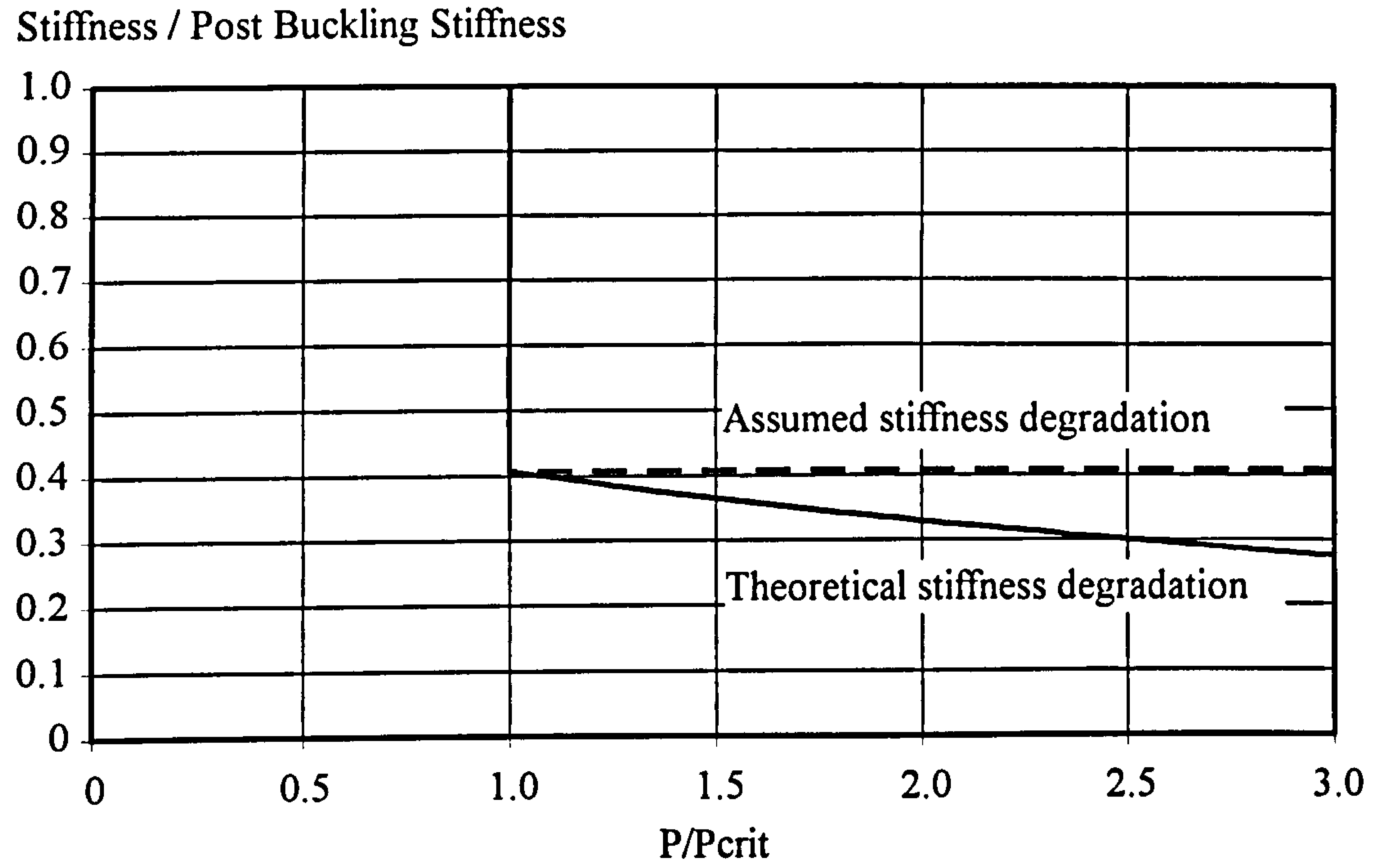


Figure 5.17. Variation of Stiffness of Simply Supported Square Plate in Compression

The implementation of Eq. 5.23. complicates the assessment of connection stiffness due to its non-linearity. Fig. 5.17 illustrates the degradation of the stiffness of a simply supported plate based on the equation presented above. It may be observed that the plate stiffness immediately after the onset of plasticity provides a reasonable representation of stiffness within the range of forces with which we are concerned. Hence, it is proposed that the buckled stiffness of the column web in the compression zone, k_{cwpt}, may be represented by:

$$k_{cwtp} = \frac{K_{cwt}}{2.45}$$ Eq. 5.24.

It has been assumed that plastic stiffness may be based on the above recommendations regardless of whether crushing or buckling resistance is predicted to prevail. Degradation of steel stiffness and capacity may once more be based on the recommendations presented in Chapter 2 for structural steel.

5.3.5. Validation of Connection Model

Initial validation of the proposed spring-stiffness flush end-plate connection model was conducted at ambient-temperatures, based on existing bare-steel major[71] and minor axis[65] connection tests. This facilitates an assessment of the capability of the model to predict the moment-rotation response of bare-steel connections to a suitable degree of accuracy whilst removing the additional complication of the influence of elevated-temperatures on connection response.

Minor axis connection tests conducted by Davison[65] provide the ability to model a flush end-plate connection, whilst isolating the influence of column behaviour. The connection tested was nominally identical to that previously tested at elevated-temperatures as described in Chapter 3, framing into the major-axis of the column, with the substitution of Grade 8.8 bolts for Grade 4.6. Nominal material and section properties were assumed as detailed in Appendix A, assuming a reduced strain-hardening modulus based on 2% of the initial Young's modulus value. Fig. 5.18 compares experimental results developed by Davison with those predicted using the spring-stiffness model described above. It may be seen that the proposed model provides a close prediction of the moment-rotation response for this connection at ambient-temperatures in terms of initial stiffness, strain hardening stiffness and capacity. The model underestimates the ultimate capacity of the connection, but the observed error is relatively small and may be attributable to variations in material properties. Indeed, an extensive survey of actual bolt characteristics conducted by Schmidt[140] suggested a mean ultimate strength for Grade 4.6 bolts approximately 24% above the nominal value. Failure was predicted as being controlled by bolt behaviour, corresponding with experimental observations, with actual failure of the connection occurring as a result of bolt stripping.

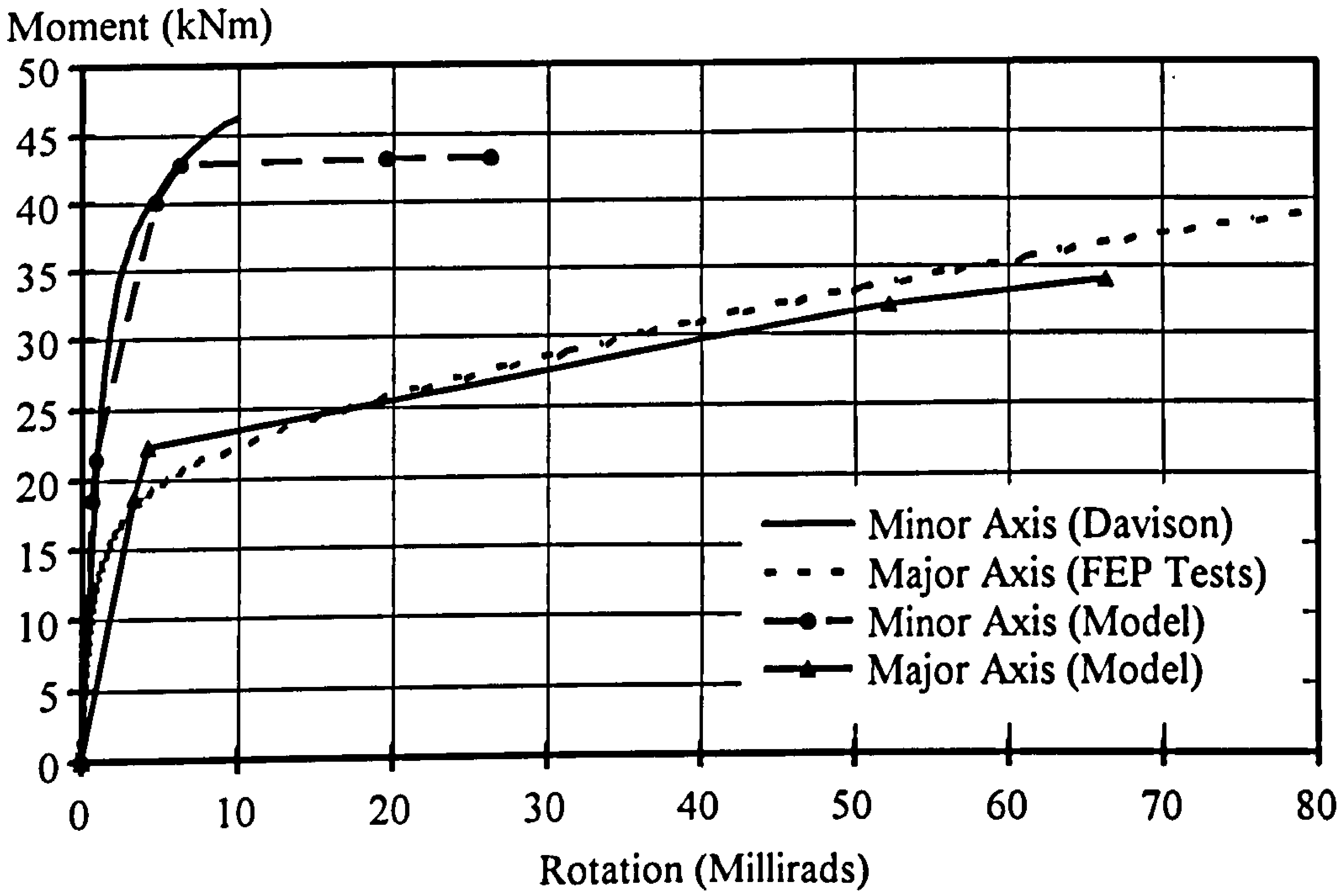


Figure 5.18. Comparison of Predicted Ambient-Temperature Response with Experimental Observations

Major-axis flush end-plate connection tests have been conducted at both ambient and elevated-temperatures as detailed in Chapter 3. Ambient-temperature experimental results have been validated by comparison with existing data[65] in Fig. 3.7. It was observed that the flexibility of the column flanges, compared to the relatively stiff end-plate, resulted in a significantly reduction in stiffness and capacity compared to the minor-axis connection, with considerable deformation of the column web and flanges being observed at ambient-temperatures. The predicted response is once more compared in Fig. 5.18, assuming experimental material properties. It may be seen that the proposed spring-stiffness model once more provides a reasonable prediction of the initial stiffness of the connection. Although the connection model did somewhat overestimate the yield capacity of the connection, it provided a close prediction of ultimate capacity and strain hardening stiffness. The proposed model predicted connection deformation as being controlled by column flange deformation in the tension zone, and column web crushing in the compression zone, corresponding with experimental observations.

Validation of the model at elevated-temperatures was based on the flush end-plate connection previously described, and existing elevated-temperature connection tests carried out by Lawson[44]. Temperature profiles and material properties were based on those obtained experimentally.

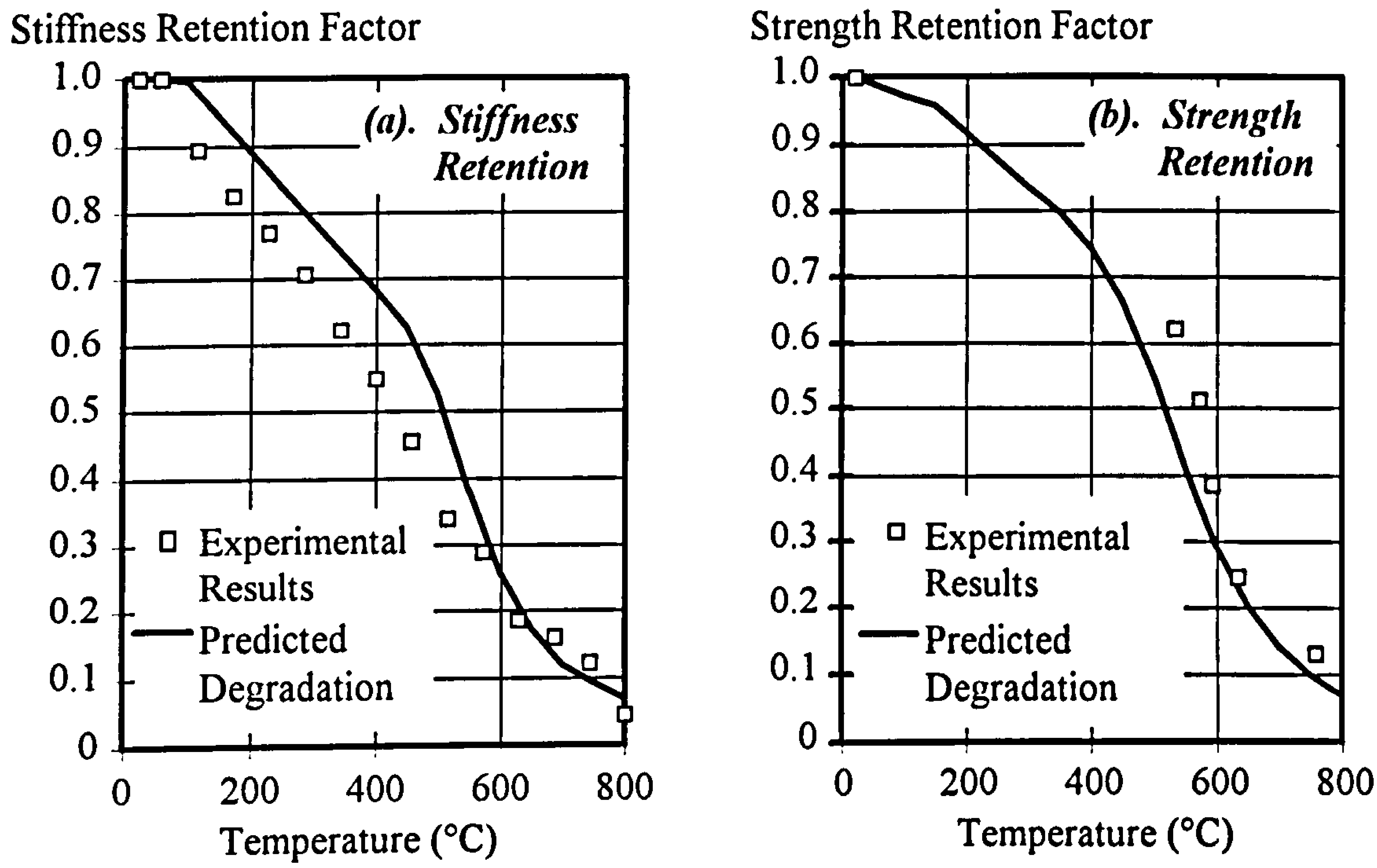


Figure 5.19. Predicted Degradation of Connection Characteristics Due to the Influences of Temperature

In the case of the flush end-plate connection assessed at ambient-temperatures, five tests were conducted under a constant level of moment with increasing temperatures, with a cruciform arrangement being adopted.

Experimental results are compared with those predicted in the form of strength / stiffness retention plots in Fig. 5.19. It may be seen from 5.19(a) that the predicted degradation of stiffness with temperature compared closely with that recorded. However, it is of concern that the model appears un-conservative in the assessment of the rate of degradation up to temperatures approaching 600°C. Predicted degradation of connection capacity once more compares closely with experimental results, although unfortunately test data was not available for temperatures below 400°C, due to the levels of loading adopted in testing. It may be seen that predicted rates of degradation of capacity remained conservative.

As was observed experimentally, the model demonstrated the increased significance of the column web in the compression zone with increasing temperatures. This casts doubt on the model's neglect of the movement of the axis of rotation based on the relative stiffnesses of the tension and compression zones. The incorporation of the movement of the neutral axis would add significant complexities in the formulation of the spring stiffness model, and the intention was to develop a simple model suited to manual calculations (although more efficiently implemented as a simple program, due to the repetitive nature of assessment at increasing temperatures). The connection tested had a comparatively 'flexible' column web, but as has been seen, the model appears to provide an acceptable representation of the influence of increasing temperatures. It seems reasonable to ignore the movement of the centre of rotation for typical bare-steel connections in which the relative stiffness of the column web is greater than for the flush end-plate connection tested.

A total of eleven elevated-temperature tests have been conducted by Lawson, two of which were on flush end-plate connections in a non-composite state. Beams supported a 120mm thick non-composite concrete slab to generate 'realistic' temperature distributions, with movement joints adjacent to the columns to prevent transfer of the moments through the slab. A cruciform arrangement was adopted consisting of 305x165x40UB43 beams framing into the flanges of a 203x203x42UC43 column. The two connections tested were nominally identical, but in the case of Test 2 sections were left unprotected, with a block infill being provided between column flanges, whereas Test 4 was protected using a vermiculite-cement spray to provide sixty minutes fire protection. In both cases a cruciform arrangement was adopted, with the specimens being subjected to a constant level of moment (equivalent to 20% of the ambient-temperature plastic moment capacity of the beam), with increasing temperatures. Experimental results for Tests 2 and 4 are compared with those predicted by the described spring-stiffness model in Fig 5.20.

Results from Test 2 demonstrated a significant variation in the rotations recorded for the two sides of the connection, with a reversal of rotation at low temperatures. It is probable that this was attributable to an overall rotation of the connection due to lack of symmetry, although it could possibly be as a result of expansion of the connection in the compression regions. The described model does not consider the effects of thermal expansion of the column web or beam lower flanges, and would therefore provide no information on these. As can be seen from Fig. 5.20*(a)*, little rotation was predicted for the connection until a time of 20 minutes, corresponding to a beam lower flange temperature of approximately 450°C. At increasing temperatures a gradual plastification of the connection was observed, having lost most of its stiffness after 25 minutes. The proposed spring-stiffness model predicted a similar response, with little rotation before 20 minutes, followed by a gradual plastification until failure at a time approaching 30 minutes, with an equivalent beam lower flange temperature of approximately 650°C. Failure of the connection was predicted to be controlled by column flange yielding in the tension zone, and web buckling in the compression zone. No description is reported for the experimental failure mechanism, although it is indicated that this was controlled by column response and by buckling of the lower flange of the beam, as this was left unprotected remote from the connection.

Once more in Test 4 the proposed model provided a close prediction of connection response with increasing temperatures, predicting failure of the connection to occur at temperatures of approximately 120 minutes, corresponding with a beam lower flange temperature of approximately 690°C. As would be anticipated, the failure temperature was similar to that for Test 2, although the failure time was significantly higher due to the application of intumescent protection. Failure mechanisms were also predicted to be similar to those for Test 2.

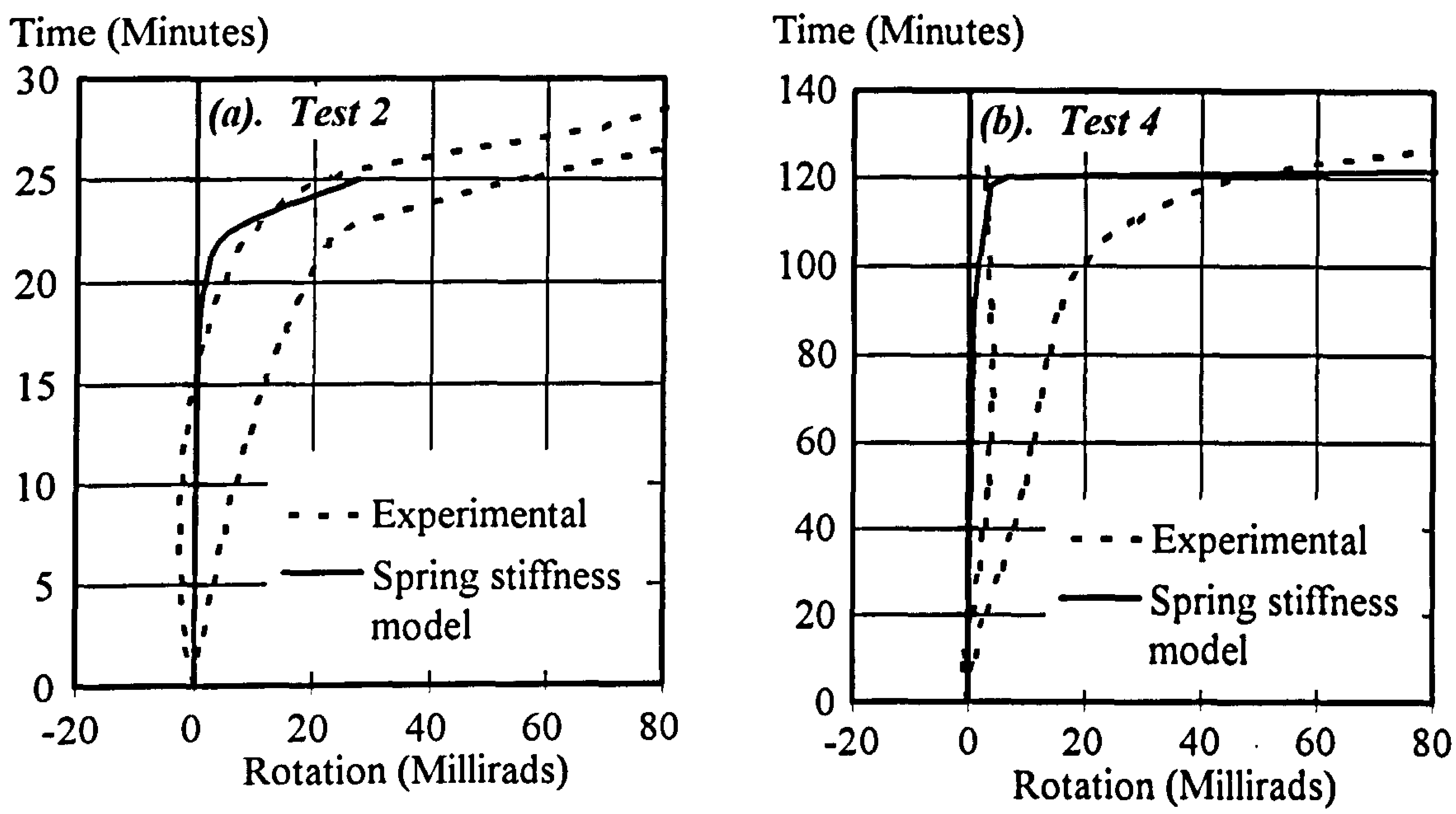


Figure 5.20. Comparison of Predicted Elevated-Temperature Response with Existing Test Data by Lawson[44]

5.4. COMPOSITE SPRING STIFFNESS MODEL

The use of 'realistic' connection characteristics is probably of greater significance in the case of composite constructions. Ambient-temperature studies have suggested that performance is significantly enhanced by the stiffness and strength provided as a result of the continuity of reinforcing bars or mesh in the tension zone. Few studies exist considering the performance of composite connections at elevated-temperatures. However, it is anticipated that performance of composite connections will be further enhanced due to the relatively low temperature of the reinforcement compared to that of the exposed steelwork.

As with bare-steel connections, a spring stiffness model has been adopted due to its ease of application, and ability to provide a reasonable representation over the full range of connection response. Spring stiffness models have been proposed for composite connections by a number of authors[141,142], assuming no slip to occur at the beam-slab interface. It was therefore possible to assume that a rigid section exists close to the column face, as illustrated in Fig. 5.21, and to determine the connection response resulting from the deformation of reinforcement and connection elements. This form of model has been adapted for a number of connection types by other authors, but has consistently been demonstrated to underestimate connection flexibility indicating that the flexibility of shear connectors should not be excluded from the derivation of composite connection stiffness.

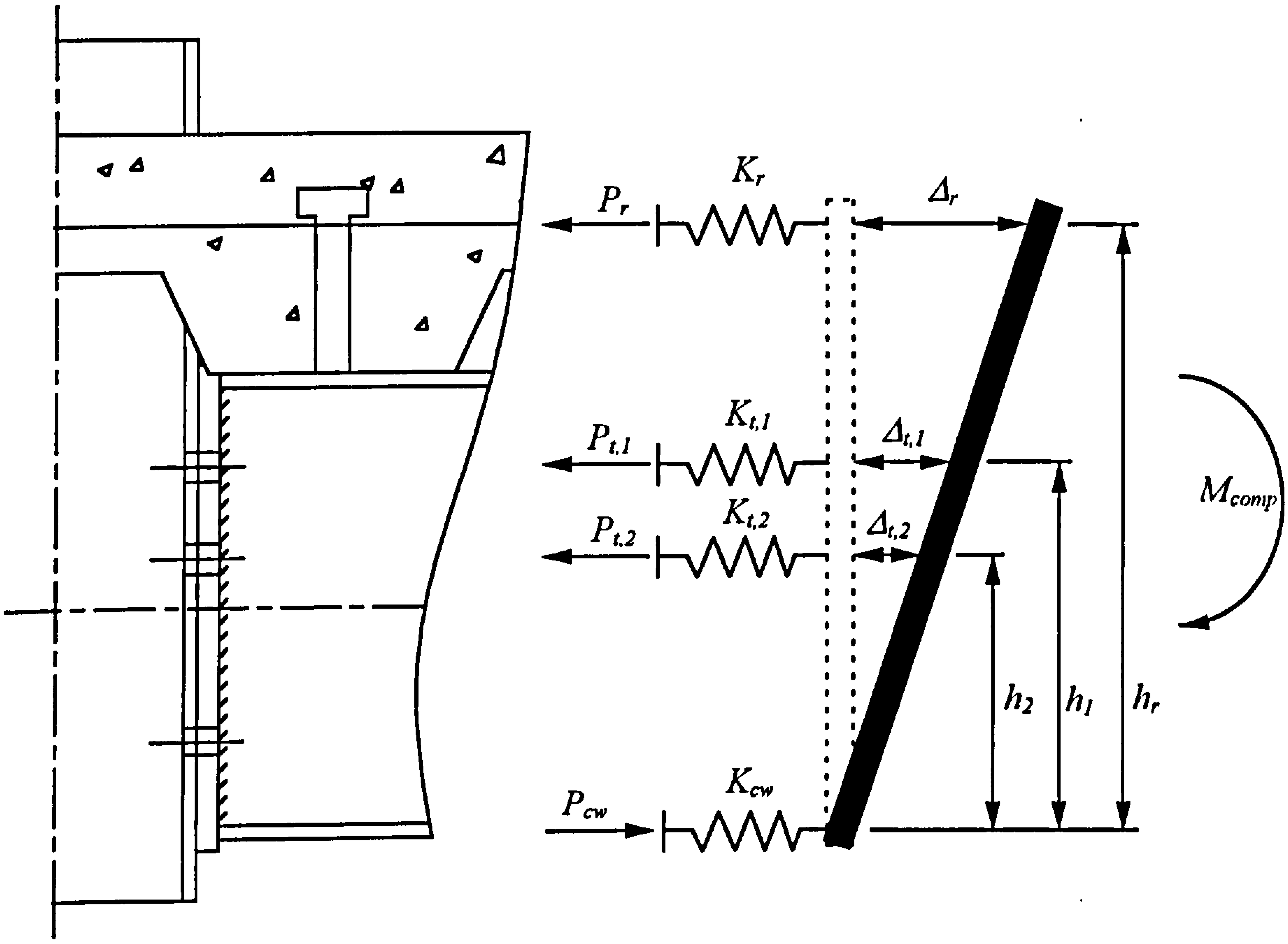


Figure 5.21. Elevated-Temperature Composite Connection Spring-Stiffness Models Neglecting Slip at the Beam-Slab Interface

This significance of the interaction at the beam-slab interface was acknowledged by Anderson and Najafi[143] and a revised connection representation was proposed as shown in Fig. 5.22. It was assumed that slip at the connection would initially depend on the nearest stud to the column, with this continuing to provide resistance to slip until the onset of plasticity, beyond which its force would remain constant. Additional load was then assumed to be resisted by the next stud deforming elastically, and so forth. The relationship between moment and rotation was defined as:

$$\phi = \frac{M}{\left[\dfrac{K_r.K_s.D_r.D}{K_r + K_s} + K_b.D_b^2\right]}$$ Eq. 5.25.

Where ϕ is the rotation of the composite connection;
M is the bending moment;
K_r is the axial spring stiffness of the reinforcement;
K_s is the axial stiffness of the shear connection;
K_b is the axial stiffness of the steelwork joint;
D_r is the distance between centroid of reinforcement and centre of rotation;
D_b is the distance between centroid of top row of bolts and centre of rotation;
D is the distance from the beam slab interface to the centre of rotation.

The model proposed by Anderson and Najafi resulted in an improved representation of the overall connection response, with the incorporation of slip at the beam-column interface producing a stiffness far closer to that observed experimentally. Equations were proposed for the derivation of reinforcement stiffness, and a constant value of 200kN/mm was adopted for the elastic stiffness of the shear connection, based on three push out tests conducted by Mottram and Johnson[60]. Rotation of the composite connection was assumed to occur about the centre of the beam lower flange, as with the bare-steel model previously described.

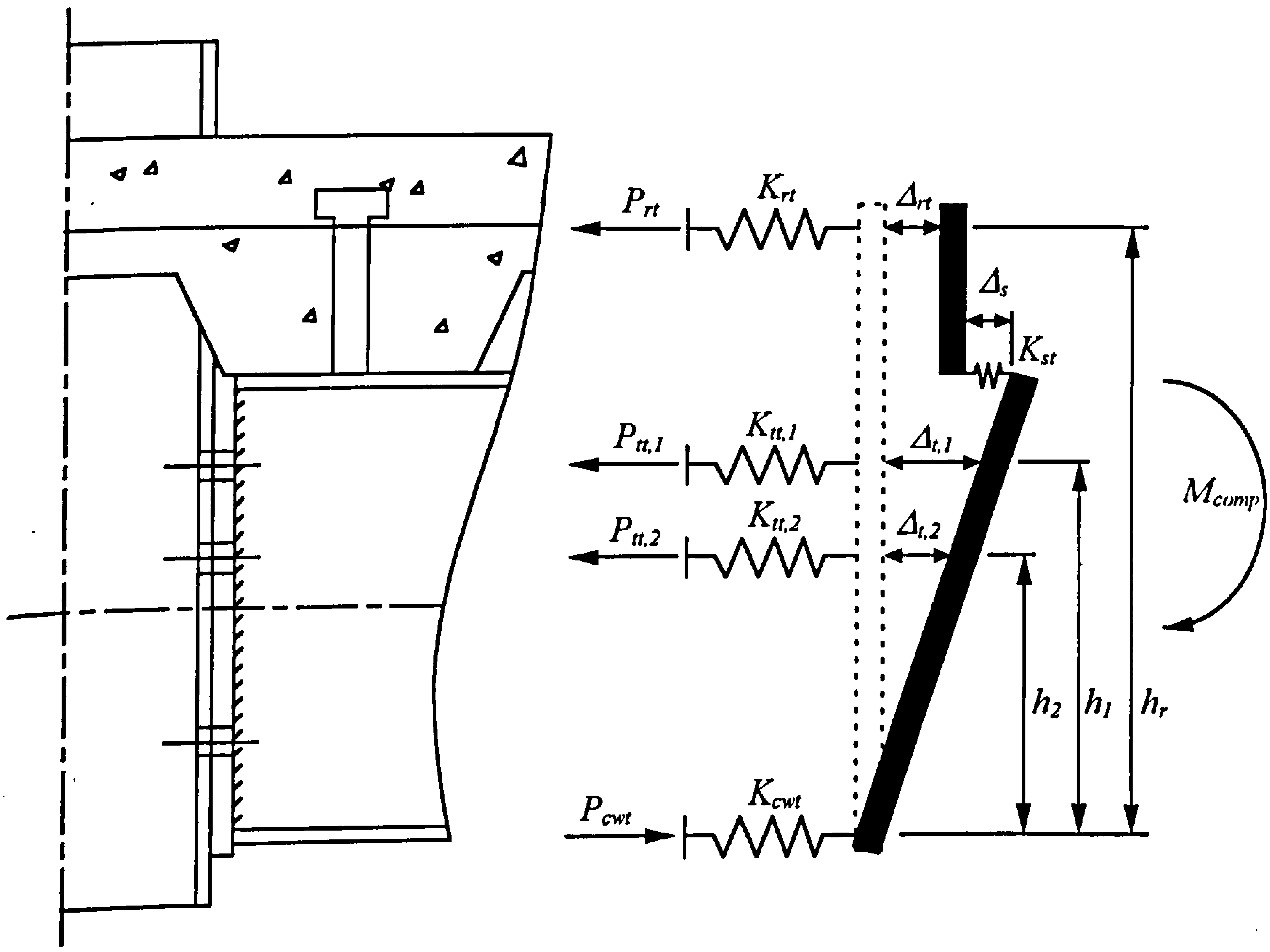


Figure 5.22. Elevated-Temperature Composite Connection Spring-Stiffness Models Incorporating Slip at the Beam-Slab Interface

It is proposed that the basic form of model adopted for elevated-temperature composite connections model follows a form similar to that proposed by Anderson and Najafi, with modifications to incorporate the influence of elevated-temperatures and to maintain consistency with the bare-steel connection model. Overall composite connection stiffness may thus be expressed as:

$$S_{cjt}^{-1} = \left\{ \frac{K_{rt} K_{st} D_r D}{K_{rt} + K_{st}} + K_{eqt} . z^2 \right\}^{-1} + \left\{ K_{cwt} . z^2 \right\}^{-1} \qquad \text{Eq. 5.26.}$$

Where S_{cjt} is the rotational stiffness of the composite connection for a given temperature;
K_{rt} is the stiffness of the spring representing the reinforcement;
K_{st} is the stiffness of the spring representing shear connection;
and K_{eqt}, K_{cwt} and z are as defined for the bare-steel spring-stiffness model.

From Eq. 5.26 it is possible to define the complete moment-rotation characteristics of the composite connection in a multi-linear form, as for the bare-steel connection, having formulated suitable temperature-dependent models for the prediction of the response of the additional elements required for composite connections. Rotational stiffness of the bare-steel connection may be based either on experimental observations or incorporated within the formulation on the basis of the elements described in Section 5.3. The incorporation of bare-steel spring elements is advantageous compared to the use of a pre-defined family of bare-steel moment-rotation curves as this allows for the incorporation of variations in the distribution of forces due to the effects of composite action.

5.4.1. Reinforcement Behaviour

Assuming the reinforcement to obey Hooke's law, it may be demonstrated that the reinforcement stiffness, K_{rt}, at a given temperature may be defined as:

$$K_{rt} = \frac{E_{rt} . A_r}{l_r} \qquad \text{Eq. 5.27.}$$

Where E_{rt} is the Young's modulus for the reinforcement at a given temperature;
A_r is the cross sectional area of the reinforcement considered;
l_r is the assumed debonded length of the reinforcement.

Various authors have suggested different assumptions for the debonded length of the reinforcement. This is difficult to assess physically since it often results in the destruction of much of the evidence required. It is generally assumed that the debonded length may be taken as either half the depth of the column, the distance from the centre-line of the column to the first shear stud, or the distance to the first cross-bar in the reinforcing mesh. The assumed debonded length can significantly influence both the capacity and ductility of the connection, as will be seen in the modelling of the elevated-temperature composite connection tests later in this Chapter.

Elastic behaviour is assumed to continue until the yield of the reinforcement, with the force P_{rt} at which this happens at a given temperature being defined as:

$$P_{rt} = f_{yrt}.A_r \qquad \text{Eq. 5.28.}$$

Where f_{yrt} is the yield strength of the reinforcement at a given temperature.

Subsequent to the onset of plasticity, a strain-hardening stiffness is assumed, and is expressed as:

$$K_{rpt} = \mu_r.K_{rt} \qquad \text{Eq. 5.29.}$$

Where K_{rpt} is the strain-hardening spring stiffness for the reinforcement at a given temperature;

μ_r is the strain-hardening coefficient for the reinforcement.

The force in the reinforcement for a given rotation may be related to the stiffness of the connected elements, and hence the capacity of the reinforcement may be obtained as:

$$P_{rt} = \phi.\left(\frac{K_{rt}.K_{st}.D}{K_{rt}.K_{st}}\right) \qquad \text{Eq. 5.30.}$$

It is proposed that the stiffness and capacity of reinforcement at elevated-temperatures may be based on the recommendations presented by Holmes *et.al.*[54], as detailed in Section 2.3.

5.4.2. Interaction at Beam-Slab Interface

As previously described, it is assumed that the slip at the connection would initially depend on the nearest stud to the column, with this stud continuing to provide resistance to slip until the onset of plasticity, at which point further load is assumed to be resisted by the next stud deforming elastically, and so forth. This allows the use of a linear-elastic representation for the stiffness as a result of slip at the beam-slab interface, K_{st}, which may be defined as:

$$K_{st} = \frac{P_{kt}}{\gamma_t} \qquad \text{Eq. 5.31.}$$

Where P_{kt} is the characteristic resistance of the stud at a given temperature;

γ_t is the corresponding slip.

Johnson and Law[96] suggested that the short-term stiffness of a stud connector (in kN/mm) may be approximated as 2.75 times the characteristic strength of the connector in kN, based on load-slip curves derived for studs in solid slabs by Menzies[144]. Current trends tend to favour the use of profiled steel sheeting in the construction of composite beams, resulting in variations in the stud behaviour. This fact was acknowledged by Mottram and Johnson[143], who conducted a series of 35 push-tests, varying the form of profiled sheeting adopted, the shear stud arrangement and concrete properties. Based on the findings of these tests it is suggested that an approximate value of 200kN/mm is adopted to define the stiffness of the studs in the elevated-temperature tests conducted[74]. Unfortunately, it is not possible to formulate general recommendations for shear stud behaviour due to the wide variation in structural forms, and so the stiffness of studs is best assessed from experimental observations at present.

It is proposed that the degradation of shear stud properties at elevated-temperatures may be based on the recommendations of Twilt[61,62] as described in Section 2.6.

5.4.3. Influence of Shear-Lag

It is generally accepted that the distribution of reinforcement influences slab behaviour due to the effects of shear-lag, with the efficiency of reinforcement reducing as its distance from the column increases. Extensive research has been conducted to assess the influence of shear lag within composite slabs, much of which is reviewed by Dowling and Burgan[145]. In design shear-lag is commonly incorporated by the assumption of effective widths. However the effective width of a slab is not only a function of the dimensions of the arrangement, but also of the type of loading, support conditions and the cross section considered, and as such is difficult to define accurately.

Whilst design code values for effective breadth are based on elastic shear-lag theory, experimental studies have shown that larger effective breadths may be assumed at the ultimate limit state. Evans and Wright[146] conducted a series of tests on composite beams with strain gauges positioned across the breadth of the slab to assess the breadth which might effectively be carrying compression. Very little strain reduction due to shear-lag was found, even when the ratio of span to slab breadth was as low as 3. Similarly, Aribert[98] conducted a series of tests considering relatively stiff bolted flush end-plate connections. Strain gauges were attached to reinforcing bars to investigate the distribution of axial forces for different composite cross sections. Aribert concluded that all re-bars within the total width of the slab participate approximately equally in resisting tension. This observation suggests that the effective width of the slab in the hogging region is at least equal to the quarter-distance between supports.

The pattern of cracking across a slab is dependent upon the stiffness of the steel connection and on the distribution of shear studs. The use of more flexible steel connections leads to almost straight cracks running transversely across the slab, whilst more stiff connections increase the shear-lag, which is indicated by an inclined pattern of cracks. This was supported by a series of tests conducted by Bernussi *et.al.*[147], in which a range of connections of different stiffness were tested in a composite condition with strain gauges attached to the reinforcement.

In the case of the composite connection tests conducted at elevated-temperatures it was observed that cracking propagated from the location of the column flanges, and ran transversely across the width of the slab. This would seem to suggest that the influence of shear lag was minimal, and thus may initially be disregarded within this composite model. The premature failure of the inner reinforcement, observed at ambient-temperatures, may have occurred as a result of the confinement of concrete between the column flanges resulting in a reduced de-bonded length for the inner reinforcement.

5.4.4. Validation of Composite Connection Model

As with the bare-steel model, initial validation was conducted at ambient-temperatures, for the test described in Chapter 3, removing the additional complications associated with temperature effects. This facilitated an assessment of the influence of the assumed de-bonded length, and validation of this compared to experimental results.

It was observed that the stiffness of the flush end-plate connection tested was significantly enhanced by the incorporation of a composite slab. However, the ultimate capacity was limited by the eventual failure of the inner reinforcement, at a rotation within the range 5 to 15 millirads. This is significantly lower than that which would be predicted based on common approximations of debonded lengths as explained in section 5.4.1, and the assumption of rotation about the centre of the lower flange. Incorporation of the movement of the centre of rotation due to the gradual yield of the column web in the compression zone would result in a greater level of rotation being required to cause reinforcement failure. The approximation of a de-bonded length between the faces of the column flanges results in the prediction of a rotation in excess of 40 millirads prior to the eventual failure of reinforcement. Assumed de-bonded lengths are compared with the range of failure observed experimentally in Fig. 5.23, in which the spring-stiffness model described was used to relate the assumed de-bonded length with the rotation at failure. This is based on rotation about the beam lower flange, experimental material properties and incorporation of the influence of slip at the beam-slab interface.

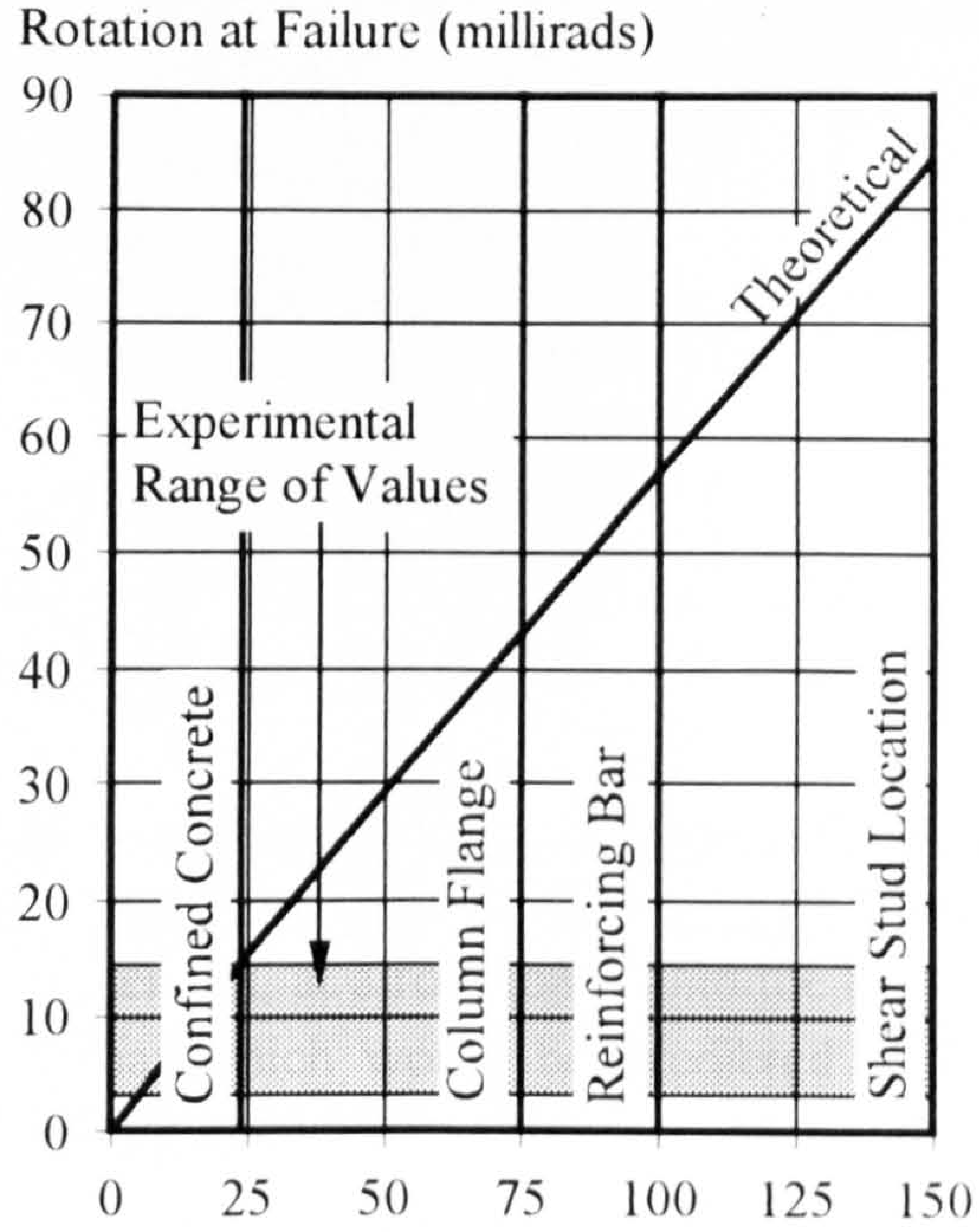


Figure 5.23. Influence of Debonded Length on Maximum Rotation

The deviation between experimental and predicted levels of rotation at failure poses the question of what may have caused the premature failure of the inner reinforcement in the ambient-temperature test conducted. It is commonly accepted that, where concrete is contained, an extended area of confinement will exist at a tangential angle of approximately 45° to the line of confinement[148]. The influence of this on a typical major axis connection with reinforcement passing close to the column flanges is shown in Fig. 5.24, where the reduction in debonded length l_r may be calculated as:

$$l_r = \frac{D_c - \{D_{rs} - B_c\}}{2} - t_{cf} \qquad \text{Eq. 5.32.}$$

Where D_c is the column depth;

B_c is the column breadth;

t_{cf} is the column flange thickness;

D_{rs} is the distance between reinforcing bars.

Assuming rotation of the concrete to occur about the column flange and incorporating the influence of confinement of concrete it may be seen that the resultant debonded length is significantly reduced to approximately 23.8mm, resulting in a rotation of 14.71 millirads at the eventual failure of the inner reinforcement.

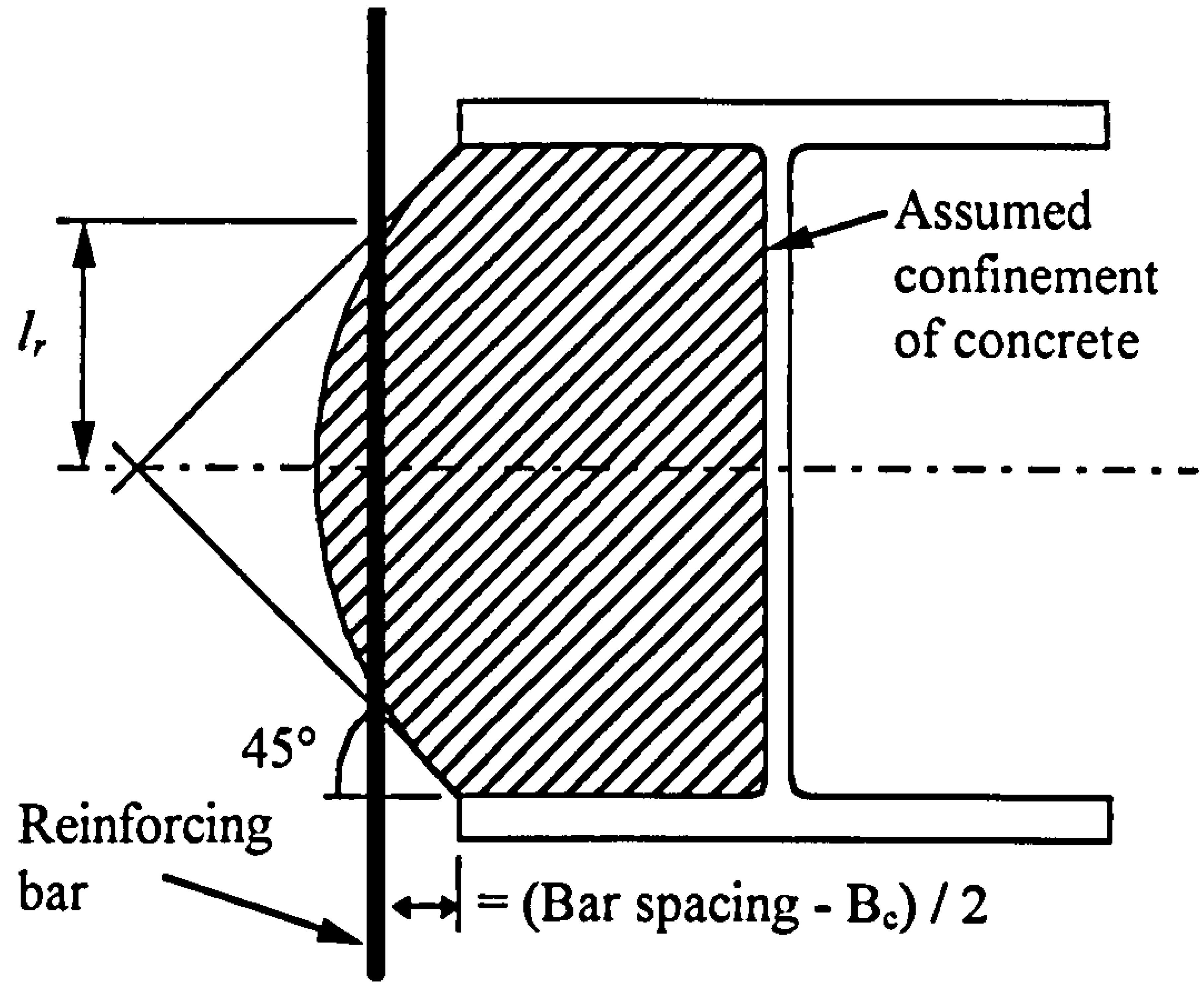


Figure 5.24. Influence of Confinement of Concrete Between Column Flanges on Debonded Length

Based on the assumption of confinement of concrete between column flanges, and experimental sectional and material properties as detailed in Appendix A, an ambient-temperature model was generated for the flush end-plate connection tested, results from which are compared with the response obtained from experimentation in Fig. 5.25. It may be seen that there is a very close correlation between predicted and actual connection response in the case of the composite connection tested, with the proposed model once more producing conservative results. As can be seen from the plotted results from the spring stiffness

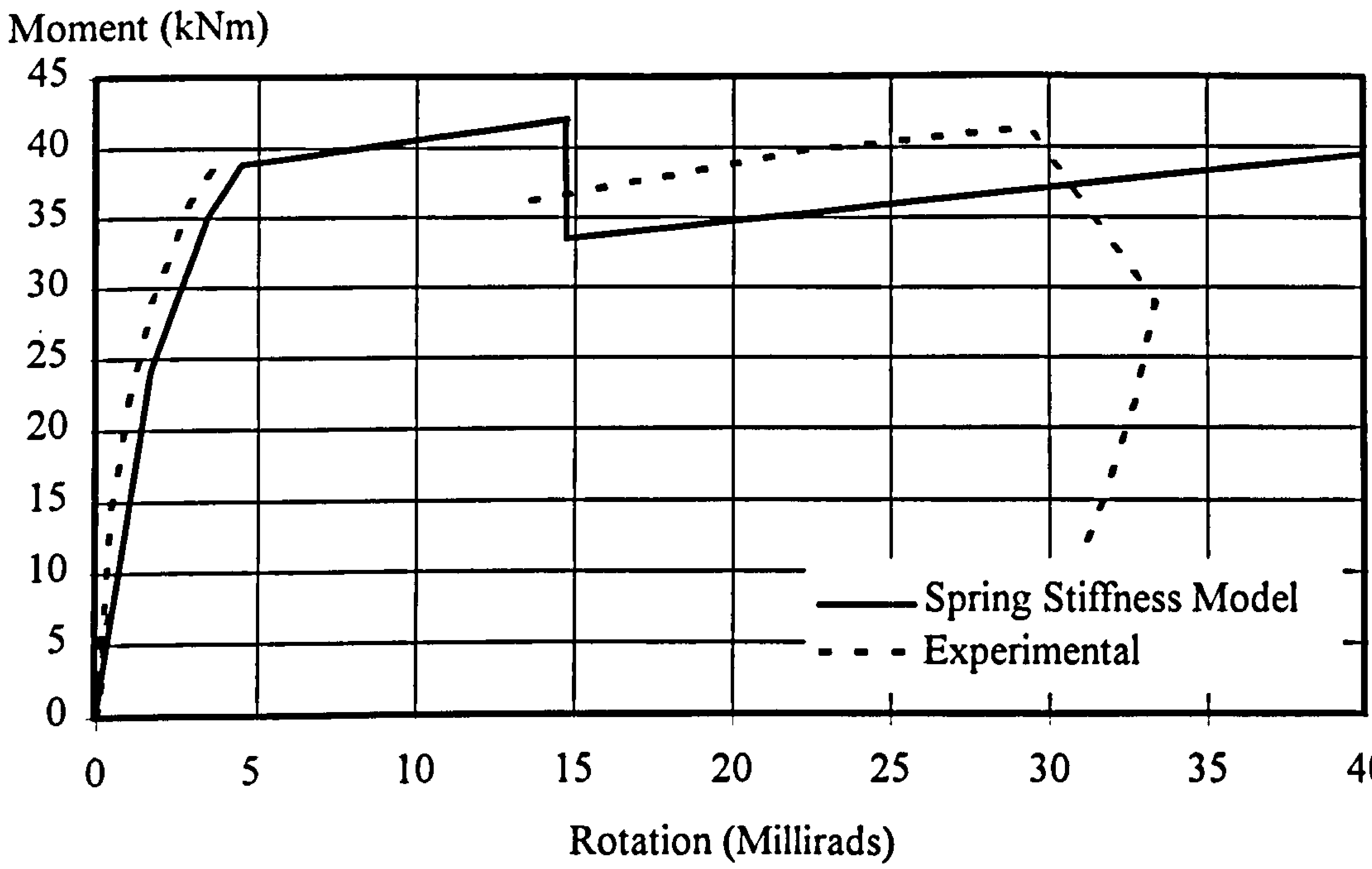


Figure 5.25. Predicted Ambient-Temperature Composite Connection Response Assuming Confinement of Concrete Between Column Flanges

model, the stiffness of the connections remains almost constant up to a moment of approximately 40kNm, after which there is a sudden reduction in stiffness due to plastification of the inner reinforcement. The capacity of the connection then continues to increase gradually until a rotation approaching 14 millirads, after which there is a sharp reduction in capacity due to failure of the inner reinforcement. Outer reinforcement is assumed to remain intact due to its greater debonded length, resulting in a capacity somewhat greater than that recorded for the bare-steel connection for the same level of rotation. Failure of the connection was correctly predicted to be controlled by yielding of the column web in the compression zone and failure of the reinforcement in the tension zone. Results are not available from experimentation in the range of 5 to 15 millirads due to the test arrangement being load-controlled, resulting in a sudden increase in the rotation subsequent to the failure of inner reinforcement, but this range of response does appear to compare favourably with that predicted.

The analysis was repeated using the recorded temperature distributions to assess the ability of the model to predict the enhancement in performance of the composite connection at elevated-temperatures. The rates of degradation predicted for both stiffness and capacity are compared in Fig. 5.26 below:

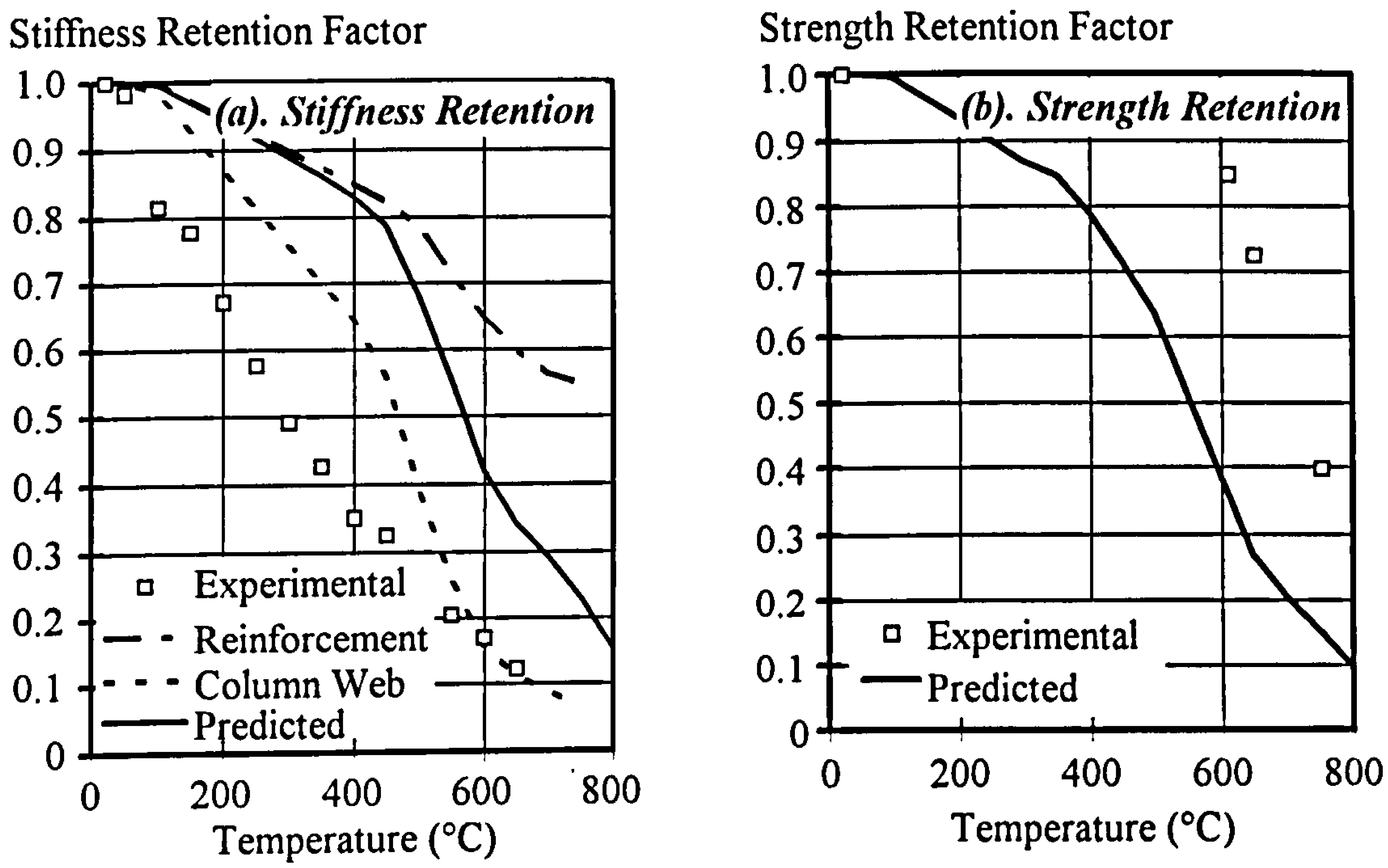


Figure 5.26. Predicted Degradation of Composite Connection Characteristics Due to the Influences of Temperature

It may be seen from Fig. 5.26*(a)* that there is a considerable deviation between the predicted rate of degradation of stiffness and that observed experimentally. To facilitate further consideration of the causes of deviation, rates of degradation obtained from the spring-stiffness model for both the exposed column web in the compression zone and the reinforcing mesh in the tension zone have been plotted. For temperatures below 400°C the predicted degradation of stiffness for the connection as a whole compared closely to that for the reinforcement, followed by a rapid reduction in stiffness, tending towards that of the column web in isolation. This seems to suggest that the stiffness of the column web remained significant within the spring stiffness model until temperatures approaching 400°C, after which the yield of the column web in the compression zone begins to control the response of the connection as a whole. For the entire range of temperatures the rate of degradation of the connection was less than that predicted for the column web, suggesting that the degradation of stiffness for a composite connection would be greater than for a nominally identical bare-steel connection. In Fig. 5.27 below, the experimentally recorded rates of degradation for both bare-steel and composite connections (nominally identical with the incorporation of a composite slab) are compared. This verifies the hypothesis that for the connection tested the rate of degradation of stiffness was greater for the composite arrangement than for the bare-steel connection. Considering the physical response of the connection this seems reasonable as the enhanced stiffness of the tension zone would result in the column web being subject to greater levels of loading, making the initial stiffness of the column web more significant. This suggests that the proposed model somewhat underestimates the flexibility of the column web in the compression zone prior to yielding, but that this was not as apparent in the case of the bare-steel connection due to the flexibility of the column web not being so critical at low temperatures.

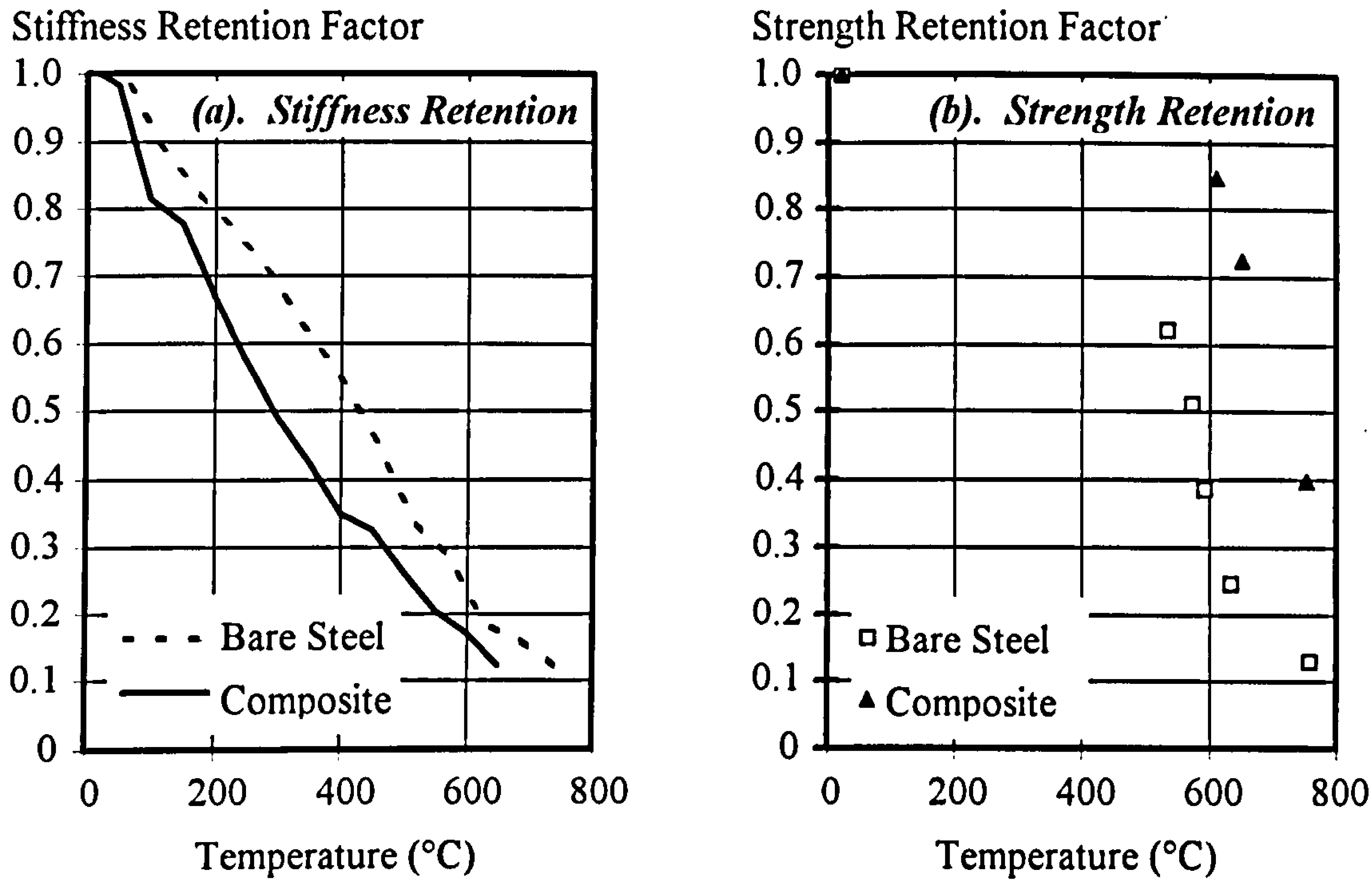


Figure 5.27. Comparison of Experimentally Recorded Rates of Degradation for Bare-Steel and Composite Flush End-Plate Connections

Considering the degradation of connection capacity, it may once more be seen from Fig. 5.26*(b)* that there was a considerable difference between predicted and experimentally observed responses. However, the nature of this deviation is different from that for stiffness in that the composite connection model predicts a greater rate of degradation than is recorded experimentally. It was observed in all of the tests that there was significant deformation of the column web in the compression zone, but that the reinforcement remained intact (whereas the reinforcement failed in ambient-temperature testing). Modelling of the connection response at elevated-temperatures resulted in failure being controlled by the eventual yield of the reinforcement in the tension zone. It is felt that the difference in predicted and experimental response indicates the need to incorporate the movement of the centre of rotation in the case of connections where the column web acting in compression is 'flexible'. As a flexible column web is loaded, gradual yielding and buckling results in the propagation of the centre of rotation upwards into the connection. This leads to less deformation of the reinforcement in the tension zone for a given rotation, and supports the hypothesis that the inability of the composite connection model to accurately predict the failure mechanism at elevated-temperatures is due to the neglect of the movement of the centre of rotation. The ability to model the movement of the centre of rotation is controlled by the effectiveness with which column web response may be modelled. As discussed previously, it is felt that the elastic response of the column web in compression is not represented accurately in the current model. Modelling of column web response in compression is complicated by the influence of web buckling and crippling at low levels of loading, and is highly non-linear, whilst most existing models assume the web to deform in a linear-elastic fashion. The natural variability of web response in compression lends itself to the use of empirical relationships, but it is felt that further experimental work is required before acceptable relationships may be established.

It would therefore seem that further experimental work is required to more accurately model the response of the column web in compression, which would then allow the incorporation of the movement of the centre of rotation within the described spring stiffness model. It would be anticipated that in the case of a connection where the column web was significantly stiffer a closer representation would be achieved from the described spring-stiffness model.

Elevated-temperature tests conducted by Lawson were once more used as an additional source of data for the validation of the spring-stiffness model at elevated-temperatures. Of the eleven elevated-temperature tests conducted by Lawson, only one test was of a flush end-plate connection with a composite slab (Test 6). The arrangement was similar to that described in Chapter 3, comprising a 120mm deep concrete slab with a typical 60mm deep trapezoidal deck profile forming the soffit to the slab. Shear studs of 100mm by 19mm dia. were used to develop composite action between the concrete slab and the beam, and a nominal A142 mesh was provided, being continuous over the support zone. The end-plate was detailed as for tests 2 and 4 conducted by Lawson. A cruciform arrangement was adopted consisting of 305x165x40UB43 beams framing into the flanges of a 203x203x46UC43 column. Based on the assumption that the moment capacity of a composite beam is typically twice that of the parent beam a constant moment of $0.4M_p$ was applied as compared to $0.2M_p$ for the bare-steel connection tests. Experimental results are compared with those obtained from the proposed spring-stiffness model in Fig. 5.28 based on experimental material properties and temperature distributions.

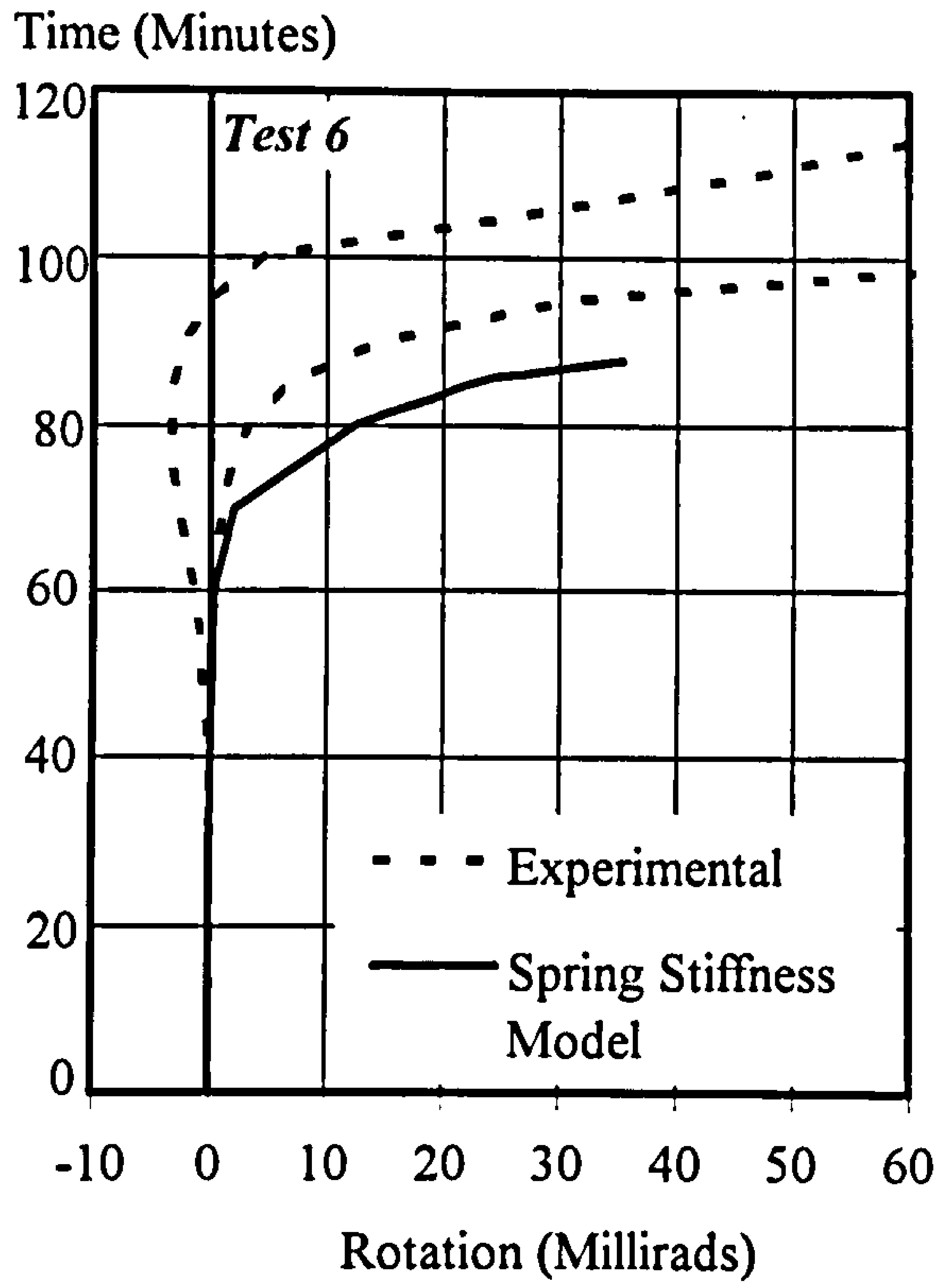


Figure 5.28. Comparison of Predicted Composite Connection Response with Existing Elevated-Temperature Test Data by Lawson[44]

It may be seen that there was a considerable variation in the results recorded for the two sides of the connection, but that the general form of failure is similar. Very little increase in rotation was observed until a time of approximately 80 minutes (corresponding with a beam lower flange temperature of 620°C), followed by a gradual reduction in stiffness until a time of approximately 100 minutes (720°C). The proposed spring-stiffness model accurately followed the form of degradation recorded experimentally, but as for the test detailed in Chapter 3 it remained conservative at all times, with a significant reduction in stiffness at a time of approximately 70 minutes, reducing gradually until a maximum time of approximately 90 minutes (680°C). This suggests a closer correlation between experimental and predicted results in the case of the test conducted by Lawson, possibly due to the enhanced stiffness of the column web in the compression zone due to the adoption of a larger column size. This supports the view that where column web stiffness is critical it is not acceptable to omit the movement of the centre of rotation from an elevated-temperature spring-stiffness model, but that in most cases column web response will not control overall connection behaviour.

5.5. SHEAR PANEL BEHAVIOUR

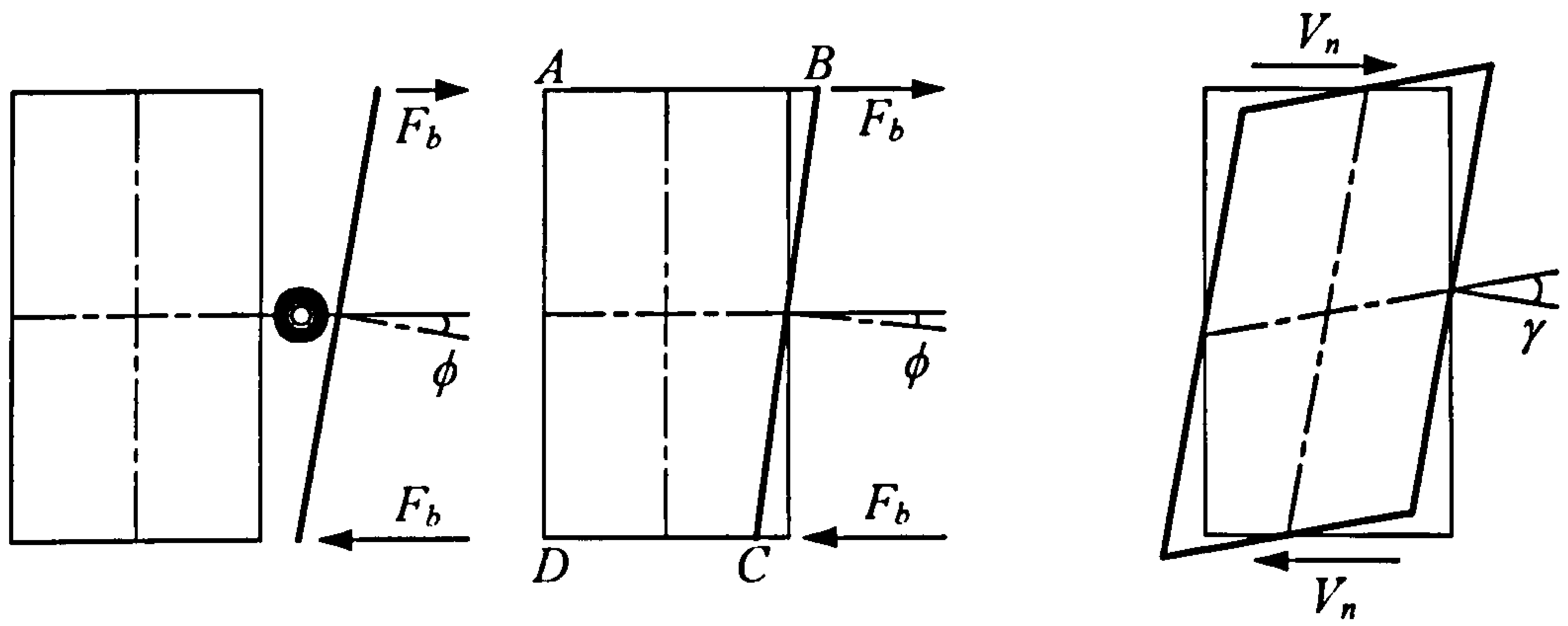
Two major sources of deformation may be identified in a major axis beam-to-column connection as:

1. ***Connection Deformation:*** Associated with the deformation of the connection elements (end-plate, bolts, column flange, etc..) and load-induced deformation of the column web;
2. ***Shear Deformation of the Column Web:*** Associated with the pair of forces F_h introduced by the beam(s) framing into the column, resulting in shear deformation of the column web.

Components of deformation are illustrated in Fig. 5.29. for the case of a single-sided major-axis connection. Deformation of the connection element is concentrated at the end of the beam as shown in (a), and the associated response may be expressed in the form of a moment-rotation curve.

Deformation of the column web panel (*ABCD*) may be divided into:

- Load-induced deformation of the column web in the tension and compression regions (elongation of the column web in the tension zone is neglected from the described model), resulting in a relative rotation between the beam and column axes along edge *BC* as shown in (b), with the response expressed in the form of a moment-rotation curve;
- Shear effects, due to a shear force V_n, resulting in a relative rotation γ between beam and column axes as shown in (c), establishing a second deformation response V_n - γ.



(a). Connection Elements ***(b). Load Introduction*** ***(c). Shear Panel Deformation***

Connection Deformation (M_c - ϕ) ***Sheared Panel (V_n - γ)***

Figure 5.29. Components of Major-Axis Connection Deformation

Aspects of connection deformation have been described in Sections 5.2 and 5.3 for both a bare-steel and composite flush end-plate connection respectively, but both the models described above are formulated assuming symmetrically loaded connections, and neglect the influence of shear panel effects.

The value of shear force V_n may be obtained from the equilibrium equation of the web panel as described below, where the elements of loading for a typical interior joint are shown in Fig. 5.30:

$$V_n = \frac{M_{b1} + M_{b2}}{d_b} - \frac{V_{c1} + V_{c2}}{2} \qquad \text{Eq. 5.33.}$$

A number of authors have addressed the problem of incorporating shear-panel effects in connection models, with most authors[90,149,150,151,152] adopting the equation described above for the assessment of the level of shear force existent within a panel zone. In some cases the equation has been simplified, neglecting aspects arising from the horizontal shear forces existent within the column, V_{c1} and V_{c2}.

Krawinkler[149] proposed a simple semi-empirical model, based on an idealised joint model which was calibrated against test data. Initial stiffness was assessed based on the shear modulus of the joint panel, and was assumed to continue until the applied shear force equalled the plastic capacity of the shear panel. The stiffness contribution from the panel web is then assumed to be zero, with further resistance arising from the stiffness of the elements surrounding the panel. Nakao[150] adopted a approach similar to Krawinkler, once more based on a simplified model calibrated against test data. The advantage of the Nakao model is the inclusion of strain hardening of the material and the effects of column axial load on joint behaviour, making it possible to obtain a more realistic representation of the joint panel behaviour. Models by Krawinkler and Nakao both assume an initial stiffness followed by a reduced plastic stiffness, resulting from a combination of strain-hardening and the stiffness of surrounding elements. This seems reasonable based on the observations of tests conducted by Fielding and Huang[153], Bertero *et. al.*[154], and Becker[155], from which it may be concluded that:

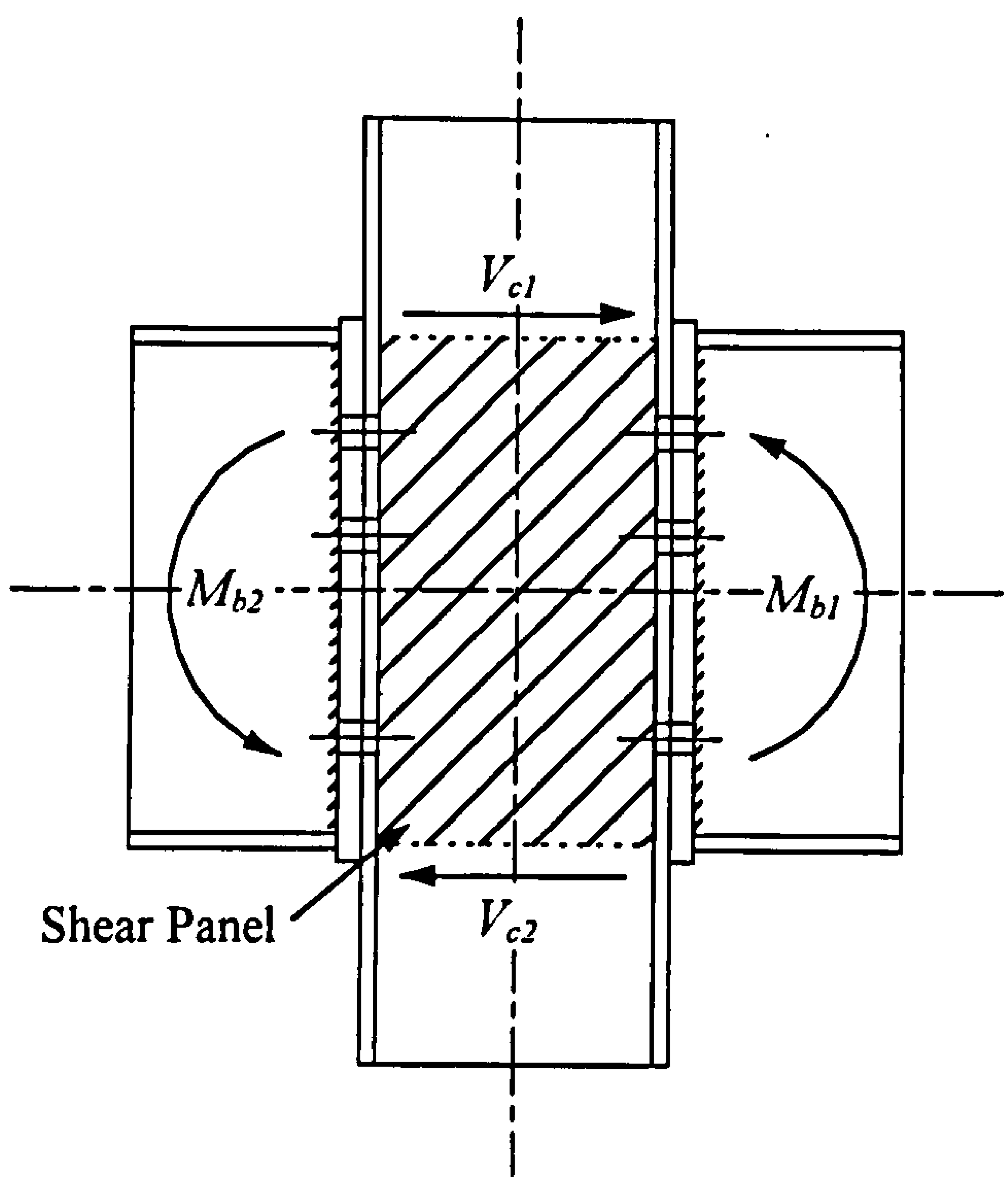


Figure 5.30. Forces Acting on Column Web Shear Panel

1. There are two distinct stiffnesses in the shear force-deformation response of a panel: an elastic stiffness, followed by a smaller, almost constant stiffness (typically 3 to 8% of the elastic stiffness), continuing for a long range of deformation;

2. The existence of post-yielding stiffness in the response may be attributed to the resistance of boundary elements such as column flanges, strain hardening of the web of the joint and restraint from adjoining beams and columns[153].

More sophisticated techniques of modelling shear-panel effects have been adopted by Kato et. al.[151] and Lui and Chen[90,152] based on finite element methods.

The difference between loading of the connection (effectively isolated from forces from adjacent members) and that of loading of a specific joint due to shear forces requires, theoretically at least, that both forms of deformation be considered independently. This approach has been adopted by a number of authors[102,107,141,156] by the incorporation of an additional rotational stiffness at connections, the deformation of which is assessed based on the levels of moment in adjacent members. However, the incorporation of an isolated spring stiffness joint to model shear deformation is only truly practicable in cases where sophisticated computer-based approaches are adopted for the analysis of frame response. A number of authors have proposed techniques of combining shear-panel response with connection response, forming a single moment-rotation characteristic[157,158].

Aspects of shear panel deformation have been neglect from the described model as it is felt that the influence of panel effects is more appropriate to frame analysis software. Additionally, the consideration of connection response in isolation from panel effects allows the development of a 'catalogue' of elevated-temperature moment-rotation characteristics to be developed for typical connection details, being applicable to any chosen structural arrangement.

The neglect of shear-panel behaviour will not influence the validity of the experimental data adopted for the verification of both bare-steel and composite connection models, as all tests were based on symmetrically loaded cruciform arrangements.

When considering the case of minor-axis connections, with beams framing into the column web, additional care should be taken in the case of unsymmetrical arrangements as the stiffness of the column web to un-balanced bending is significantly less than for major-axis connections. It would seem acceptable to neglect all stiffness provided by the web restrained along both edges by the column flanges, and modify the connection characteristics accordingly based on the level of unbalanced moment.

5.6. CONCLUSIONS

Due to the large quantity of connection arrangements commonly used it is impracticable to develop characteristics for each arrangement by experimentation. Simplified spring-stiffness models have been presented for both bare-steel and composite flush end-plate connections. The use of spring-stiffness models proved desirable due to their ease of application and the facility of this form of model to be easily modified to consider alternative arrangements.

Connections were modelled by assembling the contributions of individual elements, and representing the connection as a set of rigid and deformable components. Multi-linear modelling was adopted, neglecting the interaction between connected elements. Temperature effects were incorporated based on the recommendations presented in Chapters 2 and 3, with the separation of the connection into its constitutive parts allowing the use of any chosen temperature profile.

Whilst the use of a spring-stiffness model resulted in a simple method of solution, the number of elements incorporated and the need to repeat the analysis for increasing temperatures necessitated the use of computational methods to generate connection characteristics efficiently. However, as a linear form of modelling was adopted the development of suitable software did not become an onerous task.

The bare-steel model described idealised the connection as being formulated from tension zone (bolts, end-plate and column flange) and compression zone (column web) deformation, with rotation being assumed about the beam lower flange. The effects of prying action were neglected, and the bolt response based on Hooke's law. Column flanges were assumed to act as cantilevers of infinite length subject to a point load, based on the recommendations of Jarimillo[133]. An in-depth study was conducted into the response of flush end-plates as it was felt that this had been insufficiently addressed in existing spring-stiffness models. The plate was modelled based on thin plate bending theory and finite element analysis, and compared with common assumptions adopted within existing spring-stiffness models. It was observed that the restraint provided by welding to the beam flange becomes insignificant as the bolt location moves away from the flange, with the end-plate typically following the form of response predicted for a cantilever of infinite length as with the column flange. Yield of both column flange and end-plate was based on yield line theory. Response of the column web in the compression zone was assumed to obey Hooke's law until the onset of plasticity caused either by crushing or buckling of the web. A reduced stiffness approximately 40% of the initial stiffness was subsequently adopted based on the recommendations of Walker[139].

Comparison of the bare-steel model with existing test data for both a major and minor axis flush end-plate connection generated good results, and accurately predicted failure mechanisms in both cases. Similarly, close results were obtained in comparing the model with the elevated-temperature tests described in Chapter 3 and a further test by Lawson[44]. The model demonstrated the increased significance of the column web in the compression zone with increasing temperatures, casting doubt on the validity of neglect of the movement of the axis of rotation. However, due to the complexities of incorporating the movement of the centre of rotation and the accuracy of the results obtained it seemed reasonable to neglect this from the bare-steel model at this stage.

Formulation of the composite model was similar to that for the bare-steel model, with the incorporation of additional springs to model reinforcement deformation and slip at the beam-slab interface which had been suggested to be significant by Anderson and Najaffi[143]. Reinforcement response was based on Hooke's law, with an assumed debonded length, whilst shear stud deformation was based on test data by Mottram and Johnson[60], as the modelling of shear stud response is complicated by the range of structural arrangements and the natural variability of concrete. The influence of shear lag was neglected, having been suggested as being of little significance for the case of flush end-plate connections.

It was observed from ambient-temperature modelling that failure of the inner reinforcement occurred at a far lower level of rotation than would have been anticipated. It is felt that this may have been due to the confinement of concrete between the column flanges reducing the debonded length. Based on the assumption of confined concrete the results obtained from the composite spring-stiffness model compared closely with those recorded experimentally as detailed in Chapter 3.

There was significant difference between the rate of degradation predicted and that recorded experimentally for the elevated-temperature tests. It is suggested that this may be due to the neglect of the movement of the axis of rotation in the composite model in the context of the increased load applied to the column web. It is therefore suggested that the movement of the axis of rotation should be incorporated within connection models where the web is 'flexible', but that further understanding is required to define accurately the response of the column web in compression. Comparison with the test conducted by

Lawson[44] compared more favourably with the predicted response, possibly due to the increased web thickness.

The use of a spring-stiffness model allows easy modification for modelling of differing connection types. A frequently used form of connection in current construction is the partial-depth end-plate (as adopted in the Cardington test frame) due to its ease of fabrication compared with the full-depth end-plate. To model such a connection it would simply be necessary to modify the component of the model describing the end-plate response. A number of authors have considered a partial-depth end-plate to act simply as a rigidly fixed beam subject to a point load from the beam web. The width of the assumed 'beam' is often based on the pitch of the bolts, although in cases where the pitch dimension is great it may be more accurate to assume an 'effective width'. A detailed description of the applicability of spring-stiffness models to differing connection types, and the behaviour of the constitutive components, has been presented by Madas[103].

Shear-panel response was not included within the spring-stiffness model as this is more appropriate within frame analysis due to the influence of connected elements.

6. INFLUENCE OF CONNECTION CHARACTERISTICS ON FRAME RESPONSE

6.1. INTRODUCTION

Having defined experimentally the moment-rotation characteristics for both a bare-steel and composite flush end-plate connection accurately across a range of temperatures, it is important to consider the effects of 'semi-rigid' connection characteristics on a typical frame arrangement at elevated-temperatures. The analysis of full-frame response as compared to the behaviour of isolated components is becoming preferable due to the increasing realisation of the significant influence of continuity. Analysis of full-frame or sub-frame behaviour is generally limited to numerical modelling due to the expense of large scale testing, whilst developments such as the Cardington LBTF serve as an essential form of validation of such models.

The incorporation of experimentally generated connection characteristics into numerical models facilitates assessment of the influence of various components of connection characteristics on frame behaviour. Additionally, consideration of frame behaviour allows assessment of the accuracy with which connection characteristics need be represented to accurately model overall structural response. Based on these findings recommendations may be made regarding the level of accuracy required from experimentation and the suitability of different forms of connection model and curve-fitting for incorporation within numerical models.

6.2. FINITE-ELEMENT MODELLING

A number of commercial finite-element programs exist allowing the modelling of semi-rigid frame response at elevated-temperatures. However, due to the broad range of applicability of such software, extensively validated specific 'research based' programs are commonly found to be preferable in terms of applicability and reduced computing requirements where these exist.

The finite-element model adopted was originally based on the program INSTAF developed by El-Zantay and Murray[159] in 1980 to consider the two-dimensional response of steel frames at ambient-temperatures, incorporating geometrical non-linearity and the spread of yield. The program was subsequently extended by Saab[160] in 1990 to include elevated-temperature material properties. Najjar[21] extended the work of Saab allowing the three-dimensional behaviour of members, including warping characteristics, to be modelled. More recently Bailey[22] has made significant advances, incorporating an inelastic spring element, the effects of lateral torsional buckling and composite action. At each stage of development extensive validation was conducted demonstrating the accuracy of the model for large-deflection problems at both ambient and elevated-temperatures.

Beam-column elements are presented as two-noded line elements having eight degrees of freedom in local co-ordinates, which are transformed into eleven degrees of freedom in global co-ordinates. The member length is divided into a number of elements of 'finite' length connected at nodal points. The reference axis is assumed to be situated at the centroid of the section, which is calculated at ambient-temperatures and remains constant. Displacements of nodal points are the basic unknown parameter of the problem. By adopting the displacement field finite-element procedure, shape functions are used to define uniquely the displacement of the reference axis within an element with incrementally increasing temperatures. The state of strain may then be obtained using a large displacement-strain equation. By applying the intrinsic properties of the steel sections, the state of the stress through the member can be calculated along with the boundary stresses and the externally applied loads.

Equilibrium is enforced at nodal points based on the Principles of Virtual Work, and solved using Gaussian integration. Within the model four Gauss points are used for each element, with the position of these points along the beam, together with their weighting factors being based on standard text.

Integration over the cross section results in stress resultants, which may be obtained from section properties or, more easily for elastic cases, by direct numerical integration of the stresses. To allow for a considerable variation of stress through the cross-section, displacements and strains are defined at thirteen points (splitting the section into twelve segments). Since an iterative method is required due to non-linearities, the incremental stress resultants are required for the formulation of the tangent stiffness matrix.

Material non-linearity enters the formulation via the constitutive model, relating strain to stress and also specifying the tangent modulus of the material at a specific strain value. To calculate the sectional and sectorial properties, taking into account material non-linearity, the transformed section concept is used. This method transforms the thickness of each of the twelve elements based on the average tangent modulus of the material within the segment, thus generating an equivalent elastic cross-section.

One of the assumptions adopted within the formulation of the model is that external loads are applied at nodal positions. It has been previously suggested that the spread of yield in the proximity of nodal areas is not reflected in the element tangent stiffness, due to the distribution of Gauss points adopted. As such members were subdivided into three elements, with the central element being 80 % of the length of the member, resulting in the outer elements having Gauss points grouped near nodal positions, causing inelastic strains to be incorporated within the element stiffness matrix as they occur. An element stiffness matrix is then formed and transformed from local to global co-ordinates, and using the direct stiffness method the contribution from the element is included within the structural stiffness matrix. The above procedure basically automates the requirement of refining the size of the elements in areas of high stress gradients. However, care is still required in the definition of the mesh layout.

Since the model is highly non-linear an iterative process is required to obtain equilibrium. The basic Newton-Raphson technique is used.

A reserve of strength exists within frames designed with 'pinned' connections which may be utilised in the analysis of the structure at elevated-temperatures. The advantages of semi-rigid design are amplified at elevated-temperatures as the connections are typically at a lower temperature than the surrounding structure due to the relative massivity of the end-plate and bolts.

To allow the incorporation of realistic connection characteristics the model was extended by Bailey to include inelastic spring elements which may be degraded with temperature, allowing the incorporation of any given connection characteristics. A two-noded spring element of zero length, with eight degrees of freedom in local co-ordinates and eleven degrees of freedom in global co-ordinates, corresponding to the beam-column element, is adopted as shown in Fig. 6.1. The spring element is very versatile, and can be placed at any position within in the frame since in-plane, out-of-plane, torsion, warping and translational displacements are represented. Each of the eight degrees of freedom are modelled independently creating a stiffness matrix, in which each of the degrees of freedom may be independently specified by a moment-rotation (or force-displacement) relationship. Shear panel behaviour is not incorporated within the model at the present time.

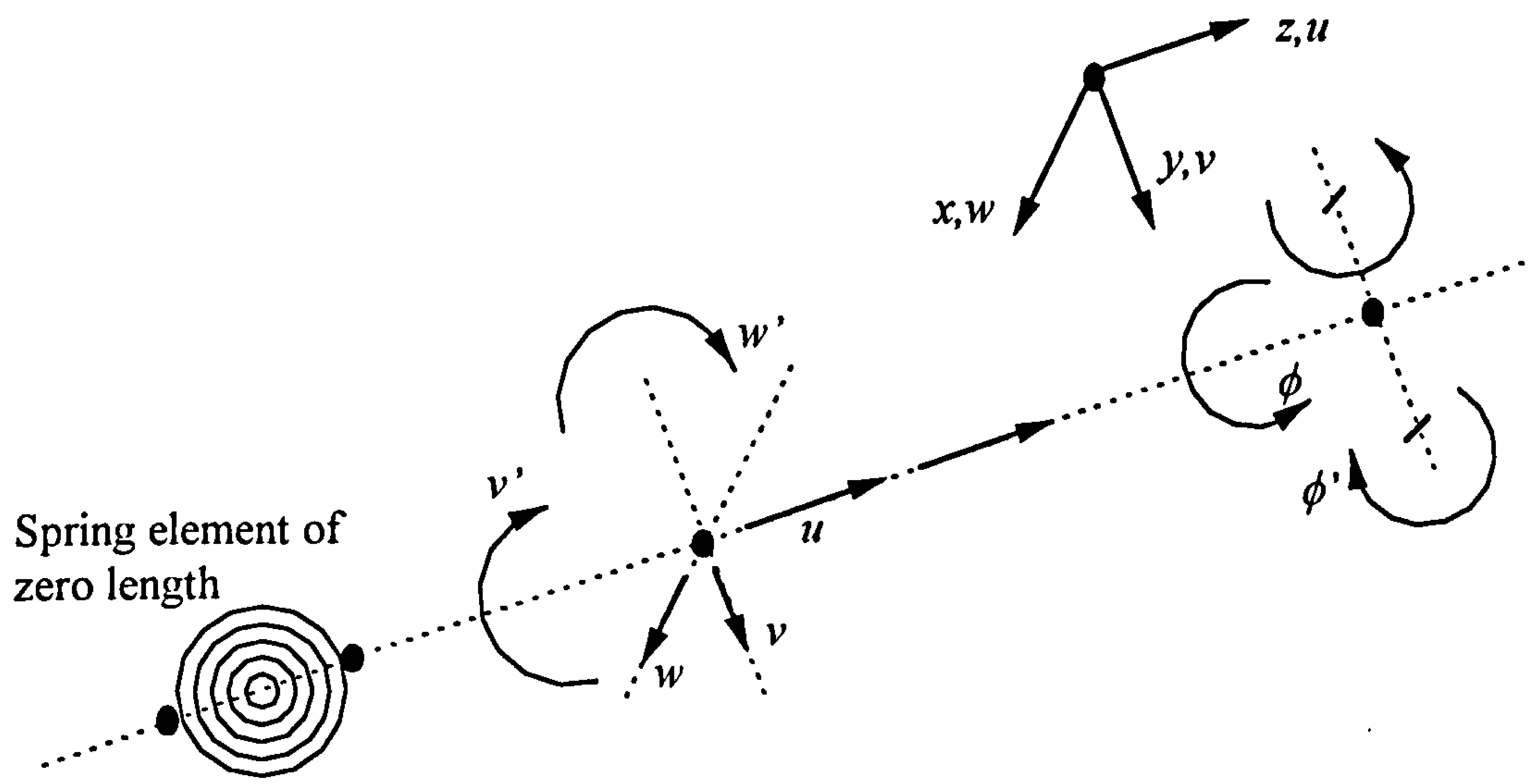


Figure 6.1. Degrees of Freedom for Two-Noded Spring Element in Local Co-ordinates

Isotropic slabs behaviour is represented in the form of shell finite-elements, which are linear-elastic and include thermal strains, although a linear temperature distribution must be incorporated across the depth of the slab. A simplified method of incorporating cracking is incorporated by placing a limit on the permissible bending stress. The nodal position of the one-dimensional beam elements may be displaced allowing connection to the two-dimensional shell elements based on the assumption of full-interaction.

6.3. INFLUENCE OF SUB-FRAME EXTENT

The analysis of sub-frames as opposed to complete structures is preferable due to the computational requirements necessitated by full-frame analysis, and the number of runs required to investigate fully the influence of semi-rigid connection characteristics on frame behaviour. As such an initial study has been conducted to establish a suitable sub-frame for the consideration of the influence of connection characteristics.

A number of sub-frames have been suggested as being suitable for modelling beam response in rigidly connected frames in BS5950[161] as shown in Fig. 6.2, for the consideration of internal and external beams, where a full beam or column length is assumed to extend past the element under consideration.

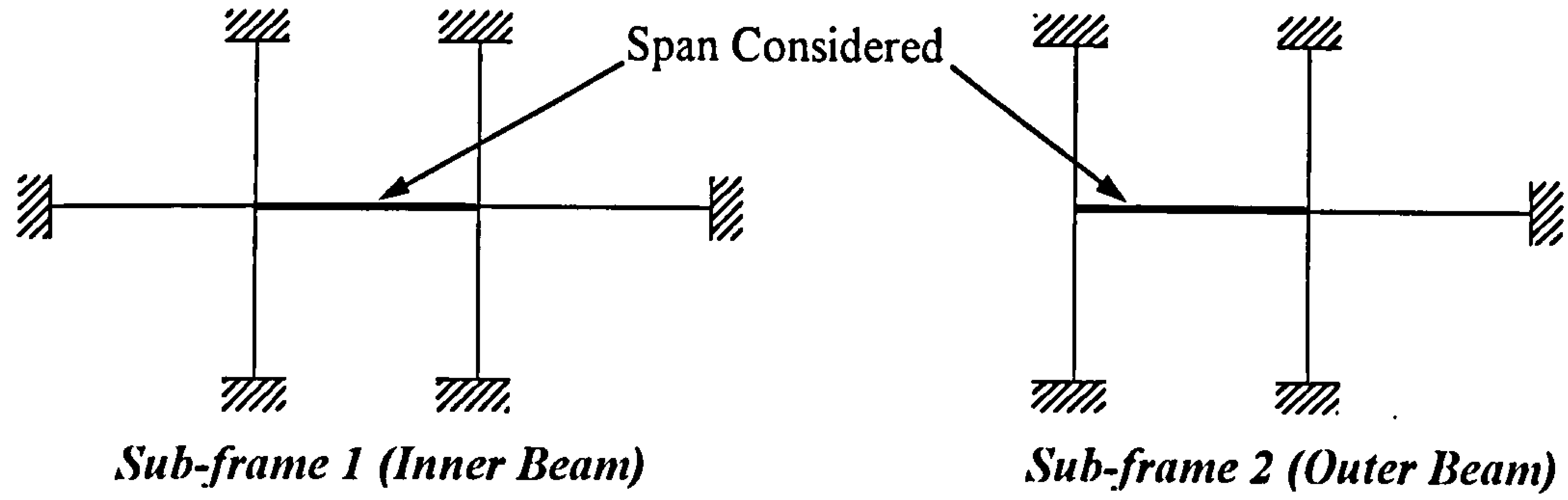


Figure 6.2. Sub-Frame Idealisations Adopted in BS 5950

It has been demonstrated by El-Rimawi[162] that the forms of sub-frame shown in Fig. 6.2 are capable of generating results which are comparable with those from full-frame analysis based on studies of the response of the Cardington test frame[12] subject to elevated-temperatures. However, it should be noted that the studies conducted by El-Rimawi, and those presented in this chapter are based on plane-frame analysis, neglecting the potentially significant influence of membrane action existent within composite construction. Further consideration has been given to the influence of out-of-plane connectivity and slab action in Chapter 7, investigating the behaviour of a 'typical' composite structure at elevated-temperatures.

In Fig. 6.3 the response of the sub-frames shown above are compared with that obtained for an isolated beam assuming rigid, semi-rigid and pinned connection characteristics. An arrangement of 254x102x22UB43 framing into the flanges of a 152x23UC43 was adopted, corresponding with the member sizes used in the elevated-temperature tests detailed in Chapter 3. Restraint conditions at the end of beams were modified to allow lateral displacement, whilst column heads were allowed to displace vertically. Analysis was conducted assuming a load-ratio of 0.6 for the beams and 0.4 for columns. Connection characteristics were incorporated at beam-column connections in the form of a fully non-linear moment-rotation curve representing the bare-

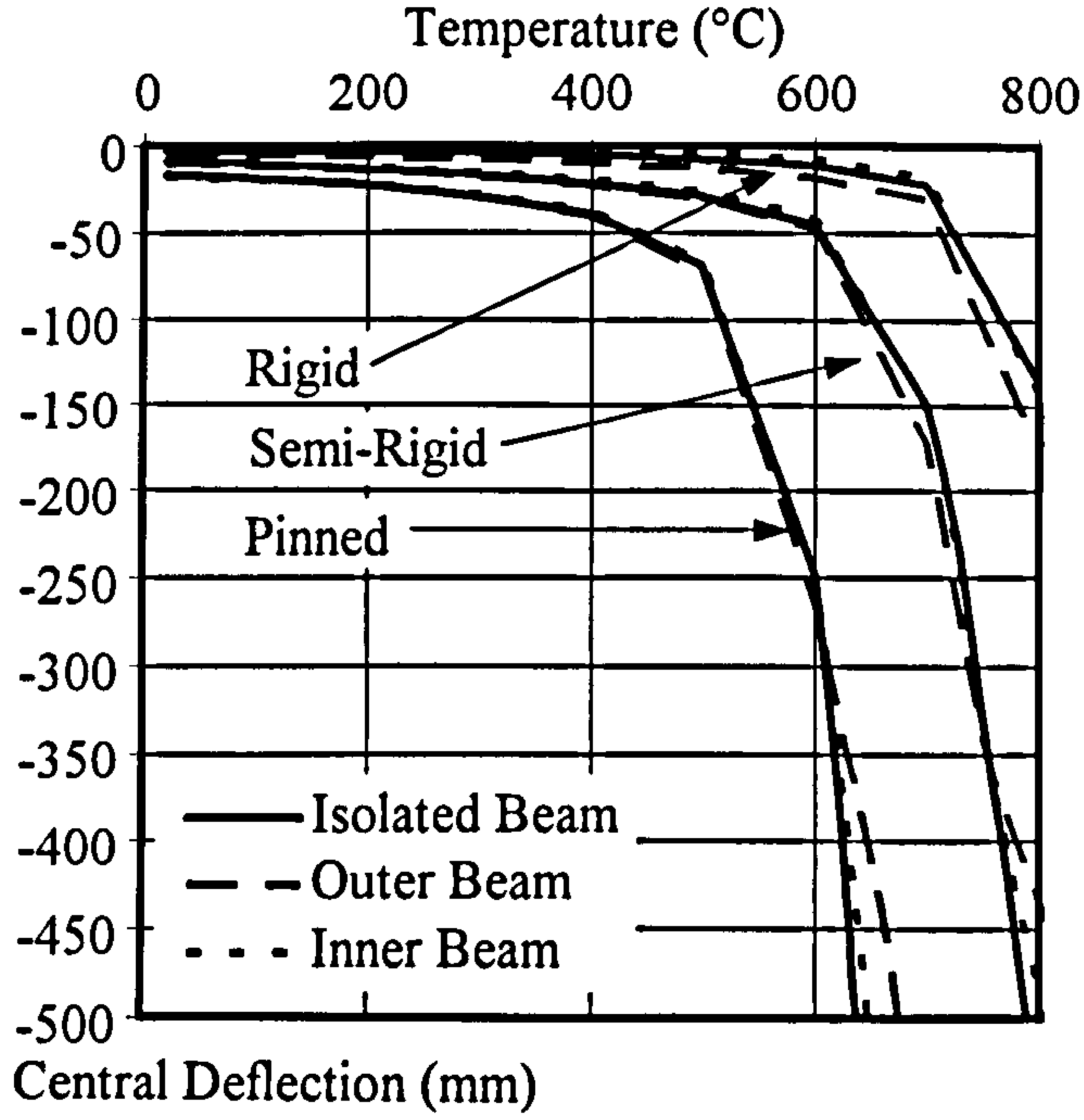


Figure 6.3. Comparison of Sub-Frame Response for Varying Connection Characteristics

steel connection tested, based on the Ramberg-Osgood form of curve-fit as described in Chapter 4. The idealised temperature distribution for the heated compartment was as shown in Fig. 6.4. Beams and columns external to the compartment were assumed to remain at ambient-temperatures, heated columns were at 50% of the beam lower flange temperature *T*, and the end sixth of heated beams was subject to a reduced temperature based on observations from experimental studies. A connection temperature of 0.7*T* was adopted for connections being based on a series of tests conducted by Lawson[44]. This is somewhat contradictory to the temperature distribution observed from experimentation as detailed in Chapter 3, in which the average connection temperature remained similar to that for the beam lower flange. However, it should be noted that the heating regime and furnace arrangement adopted was not wholly representative of the pattern of heating observed in real fire scenarios; the reduced heating rate imposed by the furnace arrangement would be expected to typically generate a more uniform temperature distribution than would occur from a 'realistic' fire-curve or the ISO form of heating curve. The question of the influence of connection temperature is discussed later in this chapter.

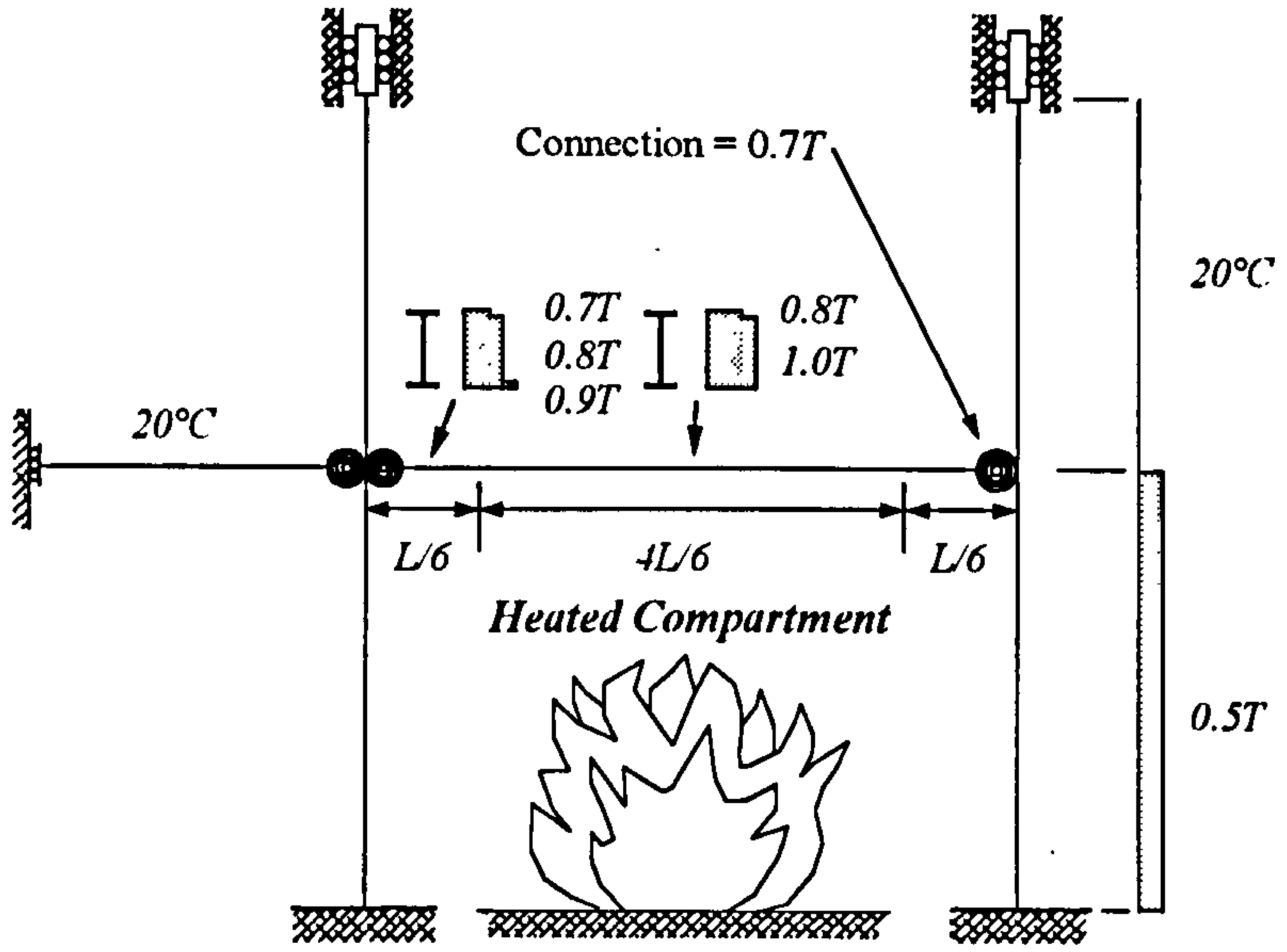


Figure 6.4. Temperature Distribution Adopted for Heated Compartment

With increasing temperatures a gradual increase in deflections was observed up to temperatures in the range of 400 to 700°C for the pinned and rigid cases respectively. This was followed by a rapid increase in the rate of deflection up to a failure-temperature in the region of 600 to 800°C. The form of response follows that which would be anticipated based on the mechanical properties of steel as described in Chapter 2, in which little reduction in strength is observed for temperatures up to 400°C, followed by a rapid reduction in capacity as shown in Fig. 2.2. For the case of the arrangement tested a significant enhancement in response of a rigidly-framed arrangement is observed as compared to the assumption of pinned connections, with the failure-temperature being approximately 200°C greater for the rigid arrangement.

The incorporation of 'realistic' connection characteristics results in a notable enhancement in frame response compared to simply-supported construction. It is interesting to note that the incorporation of semi-rigid connection characteristics resulted in a reduction in the rate of deflection for temperatures in excess of 750°C, corresponding with the phase change of the molecular structure of steel, at which point there is a reduction in the rate of thermal expansion. The change in rate of deflection may be attributable to restraint provided by the columns initially accelerating the rate of deflection. As expansion decreases columns would be anticipated to provide a degree of restrain, until such a time as the beam or column have reduced in capacity significantly for 'run-away' to proceed. The form of response for a pinned arrangement would be expected to be less pronounced as 'run-away' may be expected to occur at temperatures below the phase change for steel.

Greatest deflections were observed for the isolated-beam irrespective of the form of connection characteristics incorporated. This would be anticipated as the forms of sub-frame shown in Fig. 6.2 gain additional strength due to the restraint provided by connection to columns providing a degree of axial restraint. However, the extent of the sub-frame was observed to have limited influence on overall response for the arrangement tested, possibly due to the column adopted possessing relatively low stiffness.

The ability with which an isolated sub-frame is capable of representing full-frame response may be attributed to the ability to replicate the restraint provided by the external structure at artificially introduced supports. As described, the software adopted allows the incorporation of non-linear spring elements, having eight degrees of freedom in local co-ordinates. This allows the modelling of axial stiffness (which may be degraded with temperature), to replicate the stiffness of the external structure. Elastic flexural stiffness of a column, K_{cf}, may be approximated at ambient-temperatures assuming equal storey heights as:

$$K_{cf} = \frac{48E_c I_c}{l_c^3} \qquad \text{Eq. 6.1.}$$

Where E_c is the Young's modulus for the column;
I_c is the second moment of area about the axis considered;
l_c is the length of the column between restraints (twice the storey height);

The influence of axial restraint has been considered below for a range of stiffnesses from 500N/mm to 2000N/mm as shown in Fig. 6.5, where the effects of temperature have been included by degrading the term E_c in Eq. 6.1 for increasing temperatures. A fully-elastic stiffness has been adopted, with the entire length of the column being assumed to remain at 50% of the beam lower flange temperature. For a 152x23UC43 with a storey height of 3000mm the above expression gives a stiffness of 579N/mm at ambient-temperatures.

The incorporation of axial restraint into the analysis of an isolated-beam results in a similar form of response to that observed for typical sub-frames as shown above, with a reduction in the rate of central deflection for temperatures in excess of 750°C. With increasing stiffness greater levels of deflection are observed for temperatures below 750°C, with the adverse being true for increasing temperatures. The temperature at which the increase in stiffness occurs remains the same irrespective of the level of axial restraint adopted. To facilitate a greater understanding of the response, vertical deflections at *A* are compared with horizontal displacements at *B*. It may be seen that there is an initial positive displacement at *B*, indicating that at lower temperatures thermal expansion of the beam controls overall response. With increasing temperatures the capacity of the beam to resist

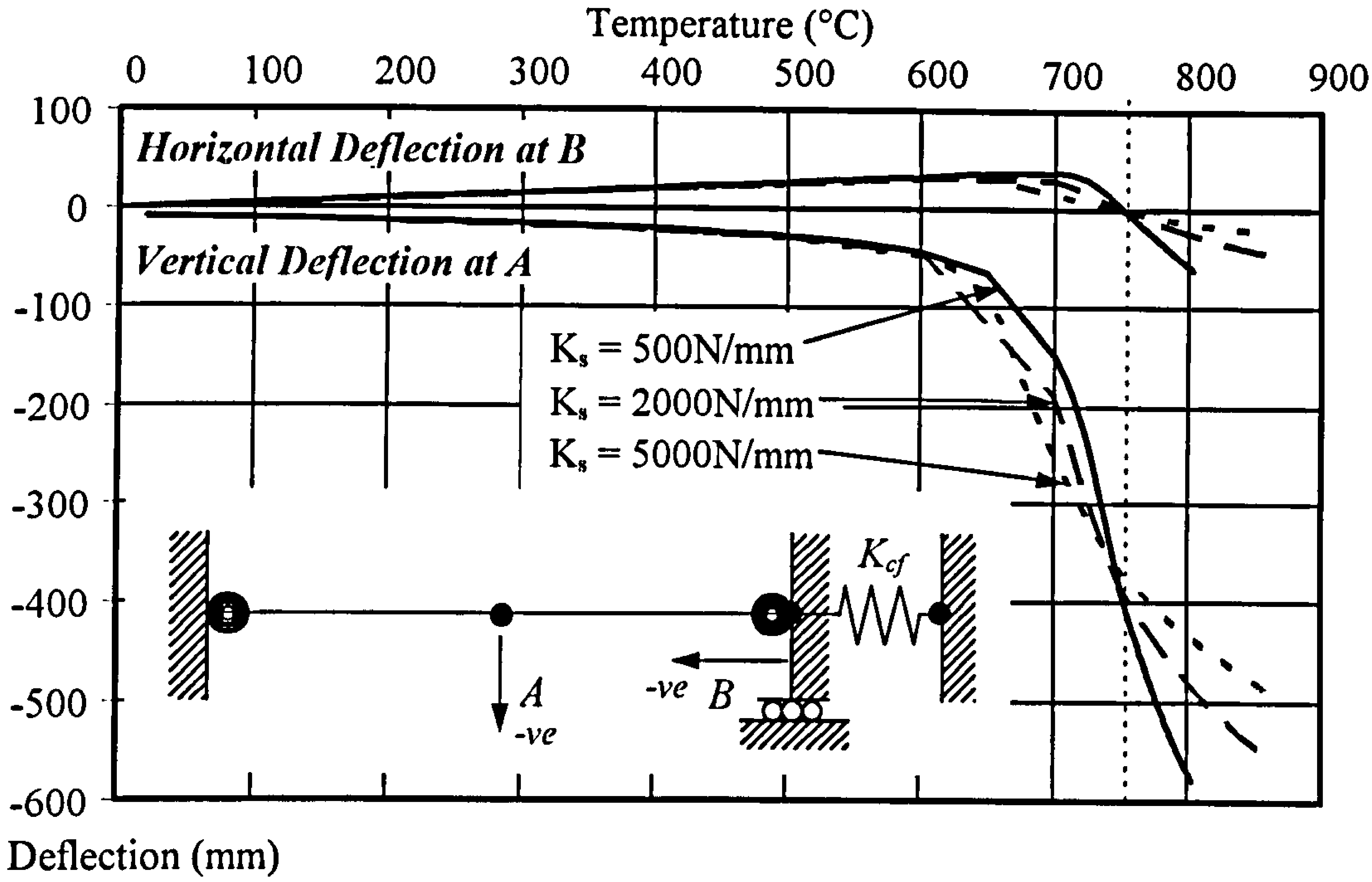


Figure 6.5. Influence of Axial Restraint on the Response of Isolated-Beam

bending decreases, resulting in gradual plastification of the beam and increasing central deflections. The axial spring representing the external structure now begins to act in tension, with the stiffness of this spring controlling the subsequent rate of deflection. Clearly it would be anticipated that a common level of central deflection would coincide with the point at which the horizontal deflection at *B* passes through its origin, as at this point the level of restraint provided has no influence. This form of response remains consistent, although more pronounced, with that observed in the sub-frame analysis described above, providing verification of the form of behaviour suggested. The extent of the study has been extended to incorporate sub-frames of increasing extent from which it was observed that the reduction in deflection at high temperatures becomes more pronounced as further bays are incorporated within the analysis.

The response of an isolated-beam with semi-rigid connection characteristics and an axial spring stiffness incorporated to represent the influence of an isolated-beam is compared with the outer-beam form of sub-frame in Fig. 6.6. It

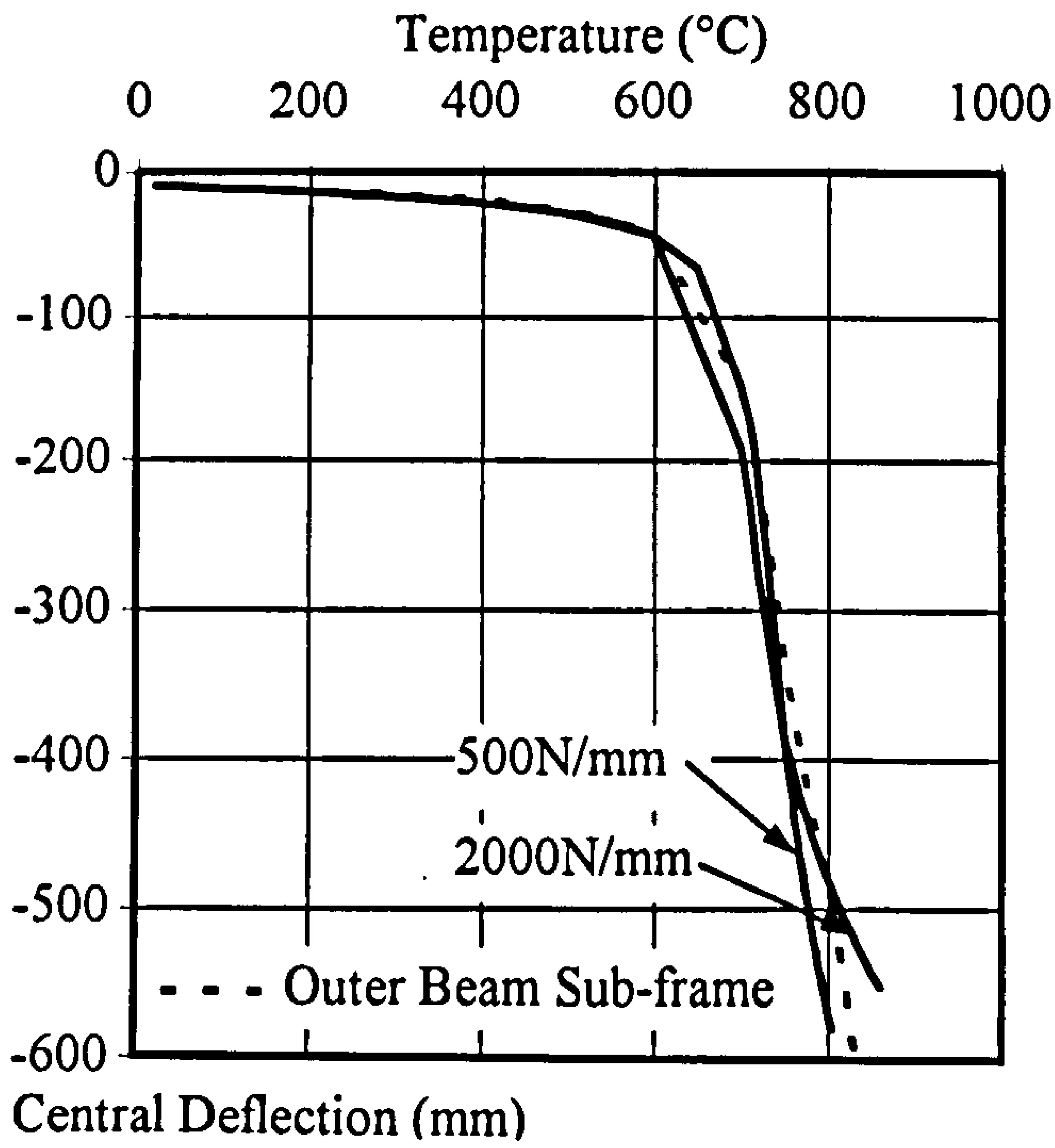


Figure 6.6. Elastic Modelling of Semi-Rigid Connection Response

may be seen that for the arrangement considered, despite a close correlation existing at low levels of deflection, the use of axial springs fails to accurately follow sub-frame response with the spring acting in tension. This may be due to inaccuracies in the assumed axial stiffness as in the sub-frame representation the upper portion of the column remains at ambient-temperatures, and a purely elastic form of response is adopted, resulting in a lower rate of degradation of stiffness and neglect of any plastification that may occur. This hypothesis is supported by the fact that the sub-frame results suggest a spring of significantly greater stiffness than 500N/mm at high temperatures. As such it seems that whilst the use of sub-frames such as those detailed in Fig. 6.2 produces results acceptably close to those obtained from full-frame analysis, it is not as simple a task as may be envisaged to replace the extent of the frame with an axial spring stiffness.

Analysis was repeated for nominally identical arrangements with the incorporation of a composite slab. A 130mm deep profiled slab was adopted providing consistency with the arrangement tested. Due to the existence of voids within the slab resulting in anisotropic behaviour, only the top section of the slab has been incorporated in all subsequent two and three-dimensional analysis, neglecting the area of concrete contained between voids. Temperature distributions adopted were as for the bare-steel arrangement, with the composite slab remaining at 20% of the beam lower flange temperature. Fully non-linear connection characteristics were once more incorporated as described in Chapter 4. Studies contained within this chapter are restricted to two-dimensional analysis, and as such the composite slab was incorporated based on an effective width of one-sixth of the span. The shear stud arrangement adopted in the experimental studies detailed in Chapter 3 provide full-interaction, resulting in a moment capacity of approximately 205kNm at ambient-temperatures.

Response for isolated-beam, inner-beam and outer-beam sub-frames are compared for a composite arrangement in Fig. 6.7. Isolated-beam results are plotted for rigid, semi-rigid and pinned connection characteristics, whilst inner and outer sub-frames are plotted assuming only semi-rigid characteristics to maintain clarity of results.

Based on the assumption of rigid connections, low levels of deflection were observed up to temperatures of approximately 900°C, followed by a rapid increase in central deflections.

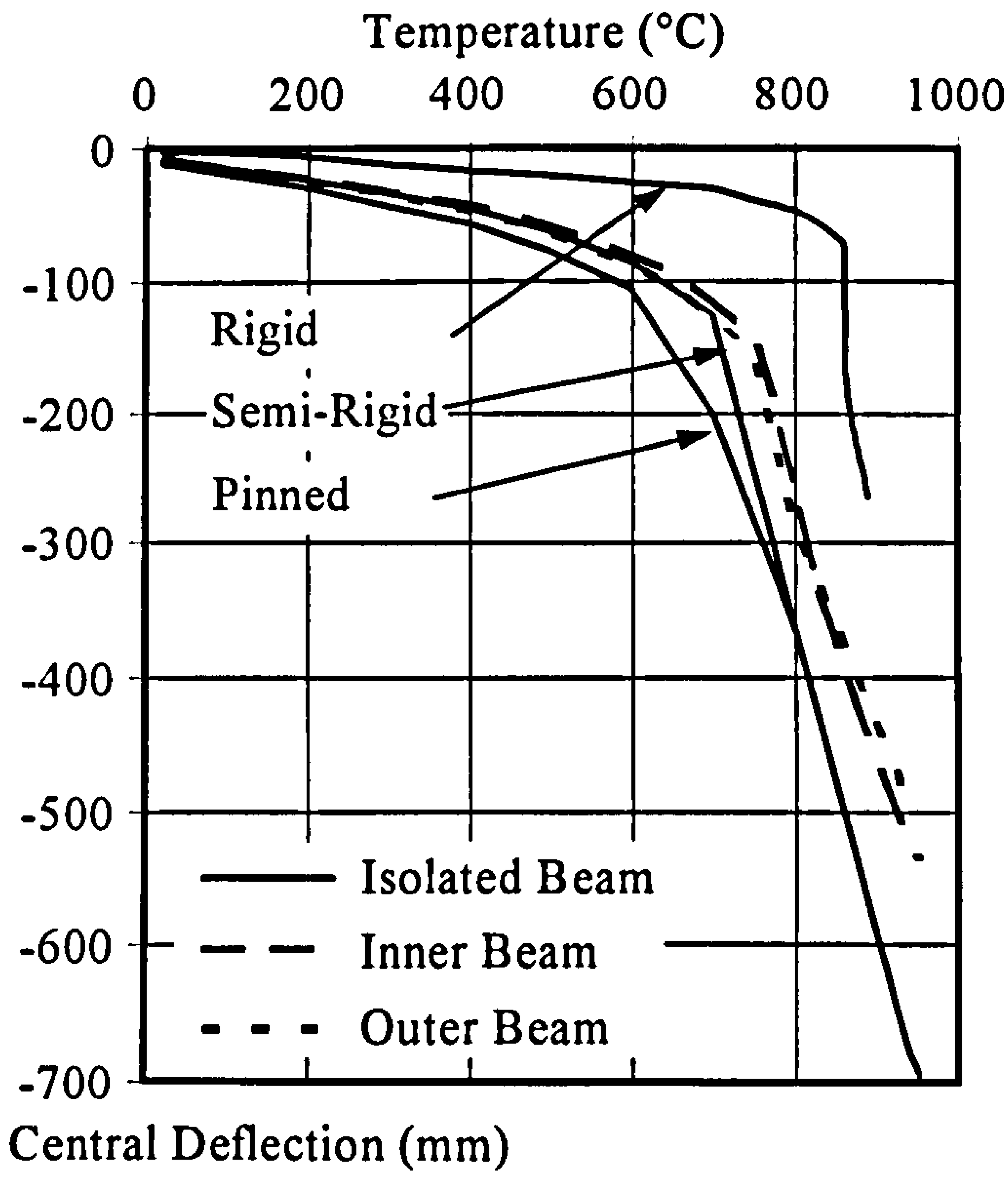


Figure 6.7. Comparison of Sub-Frame Response for Composite Arrangement

This represents a significant enhancement in capacity compared to the bare-steel arrangement reflecting the reduced temperature, and thus rate of degradation of capacity of the composite section. The abrupt increase in deflections with temperature is attributable to cracking of the concrete slab resulting in a sudden reduction in capacity of the section. Similar behaviour was observed for both the inner and outer-beam sub-frames although these results are not plotted.

Considering semi-rigid behaviour it may be seen that all arrangements behaved similarly up to temperatures of approximately 700°C, with a significant enhancement in performance compared to the assumption of pinned connections. With increasing temperature there was an increase in the rate of deflections for the isolated-beam, tending towards the response observed based on the assumption of pinned connection characteristics. Both the inner and outer sub-frames proceed to show an enhanced capacity over the isolated-beam. As with the isolated-beam, response predicted based on semi-rigid connections becomes comparable with that for pinned connections for both the inner and outer sub-frames at temperatures of approximately 850°C. The tendency of semi-rigid arrangement to follow the response predicted assuming pinned connections with increasing temperatures indicates a significant reduction in connection capacity at high temperatures as compared to the capacity of the composite section in sagging, due to the flexibility of the connection in the compression zone resulting in a rapid reduction in capacity for temperatures in excess of 600° (See Fig. 3.43). This effect was reversed in the case of the bare-steel arrangements studied due to the capacity of the beam degrading at a higher rate than the connection, due to the connection remaining at a reduced temperature.

Based on the above studies for both bare-steel and composite arrangements, it is apparent that analysis of the influence of connection characteristics is not satisfactorily represented by an isolated-beam arrangement. Similarly, whilst the inclusion of an axial spring to represent the influence of the external structure generated results which were more comparable to those obtained from both inner and outer sub-frames, accurate definition of the representative stiffness is complicated by the variations in temperature along the length of the column, and the non-linear form of column response. Whilst in the case of the composite arrangement, the response predicted for both the inner and outer arrangements was almost indiscernible, in the case of the bare-steel arrangement, the outer-beam sub-frame highlighted more visibly the influence of axial restraint provided by the external structure, a phenomenon which becomes yet more pronounced as the extent of the sub-frame is increased. As such it is recommended that the outer-beam sub-frame represents an acceptable arrangement, being capable of representing the influence of the external structure on beam response, and is thus adopted in the further studies detailed.

6.4. INFLUENCE OF THE APPLIED LOAD-RATIO

The arrangements studied above were subject to a load-ratio of 0.6, having been previously suggested as representing the typical loading existent within a fire scenario. Clearly it is necessary to ascertain that the load-ratio applied is not so low as to induce only nominal moments within the connection, resulting in the response of the structure becoming controlled primarily by thermal effects, or conversely so high as to result in the rapid onset of failure.

Failure-temperatures for load-ratios up to 1.00 (representing the design capacity of the section at ambient-temperature) are plotted in Fig. 6.8 below, for both bare-steel and composite sections. The term 'failure-temperature' is deemed to mean the temperature at which the central-deflection of the beam reaches a limiting deflection of span/30, or, where ascertained, a limiting temperature of 950°C imposed by the program. Whilst it is realised that much controversy exists as to when true 'failure' occurs, and that at this point integrity of the structure may well remain, the term 'failure-temperature' is adopted purely as a bench mark by which to compare response, corresponding with the limiting deflection specified in BS8110: Part 8[3] assuming a rate of deflection of $span^2/(9000 \times \text{member depth})$ is exceeded (reducing to span/20 in BS5950: Part 8 for reduced rates of deflection).

Fig. 6.8 demonstrates that at low load-ratios failure-temperatures for both bare-steel and composite arrangements reached 950°C, corresponding to the maximum temperature for which material properties are defined within the program adopted. For the composite arrangement there was no change in failure-temperature up to a load-ratio approaching 0.5. This is due to the fact that with increasing temperatures the load-ratio of the composite section increases at a lower rate than for the bare-steel section due to the reduced temperature, and hence capacity, of the concrete slab acting compositely with the steel beam. The applied load-ratio for the bare-steel section has a almost linear influence on the resultant failure-temperature. As such, the load-ratio of 0.6 adopted appears satisfactory, being representative of that which would be expected to exist for a typical structure, and of a high enough value to induce failure within both the bare-steel and composite sections prior to the limiting temperature of the software.

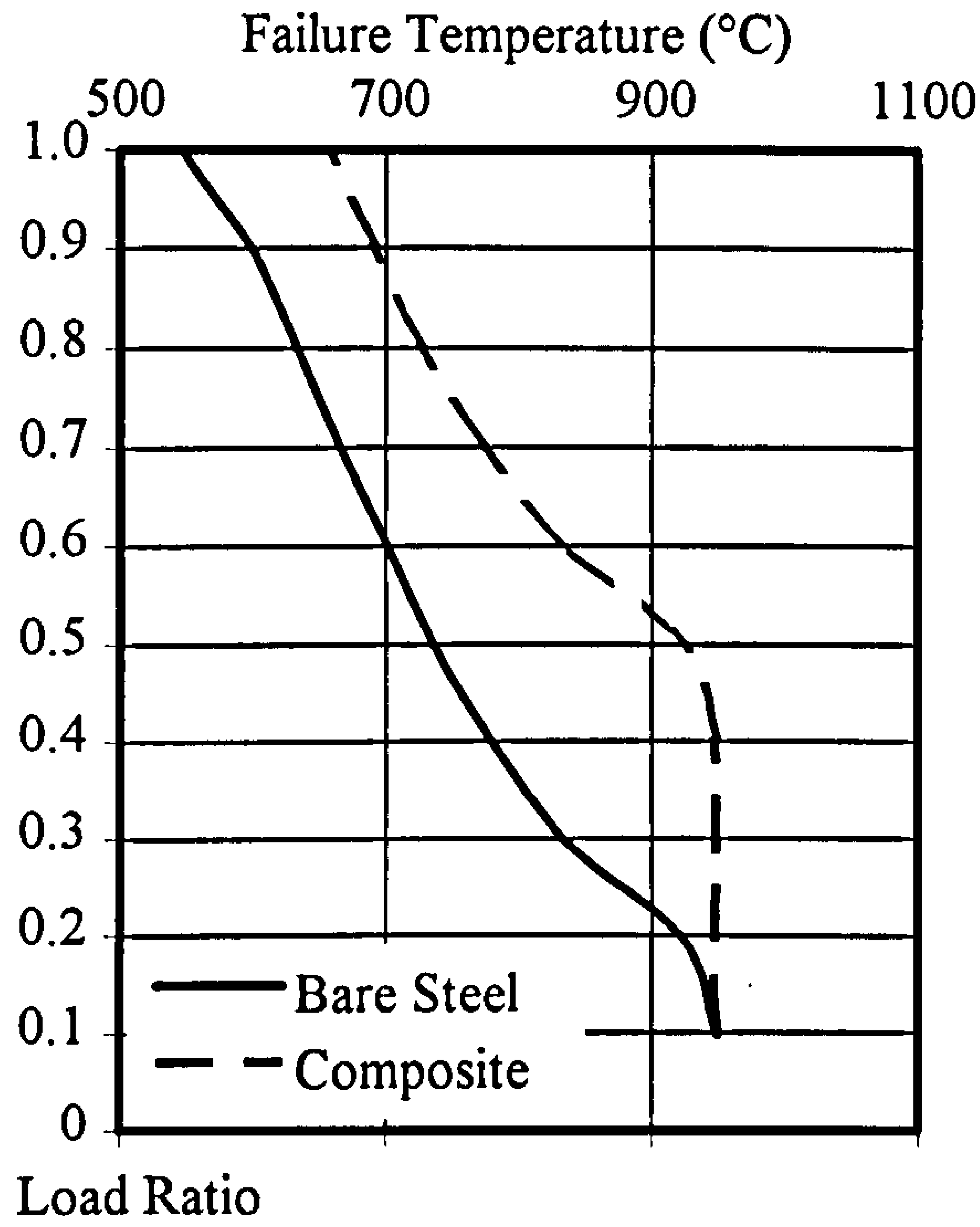


Figure 6.8. Influence of Applied Load-Ratio on Sub-Frame Response

6.5. INFLUENCE OF CONNECTION TEMPERATURE

The connection temperature adopted within these initial parametric studies, being 70% of the beam lower flange temperature, has been previously recommended by Lawson[44] based on a series of furnace tests using the ISO standard time-temperature regime[24]. The use of a connection temperature 70% of the beam lower flange temperature is somewhat contradictory to the temperature distributions recorded in the bare-steel and composite connection tests described in Chapter 3, in which little variation in the temperature of the connection and that of the beam lower flange was observed as detailed in Tables 3.2 and 3.4. Connection temperature is influenced by a number of factors such as material thickness, the degree of shielding and the rate of heating. As such furnace tests in which the form of heating is not truly representative of that obtained from realistic fire scenarios does not represent the most acceptable source of information.

A range of ratios between the connection temperature and that of the beam lower flange, and the influence on the resultant failure-temperature, are considered in Fig. 6.9, illustrating the significance of the temperature adopted. At low temperature-ratios resultant failure-temperatures tend towards those obtained assuming rigid connections (failure temperatures being 780°C and 950°C for bare-steel and composite arrangements respectively). This behaviour is more pronounced in the consideration of the influence of bare-steel connections, assumably due to the fact that with increasing temperatures the capacity of the bare-steel section would degrade at a rate such that the moment capacity of the connection (remaining at a significantly reduced temperature) would exceed that of the beam or column, resulting in an effectively rigid connection. The capacity of the composite section degrades at a slower rate due to the influence of the concrete slab, and this acting in combination with the lower ratio of connection-to-beam moment capacity at ambient-temperatures results in a connection which tends towards rigid support, but does not achieve full continuity for the arrangement considered. Similarly, for increasing temperature ratios, there is a tendency for the both bare-steel and composite arrangement to behave as though pinned connections were incorporated (failure-temperatures being 542°C and 722°C for bare-steel and composite arrangements respectively), due to the increased rate of degradation of the connection characteristics.

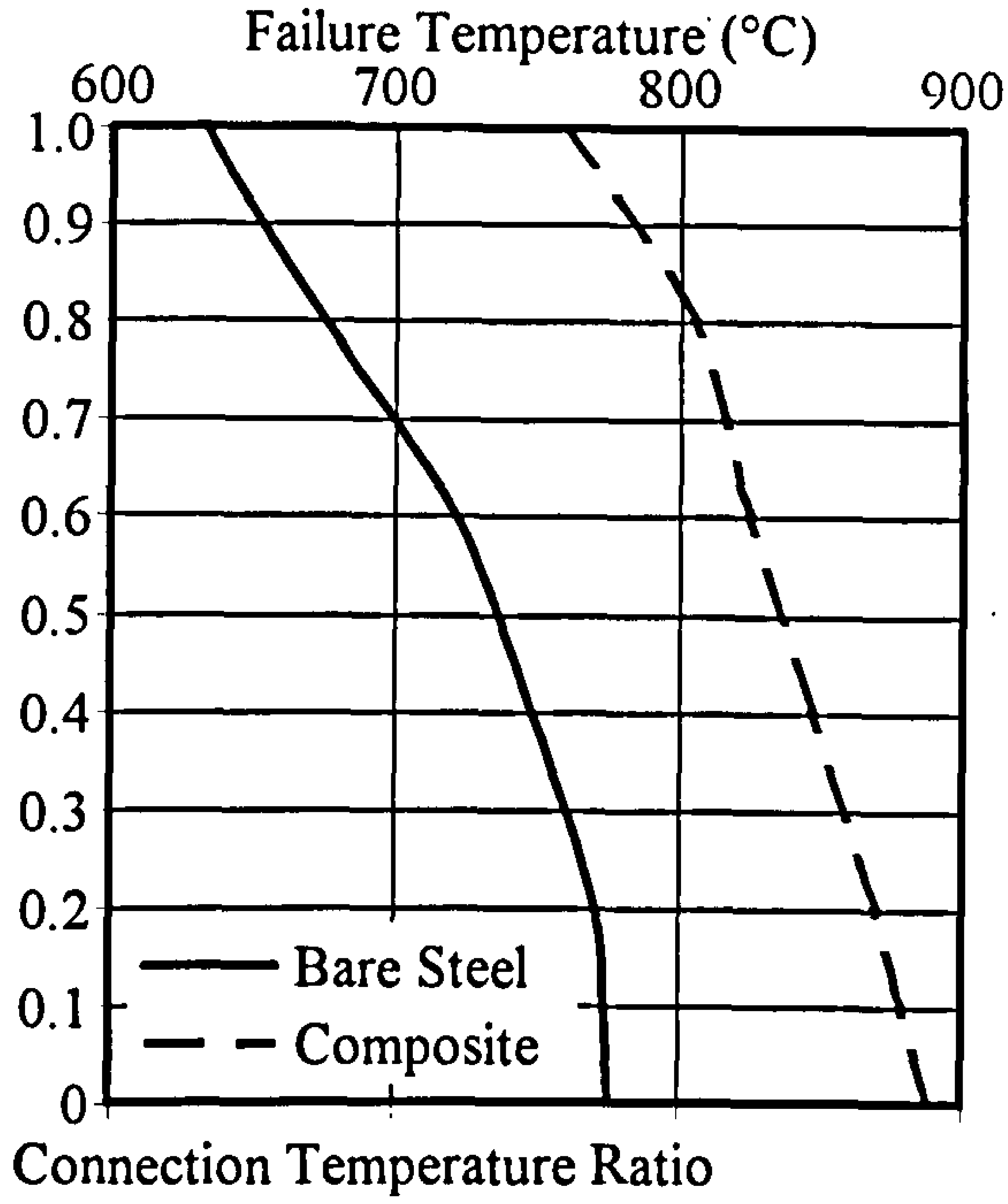


Figure 6.9. Influence of Connection Temperature on Sub-Frame Response

The highly sensitive nature of frame response to the temperature of connections demonstrates the need to ascertain the actual temperature of connections under realistic fire conditions. Unfortunately this is difficult to ascertain from furnace testing due to the heating regimes imposed by the capacity of the burners and distribution of temperature within the compartment. Indeed, it is felt that true temperature profiles may only be obtained accurately from fire tests using realistic fuels, although the use of fully validated temperature flow models provides an essential tool for the extrapolation of temperature profiles for a wide range of structural arrangements.

6.6. INFLUENCE OF FORM OF CURVE-FIT ON SUB-FRAME RESPONSE

As described in Chapter 4, numerous forms of curve-fitting techniques exist which are applicable to modelling connection characteristics for incorporation within finite-element analysis. It is thus important to assess the sensitivity of frame response to the form of curve-fit adopted.

Within ambient-temperature numerical modelling, connection characteristics have frequently been idealised as purely elastic, based on the initial tangent-stiffness of the connection. This form of curve-fit offers a number of advantages, being easy to incorporate within analysis and comparatively easy to define (with no consideration of the capacity of the connection or plastic response being required). The use of an elastic representation seems reasonable at ambient-temperatures due to the limited level of rotation experienced, and the desire to maintain response within the elastic range. However, under fire conditions far higher levels of deformation are permissible, with the typical limiting deflection of span/20 corresponding with a rotation of approximately 150 millirads for a pinned connection (span/30 giving a rotation of 90 millirads). Hence it seems probable that typical 'semi-rigid' connections will enter the plastic range of response.

The bare-steel outer-beam form of sub-frame adopted above has been reanalysed with connection characteristics incorporated as linear-elastic (based on the initial secant-stiffness of the connection), bi-linear (based on the initial tangent- and plastic-stiffness of the connection) and fully non-linear (adopting the Ramberg-Osgood from of curve-fit). A connection temperature 70% of the beam lower flange temperature has been adopted in all cases. Central beam deflections and corresponding rotations are plotted in Fig. 6.10 below, and compared with the assumptions of 'rigid' and 'pinned' connection characteristics.

Fig. 6.10 demonstrates the need for the form of curve-fit adopted to follow the plastic response of the connection. Incorporating linear-elastic connection characteristics overall frame behaviour is comparable with that assuming rigid connections. This would be anticipated from consideration of associated rotations, as the Ramberg-Osgood form of cure-fit shows that rotations in excess of 100 millirads would exist at a limiting deflection of span/20, corresponding with a rotation significantly beyond the onset of plasticity.

The Ramberg-Osgood and Bi-linear form of curve-fit compare closely in terms of both deflections and rotations for temperatures up to approximately 720°C. With increasing temperatures there is a deviation in response, with the bi-linear representation predicting lower levels of rotations at equivalent temperatures. It is interesting to note that a temperature of 720°C corresponds with a rotation of 100 millirads. In applying both the Ramberg-Osgood and Bi-linear curve-fits, the curve was modelled over a range of rotations up to 100 millirads. For increasing levels of rotation the Ramberg-Osgood representation tends to flatten out, representing the reduction in the plastic-stiffness with increased rotation, whilst the bi-linear fit follows the initial plastic-stiffness, thus overestimating the capacity of the connection for increasing levels of rotation.

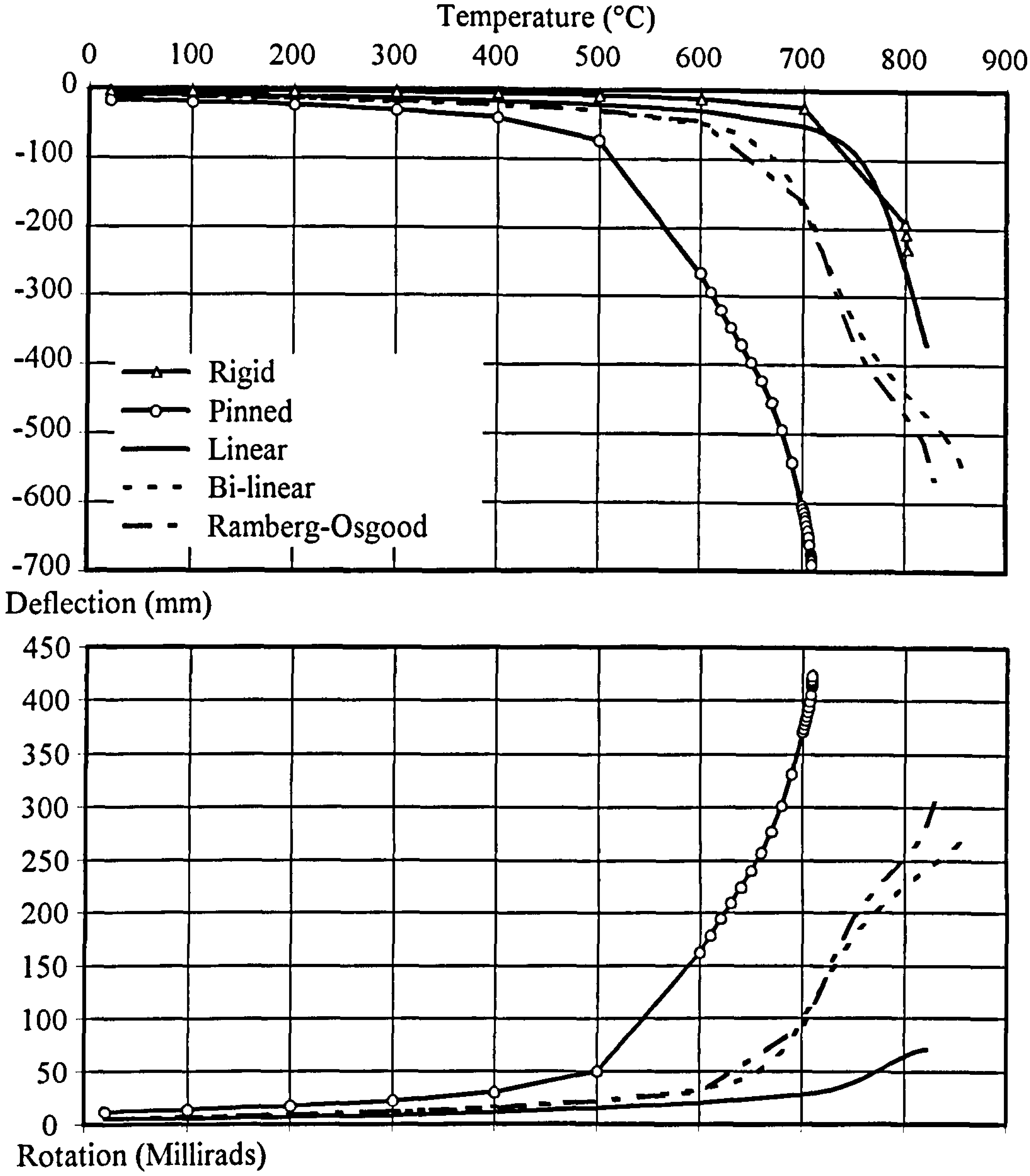


Figure 6.10. Resultant Deflections and Corresponding Levels of Rotation for Commonly Adopted Approximations of Connection Response (Bare-Steel)

Based on the above observations it is apparent that the linear form of curve-fit is not applicable to elevated-temperature analysis due to the levels of rotation permissible. Whilst the bi-linear representation resulted in response indiscernible from that assuming a fully non-linear curve-fit, for increasing levels of rotation the bi-linear form of curve-fit became un-conservative, overestimating the capacity of the connection. This suggests that a simple multi-linear form of curve-fit would prove acceptable, provided that a 'plateau' was introduced, limiting the capacity of he connection at high levels of rotation. Similarly, where the application of the Ramberg-Osgood equation does not result in a limit on capacity within the range of rotations over which the curve is modelled it would seem reasonable to modify the general form of the equation so as to include a limiting capacity for the connection. Analysis was repeated for the composite arrangement based on the forms of curve-fit described above, resulting in a comparable form of behaviour.

6.7. INFLUENCE OF CONNECTION STIFFNESS AND CAPACITY

The response of connections is frequently idealised in terms of two constituent parts - initial-stiffness and moment capacity. It would be anticipated that at elevated-temperatures the influence of these two key factors on the overall frame response would differ from that at ambient-temperatures, with the response becoming less sensitive to initial-stiffness due to the large levels of rotation experienced, as shown in Fig. 6.10.

The use of the Ramberg-Osgood form of equation facilitates assessment of the sensitivity of a given arrangement to changes in stiffness and capacity by the modification of the terms A and B contained within the equation described in Chapter 4, where these represent the initial-stiffness and capacity of the connection respectively.

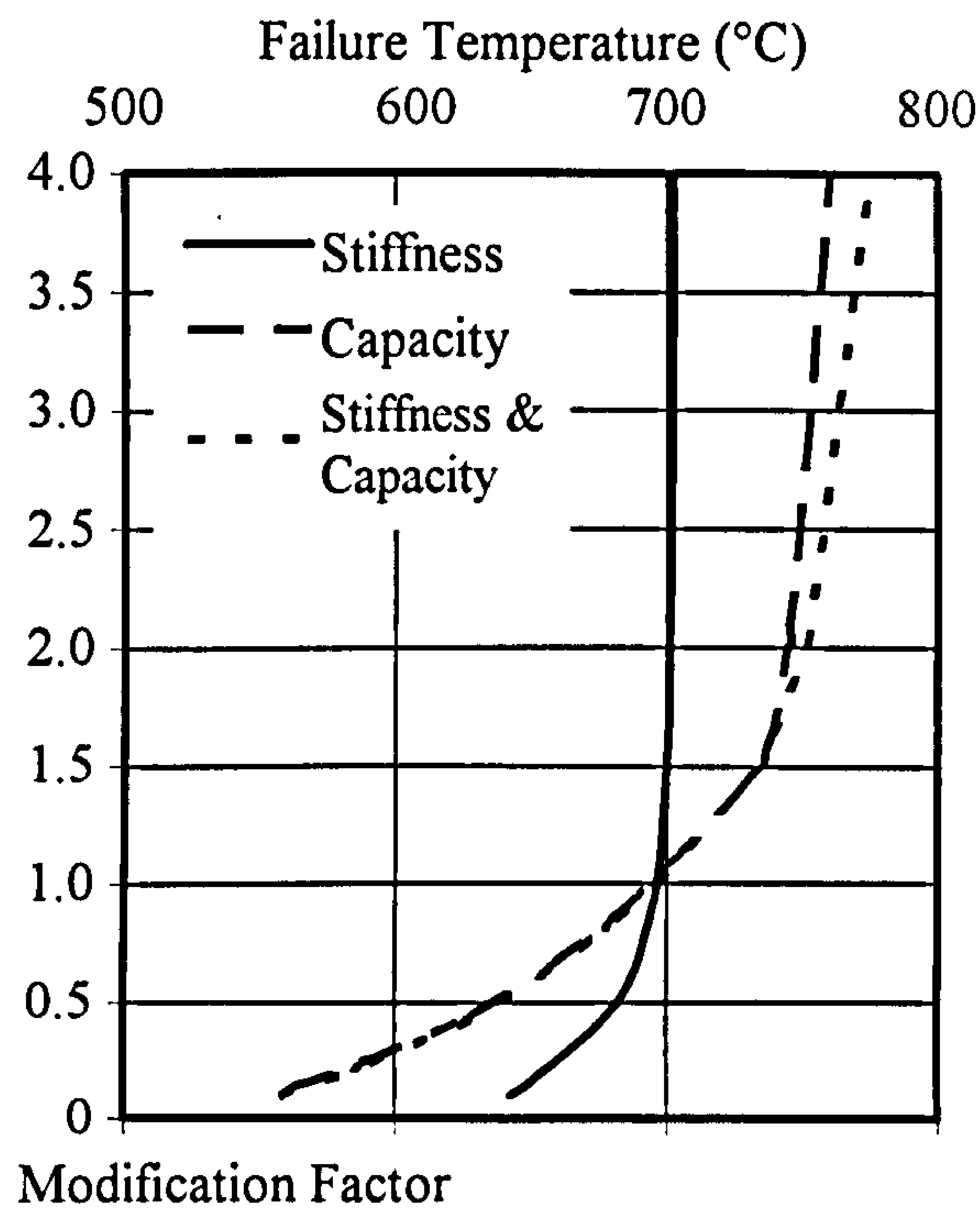


Figure 6.11. Influence of Connection Stiffness and Capacity on Bare-Steel Sub-Frame Response

The bare-steel arrangement described has been analysed based on modified values of initial-stiffness, moment capacity and both stiffness and capacity for values up to four times greater than those obtained from experimentation. Resultant failure-temperatures are compared in Fig. 6.11. For levels of stiffness in excess of those obtained from experimentation only a gradual increase in failure-temperature is observed, supporting the opinion that at elevated-temperatures frame response is less sensitive to the initial-stiffness of the connection than with ambient-temperature studies. For levels of stiffness below the recorded value there is a gradual reduction in failure-temperature, although even modest values of stiffness result in a significant enhancement over the pinned failure-temperature of 542°C. The connection tested was unstiffened, and the column to which it was connected was relatively flexible due to the low flange and web thickness. It would be anticipated that this would result in a connection of stiffness typical for the flush end-plate type connection. This seems to suggest that, as long as the connection type considered may be shown to possess a modest initial-stiffness, it may be satisfactory to consider the influence of the connection characteristics at elevated-temperatures based purely on the capacity of the connection.

The capacity of the connection may be seen to have an almost linear influence on failure-temperature tending from 'pinned' response assuming zero stiffness to 'rigid' for a level of capacity 50% higher than that recorded experimentally. For increasing levels of capacity the influence reduces, with failure-temperature tending more gradually towards the rigid failure-temperature of 780°C. The effect of combining increases in both connection stiffness and capacity result in a form of response similar to that obtained from simply increasing the capacity of the connection, although for factors greater than 1.5, the stiffness of the connection becomes more influential, presumably due to the need for a higher moment to exist within the connection prior to the onset of plastification, and thus a tendency for the response of the connection to remain within the elastic range.

The analysis was repeated for the composite arrangement, again varying the terms A and B within the Ramberg-Osgood equation, as shown in Fig. 6.12. It may be seen that the initial-stiffness of the connection once more had a limited influence on the resultant failure-temperature of the arrangement, with the initial-stiffness becoming insignificant for a value half that obtained experimentally. The capacity of the connection is once more seen to have an almost linear influence on the failure-temperature of the arrangement across the range of temperatures between those obtained assuming pinned and rigid connection characteristics. For a capacity twice that recorded experimentally the failure-temperature remains constant at 950°C, being fixed by the limiting temperature of the software. When the effects of stiffness and capacity are combined the response become indiscernible from the results obtained by simply varying the capacity of the connection.

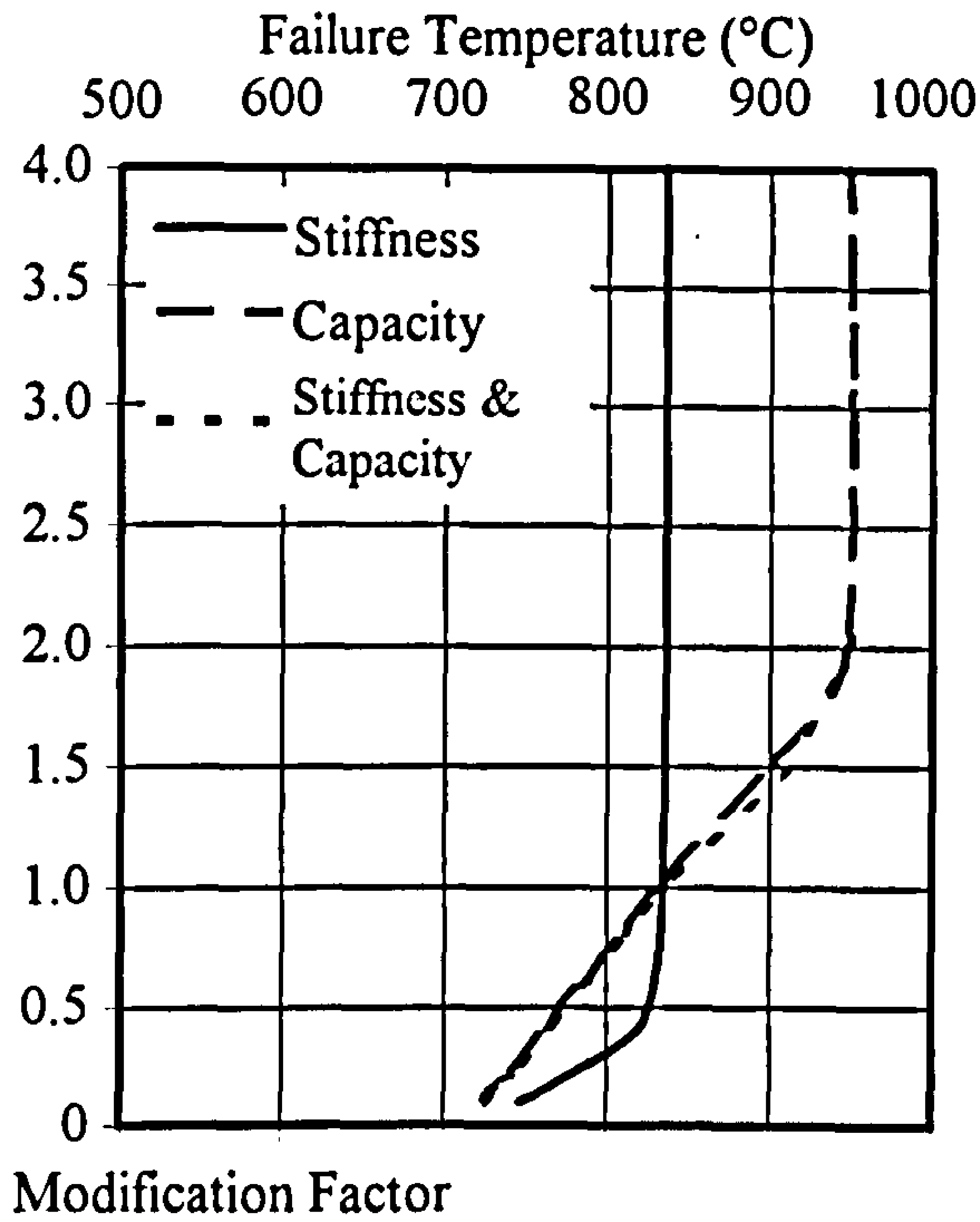


Figure 6.12. Influence of Connection Stiffness and Capacity on Composite Sub-Frame Response

6.8. THE INFLUENCE OF THE USE OF CONNECTION MODELS

Due to the expense of testing it is desirable to develop connection models allowing the generation of moment-rotation characteristics for a broader range of connection arrangements. Existing forms of connection model have been reviewed in Chapter 4, and based on the findings of previous research it has been suggested that the use of a spring-stiffness model represents a suitable form of model for elevated-temperature analysis, being relatively easy to apply and capable of providing a reasonable representation of the full range of connection response. An elevated-temperature spring-stiffness form of model has been presented for both bare-steel and composite flush end-plate connections in Chapter 5.

Comparison of the predicted moment-rotation response with that obtained from experimentation has been considered. It was observed that whilst both the bare-steel and composite models provided an acceptable representation of connection behaviour at ambient-temperatures, the composite model did not accurately follow the degradation of connection characteristics due to the complexities associated with buckling of the column web in the compression zone. Predicted rates of degradation for the bare-steel connection compared closely with those recorded.

It is important to consider the influence that inaccuracies within the described spring-stiffness model have on overall frame-response for both bare-steel and composite arrangements. To facilitate this the forms of sub-frame described above have been analysed with semi-rigid connection characteristics being represented in a multi-linear form based on the results obtained from the spring-stiffness model. The resultant behaviour is compared with that incorporating experimental moment-rotation characteristics, and the assumptions of pinned and rigid connection characteristics, for both bare-steel and composite arrangements in Figs. 6.13 and 6.14 respectively.

It may be seen from Fig. 6.13 that the response predicted incorporating connection characteristics generated by the proposed bare-steel spring-stiffness model compare closely with that obtained from the incorporation of experimentally derived connection characteristics. Predicted deflections remained greater than those based on experimental results across the entire range of response, resulting in a reduction of approximately 15°C in the failure-temperature. This form of behaviour would be anticipated based on the behaviour of the bare-steel connection predicted. As can be seen from Fig. 5.18, whilst the model overestimated connection capacity throughout the rounded knee of the moment-rotation curve, for increasing levels of rotation the predicted curve lies below that from experimentation. Fig. 5.19 demonstrates that the predicted rate of degradation of connection capacity also remains conservative with increasing temperatures.

Incorporation of composite connection characteristics generated by the spring-stiffness model results in a form of response which, whilst closely following that predicted assuming experimental characteristics at low temperatures, begins to overestimate the rate of deflection for increasing temperatures. Ambient-temperature connection characteristics generated by the spring-stiffness model represent a reasonable approximation of connection response as shown in Fig. 5.24. However, it may be seen from Fig. 5.25 that the predicted rate of degradation of connection capacity is far greater than that observed. It was suggested in Chapter 5 that inaccuracies within the composite model resulted from the inability of the spring-stiffness model to predict the influence of the buckling of the column web in the compression zone. This results in the premature yielding of the reinforcement (failure of the reinforcement was not observed in the series of elevated-temperature composite connection tests conducted), and for increased levels of rotation the described model predicts complete loss of capacity arising from the reinforcement. Analysis was repeated incorporating bare-steel connection characteristics within the composite sub-frame analysis. This was seen to result in a form of behaviour indiscernible from that incorporating the predicted composite characteristics.

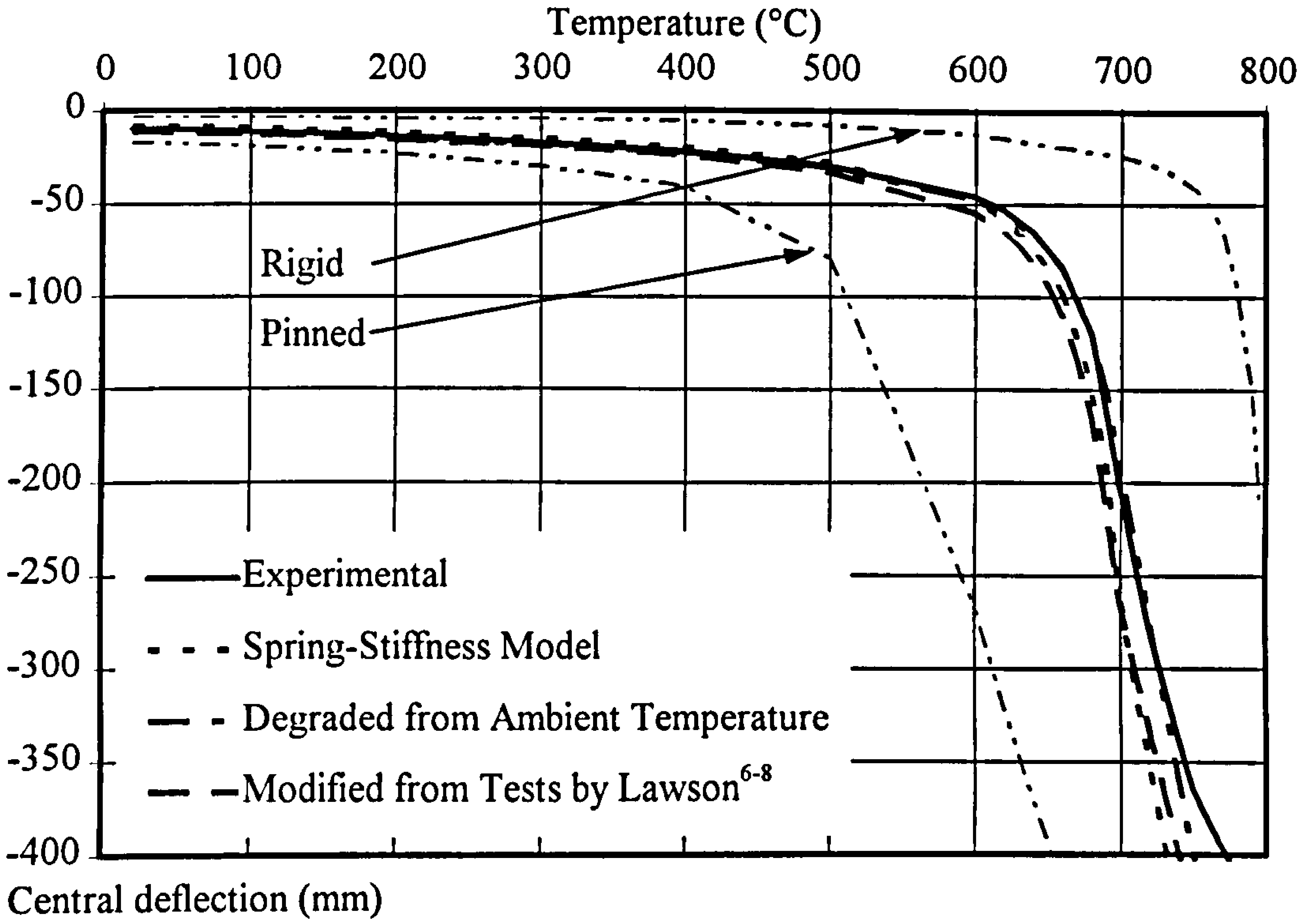


Fig. 6.13. Influence of Forms of Connection Model on Bare-Steel Frame Response

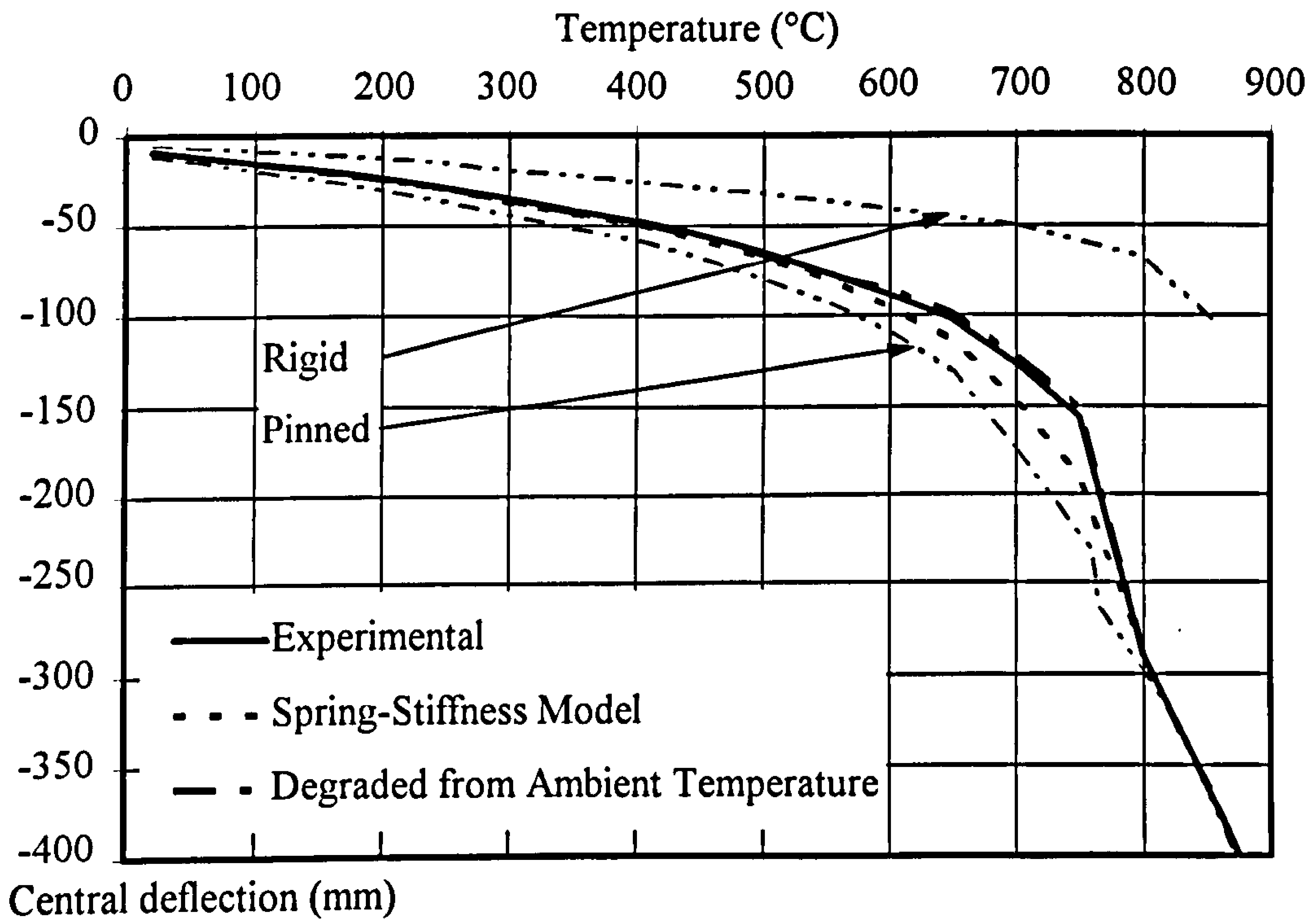


Fig 6.14. Influence of Forms of Connection Model on Composite Frame Response

The correlation between response from the incorporation of bare-steel and composite connection characteristics within a composite sub-frame analysis highlights the need to consider the potentially significant influence of yielding of the column web in the compression zone, and the resultant influence this has on reinforcement acting in tension.

Care should be taken when considering the influence of composite connection characteristics on frame behaviour to ensure that reinforcement is capable of withstanding considerable levels of rotation (in excess of 100 millirads) prior to yielding. As described in Chapter 3 the assessment of the rotation capacity of reinforcement is complex, being dependent upon the de-bonded length of the reinforcement. Integrity of reinforcement acting in tension may be maintained through the artificial de-bonding of reinforcement, and it is suggest that such detailing may prove desirable where advantage is taken in design of the enhancement in moment capacity provided by reinforcement acting at a significantly reduced temperature. Increasing the de-bonded length will result in a reduction in connection stiffness, but as suggested by these initial studies, capacity and ductility have a more significant influence on frame response than initial-stiffness in the consideration of the effects of semi-rigid connection characteristics on failure-temperatures.

As discussed in Section 3.4, it is advantageous to consider the ability with which connection characteristics may be degraded from ambient-temperatures moment-rotation characteristics, to account for the influence of increasing temperatures, as an extensive fund of ambient-temperature tests data exists[36]. Possible methods by which both bare-steel and composite connection characteristics may be degraded theoretically were compared with the rates of degradation recorded. It was observed that a reasonable representation of the degradation of bare-steel connection capacity and stiffness was possible by simply degrading the stiffness and capacity of the connection according to the rates of degradation of the elastic-stiffness and ultimate stress capacity of the critical component, at the associated temperature. Degradation of composite connection capacity proved more complex, with the degradation of initial-stiffness being controlled by compression zone deformation, whilst degradation of capacity initially occurred at a reduced rate due to the influence of the reinforcement, until such a time as deformation of the column web once more controlled, resulting in a rapid reduction in capacity.

Both bare-steel and composite connection characteristics have been degraded from experimentally derived ambient-temperature moment-rotation curves for increasing temperatures based on the recommendations of Section 3.4. In the case of the composite connection capacity it was assumed that 45% of overall capacity was attributable to the reinforcement at ambient-temperatures based on the relative capacities of the bare-steel and composite connections recorded. This results in a rate of degradation of capacity which whilst being conservative at low temperatures does not accurately follow the accelerated rate of reduction in capacity that was observed with increasing temperatures as shown in Fig. 3.43.

It may be seen from Fig. 6.13 that overall frame response based on the incorporation of degraded bare-steel connection characteristics closely follows that assuming experimental elevated-temperature characteristics. It is interesting to note from Fig. 6.14 that even when considering the incorporation of degraded composite connection characteristics, the degradation of which was not accurately predicted by simplified methods, the resultant frame behaviour once more closely follows that assuming experimental characteristics.

This suggesting that the incorporation of 'approximate' connection characteristics may result in an acceptable representation of overall frame response.

El-Rimawi[163] proposed that a simplified form of model may be adopted to approximate elevated-temperature connection characteristics for any given beam size, for both extended and flush end-plate connections, based on the modification of results obtained from a series of elevated-temperature tests conducted by Lawson[44]. A cruciform arrangement was adopted consisting of 305x165x40 beams framing into the flanges of 203x203x52 column section. The resultant ambient-temperature moment-rotation response was defined by El-Rimawi based on the Ramberg-Osgood form of curve-fit, as described in Chapter 4, by the parameters: $A = 6.3300$; $B = 21.3578$ and $n = 10.4143$.

It was proposed by El-Rimawi that assuming the connection to have a comparable form of response that moment capacity and stiffness may be modified for beam depth:

$$M_{c1} = f.M_{c305} \qquad \text{Eq. 6.2.}$$

$$S_{c1} = f^2.S_{c305} \qquad \text{Eq. 6.3.}$$

Where M_{c1} and S_{c1} are the modified characteristics;

$$f = (D_c - 50)/(303.8 - 50); \qquad \text{Eq. 6.4.}$$

D_c is the depth of the new cross-section.

The concept of generating connection characteristics for a broad range of arrangements based on the findings of a representative series of tests is advantageous as a wide variety of dimensional configurations may exist for otherwise similar connections. This is particularly relevant as general opinion currently prefers the option of standardisation of connection characteristics where possible, allowing response to be investigated more closely for these arrangements, and potentially resulting in simplified design approaches. However, care should be taken as it is necessary to ensure that the mechanism of failure at elevated-temperatures is consistent for different arrangements. This may not be true for beams of increasing depth as it is not typical to increase aspects of the connection detail such as plate thickness accordingly. Indeed, in the SCI guide to *Joints in Simple Construction*[63] in which an attempt was made to standardise connection detailing, only two value of plate thickness were suggested for end-plate connections for the range of beam sections.

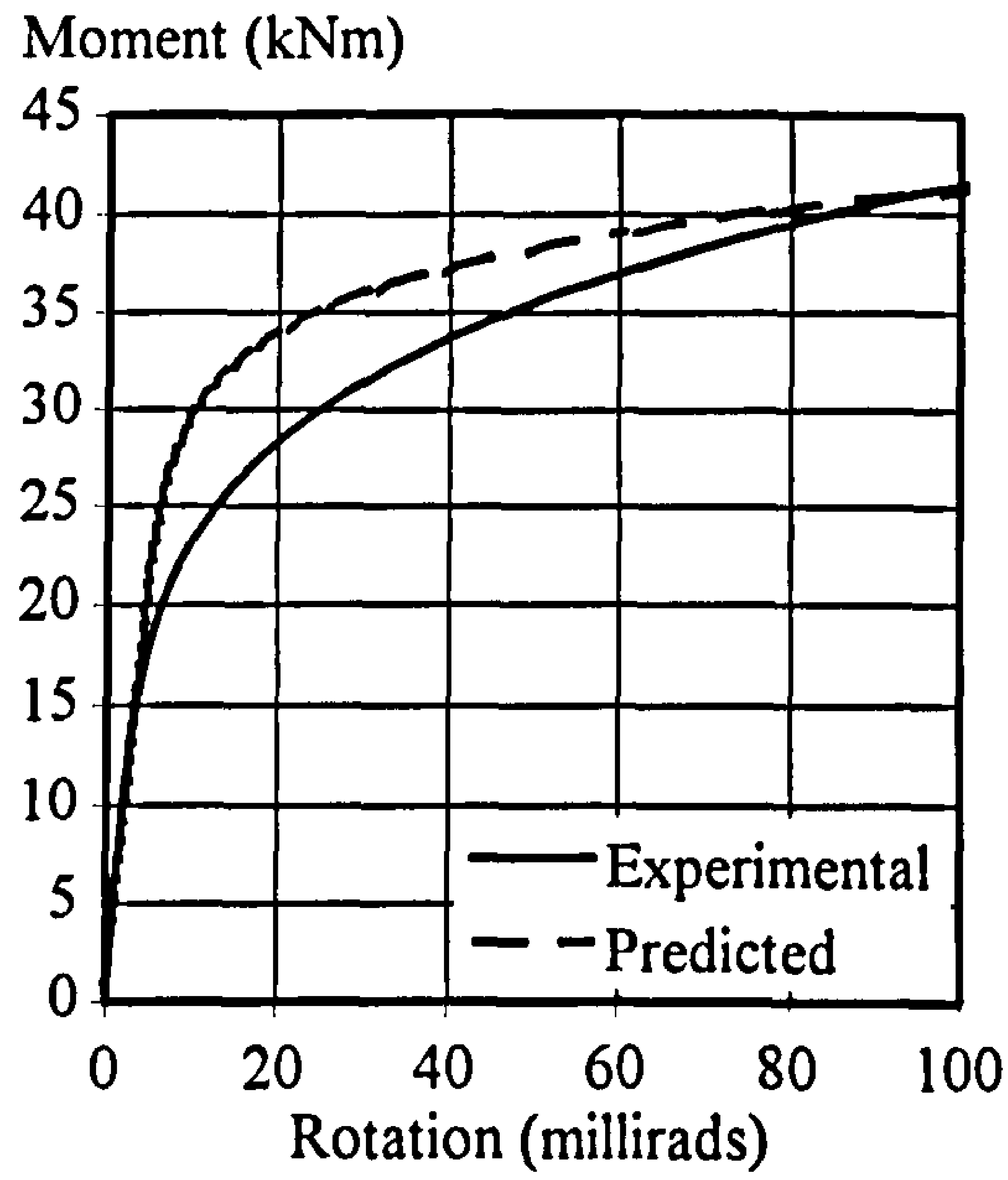


Figure 6.15. Prediction of Bare-Steel Moment-Rotation Response from Tests by Lawson[44]

The equation described by El-Rimawi has

been used to predict the elevated-temperature response of the bare-steel connection tested, and the results incorporated in the analysis of the bare-steel sub-frame as shown in Fig. 6.13. The connection response predicted at ambient-temperatures is compared with that recorded experimentally in Fig. 6.15. It was observed that predicted response based on the results presented by Lawson results in a connection of similar overall response, but with a higher capacity at low rotations followed by a sharp knee in the moment-rotation curve. For increasing rotations the capacity predicted flattens out at an increased rate, resulting in a connection of reduced moment capacity for levels of rotation exceeding 100 millirads. Predicted rates of degradation of connection capacity and stiffness compared closely with that recorded experimentally.

It may be seen from Fig. 6.13 that the incorporation of the predicted connection characteristics results in a form of frame response comparable with that observed from the incorporation of experimental moment-rotation characteristics. Predicted deflections lie below those assuming experimental characteristics for increasing temperatures. This is in part due to a slight increase in the rate of degradation of connection capacity based on tests by Lawson, with rotations experienced at the lower range of temperatures being below 100 millirads, and in part due to the reduced capacity of the connection for the increased levels of rotation experienced at higher temperatures. However, in general the predicted response closely follows the true behaviour. This suggesting that the modification of connection characteristics to account for beam depth may prove viable where similar arrangements are to be adopted, although this requires extensive validation, and it would be anticipated that more stringent guidelines would be necessitated ensure that connections of a similar form are detailed as to respond in a comparable mechanism with increasing temperatures.

6.9. THE CONCEPT OF CONNECTION CLASSIFICATION

Despite the increased level in understanding of connection response over recent years, and the now extensive quantity of qualifying test data that exists, the incorporation of semi-rigid connection characteristics within design (even at ambient-temperatures) remains uncommon due to the associated increased complexity of analysis. As such it has been suggested by Bjorhovde[164] that to facilitate economical design it is necessary to develop a system of connection classification to categorise the necessary design parameters governing the behaviour of connections and their associated influence on frame response, without the need to resort to numerical modelling. Such an approach would remain advantageous for the categorisation of elevated-temperature connection characteristics, facilitating an expedient approximation of the possible enhancement in failure time that the incorporation of semi-rigid connection characteristics within analysis may demonstrate.

Bjorhovde considered moment-rotation response to fall into three basic categories: flexible connections (pinned), rigid connections (fixed) and semi-rigid connections, with connections characteristics being categorised according to strength, rigidity and ductility. A similar form of connection classification has more recently been incorporated in EC3. Requirements in terms of moment resistance, rotational stiffness and rotation capacity are discussed below:

- ***Moment Resistance:***

The connection may either be full-strength, partial-strength or nominally pinned (i.e. not moment resisting). At elevated-temperatures, where permissible rotations are far greater than those experienced at ambient-temperatures, it would be expected that most connections would enter the plastic range of response, and as such moment capacity would be anticipated to control overall response.

- ***Rotational Stiffness:***

The connection may be either rigid, semi-rigid or nominally pinned. Based on the initial findings of these parametric studies it would be anticipated that the failure-temperature of a given arrangement would be comparatively insensitive to the initial-stiffness of the connection.

- ***Rotation Capacity:***

Ductility of connections is significant in terms of maintaining structural integrity, and it is desirable that connections should be able to rotate plastically at some stage within the loading cycle without failure. Ductility may generally be achieved through correct detailing, such as that described in the SCI/BCSA publication '*Joints in Simple Construction*'. At elevated-temperatures ductility of the connection would increase, due to the increased malleability of the material. This is supported by the elevated-temperature tests conducted on flush end-plate connections in which rotations in excess of 120 millirads were achieved with no visible signs of the onset of brittle failure. Similarly, elevated-temperature tests conducted by Lawson for a range of semi-rigid connections recorded maximum rotations in the region of 140 millirads. It is appreciated that the levels of rotation which may be experienced at elevated-temperatures are significantly higher than those at ambient-temperatures as shown in Fig. 6.10, and as such it would be desirable to conduct tests to ascertain permissible levels of rotation at elevated-temperatures.

In order that the form of classification adopted remains applicable to all arrangements moments and rotations need to be considered in a non-dimensionalized form. The non-dimensional parameters used in the classification of connections within EC3 are:

$$\bar{m} = \frac{M}{M_{b,pl,Rd}} \qquad \text{Eq. 6.5.}$$

$$\bar{\phi} = \frac{EI_b \phi}{L_b M_{b,pl,Rd}} \qquad \text{Eq. 6.6.}$$

Where $\bar{m}$ is the non-dimensionalized moment;

$\bar{\phi}$ is the non-dimensionalized rotation;

$M_{b,pl,Rd}$ is the is the design plastic moment resistance of the beam;

I_b is the moment of inertia of the beam;

L_b is the length of the beam.

A similar approach is adopted by Bjorhovde, except that the term $\bar{\phi}$ is represented assuming a reference beam length of $5d$ as:

$$\bar{\phi} = \frac{EI_b \phi}{5dM_{pl.Rd}} \qquad \text{Eq. 6.7.}$$

Where d is the assumed beam depth.

The form of classification adopted by Bjorhovde and that incorporated within EC3 are essentially the same, except that Bjohovde considers an effective beam length of $5d$. Due to the assumption of an effective beam length within the method presented by Bjorhovde, the classification system incorporated within EC3 is more accurate where the layout and member details of the structural system are known, as concluded by Liew[166]. The classification system presented in EC3 is dependent on the type of structure since the semi-rigid action is different between braced and un-braced frame systems. For the purposes of this study attention has been restricted to braced frame arrangements.

According to the recommendations of EC3, connections may be classified as rigid according to strength where:

$$M_{j,Rd} \geq M_{b,pl,Rd} \qquad \text{Eq. 6.8.}$$

and pinned where:

$$M_{j,Rd} \leq 0.25 M_{b,pl,Rd} \qquad \text{Eq. 6.9.}$$

Where $M_{j,Rd}$ is the design moment capacity of the connection;
$M_{b,pl,Rd}$ is the design plastic moment resistance of the beam.

Similarly, connections may be classified according to stiffness as rigid where:

$$S_{j,ini} \geq 8EI_b / L_b \qquad \text{Eq. 6.10.}$$

and pinned where:

$$S_{j,ini} \leq 0.5EI_b / L_b \qquad \text{Eq. 6.11.}$$

Where $S_{j,ini}$ is the initial-stiffness of the connection.

From a strength viewpoint, connections are classified as rigid, based on the full plastic moment capacity of the beam, whilst from a stiffness viewpoint boundaries were chosen so that the resultant drop in load-carrying capacity (evaluated from the Merchant-Rankine formula) based on the analysis of a goal-post sub-frame was less than 5%[167].

The ambient-temperature moment-rotation curve for the flush end-plate connection tested has been represented in a non-dimensionalized form in Fig. 6.16, and compared with the form of classification adopted in EC3 assuming a braced frame. It may be seen from Fig. 6.16 that a tri-linear form of representation is actually adopted within EC3 to account for the non-linear behaviour of semi-rigid connections. However, this is seen to be of limited influence when considering the increased range of rotations experienced at elevated-temperatures.

The experimentally recorded connection characteristics may be seen to fall into the categorisation of semi-rigid at ambient-temperatures in terms of both stiffness and capacity. The stiffness of the connection at ambient-temperatures was recorded as approximately

8.5×10^9 Nmm/radian compared with a value of 11.5×10^9 Nmm/radian necessitated for classification as rigid according to EC3. Capacity of the connection may be seen to more closely follow the classification as pinned at low levels of moment, although for a rotation of 100 millirads, experimental connection characteristics become significant, relating to a value of approximately $0.5\bar{m}$.

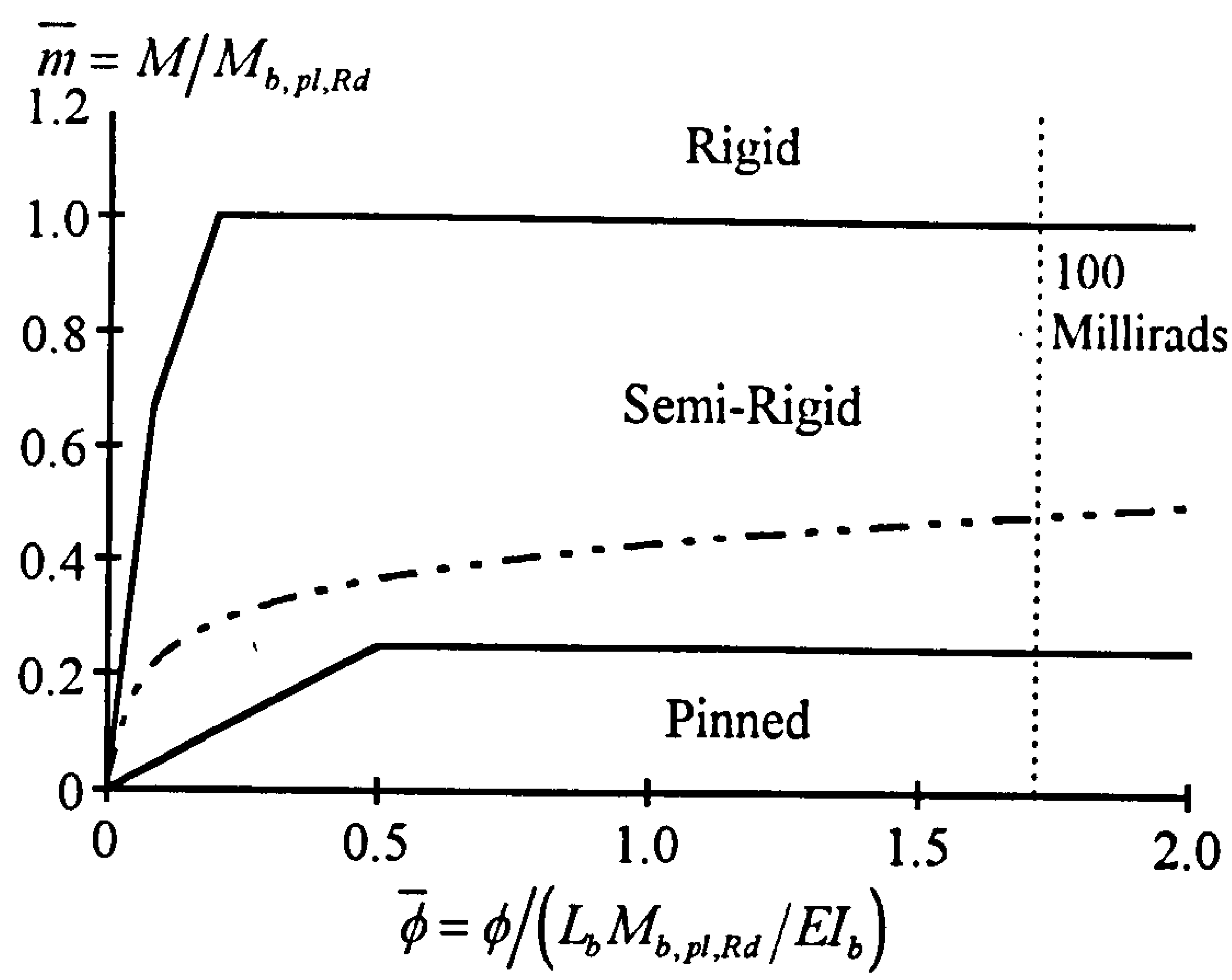


Fig. 6.16. Classification of Connections According to EC3[165]

To facilitate an understanding of the influence of connection capacity and stiffness in a non-dimensionalized form, the bare-steel arrangement described above has been analysed incorporating rigid connection characteristics according to the classification system proposed in EC3. Connection stiffness and capacity have been defined in a bi-linear form at ambient-temperature according to Eqs. 6.7 and 6.9, and analysis repeated for incrementally reducing values of capacity and stiffness. A connection temperature 70% of the beam lower flange temperature has once more been adopted, and capacity and stiffness of the bi-linear curve reduced for increasing temperatures based on the rates of degradation of connection capacity and stiffness observed from experimentation of the flush end-plate connection detailed in Chapter 3. The resultant influence on failure-temperatures is shown in Fig. 6.17*(a)*.

It may be seen that, for the arrangement of a 254x102x22UB(43) framing into the flanges of a 152x23UC(43), increased levels of connection stiffness has little influence on the resultant failure-temperature. This corresponds with the conclusions drawn from studies varying the initial-stiffness of the elevated-temperature moment-rotation curves obtained experimentally, as shown in Fig. 6.12. An almost linear increase in failure-temperature was observed for increasing capacity up to a maximum value corresponding with the plastic moment-capacity of the bare-steel beam. The recorded capacity of the flush end-plate connection tested, being $0.5\bar{m}$ at 100 millirads, would suggest a failure-temperature of approximately 700°C according to Fig. 6.17*(a)*. This corresponds with the failure-temperature obtained incorporating the true elevated-temperature moment-rotation characteristics.

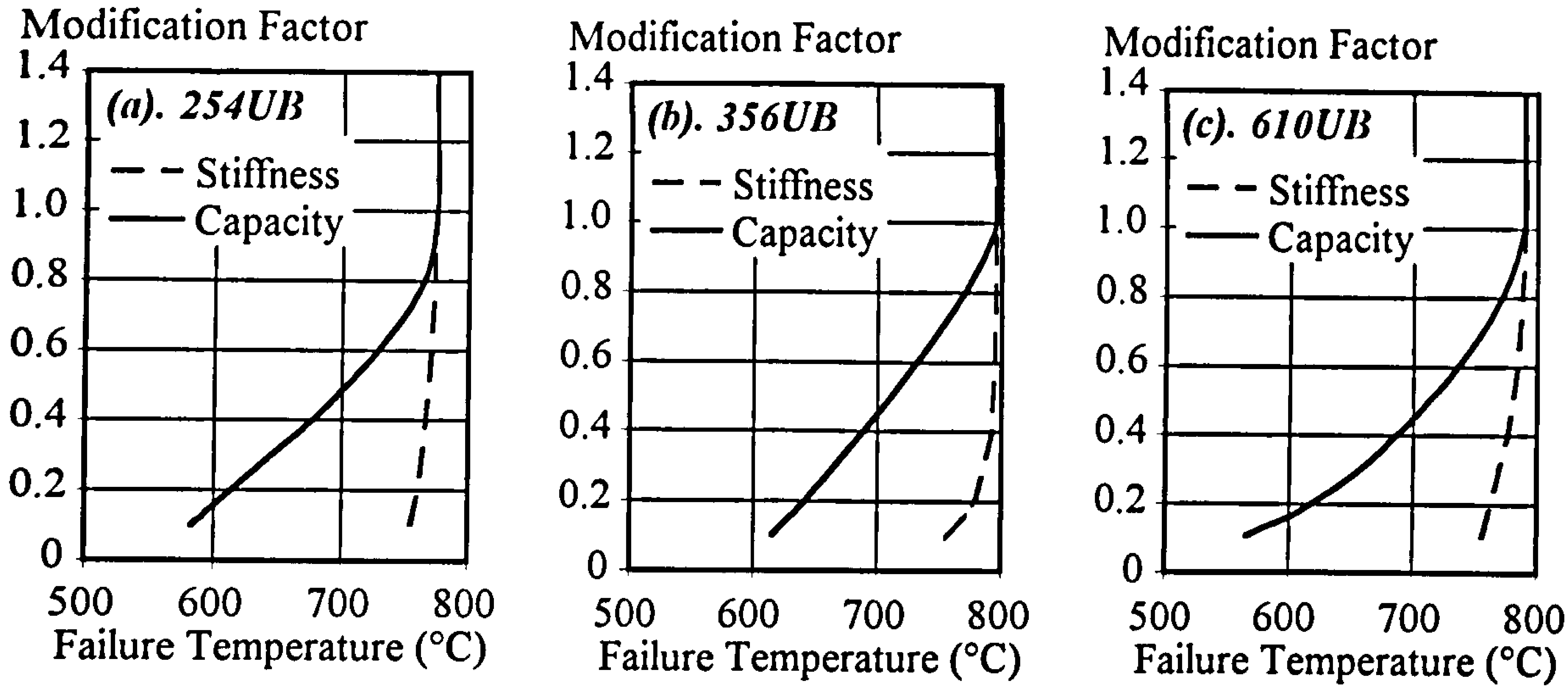


Figure 6.17. Influence of Connection Stiffness and Capacity Considered in a Non-Dimensionalized Form According to the Classification System of EC3[165]

The analysis was repeated considering the influence of semi-rigid connection characteristics for alternative arrangements of beam and column sections, assuming the rates of degradation of connection capacity and stiffness adopted above. A 356x171x51UB(43) spanning 6000mm between the flanges of a 254x89UC(43) was analysed for a load-ratio of 0.6, based on the sub-frame configuration shown in Fig. 6.4 and a storey height of 4185mm, results from which are shown in Fig. 6.17*(b)*. Similarly, a 610x229x101UB(43) spanning 9000mm between the flanges of a 305x137UC(43) was analysed for a load-ratio of 0.6 as shown in Fig. 6.17*(c)*. Section sizes and spans were selected to correspond with those adopted in the Cardington test frame[123], as discussed further in Chapter 7. The assumption of a constant rate of degradation for increasing connection sizes is an approximate one, and further testing is necessitated to define accurately the influence of connection size on the rate of degradation. However, assuming connections to be of a similar form to the flush end-plate tested, the proposed rate of degradation would be anticipated to be similar for alternative arrangements.

It may be seen from Figs. 6.17 that a similar form of response is observed irrespective of the arrangement of beam and column sections adopted, with stiffness having a negligible influence on resultant failure-temperature, and capacity directly controlling the predicted failure-temperature between the ranges of pinned and rigid characteristics. In all cases a significant enhancement in fire resistance is achieved through the incorporation of rigid connection characteristics, with the resultant failure-temperature typically being in the region of 200°C higher than that assuming pinned characteristics. For a connection which demonstrates a capacity 50% of the moment capacity of the beam, for rotations approaching 100 millirads, this suggests an enhancement of approximately 100°C in the failure-temperature. Such an increase in failure-temperature may in many instances be influential in increasing the fire resistance period of an unprotected bare-steel arrangement to 30 minutes.

The classification of composite connection characteristics with increasing temperatures has not been considered at present due to the uncertainties surrounding the rate of degradation of stiffness and capacity for alternative arrangements. The concept of connection classification has not been incorporated within Eurocodes at present for composite connections due to the increased complexity of response.

6.10. CONCLUSIONS

The influence of semi-rigid connection characteristics on elevated-temperature frame response has been investigated using a finite-element program developed by Bailey[22]. The program adopted was chosen due to the ability to incorporate semi-rigid connection characteristics within three-dimensional frame analysis at elevated-temperatures, having been extensively validated against test data. Initial studies were conducted investigating the ability with which sub-frame extent may be minimised through the incorporation of spring-stiffness elements representing the stiffness of the external structure. It was concluded that whilst the use of spring elements generated results similar to those obtained from the analysis of sub-frame arrangements, the accurate representation of an equivalent stiffness is complicated by variations in column temperature and the non-linear form of column response. As such an outer-beam form of sub-frame was adopted in subsequent analysis, having been demonstrated to more accurately represent the restraint provided by the structure as a whole. A load-ratio of 0.6 was adopted for beams and 0.4 for columns, having previously been suggested as being representative of the level of loading which may realistically exist under fire conditions.

Initial studies incorporating semi-rigid connection characteristics within both bare steel and composite sub-frame analysis with the assumptions of pinned and rigid connection response indicated that a significant enhancement in failure-temperature may be achieved through the incorporation of the fully non-linear connection characteristics. In the case of the bare-steel sub-frame analysed the resultant increase in failure-temperature was observed to be of the order of 100°C, falling approximately mid-way between the response observed from pinned and rigid connection characteristics. For the composite arrangement analysed the increase in failure-temperature was seen to be slightly less significant (approximately 50°C), presumably due to the capacity of the composite beam in compression reducing at a significantly slower rate.

It was demonstrated that failure-temperature was highly sensitive to the connection temperature adopted. In the tests described in Chapter 3 it may be seen that an almost linear temperature profile was observed across the depth of the connection. This is contrary to the temperature distributions recorded by Lawson[44] in which a more representative heating regime was adopted, suggesting a connection temperature approximately 70% of the beam lower flange temperature. As such it is suggested that further testing is required to allow an accurate assessment of connection temperatures subject to a realistic heating curve. The sensitivity of frame response to temperature is beneficial where it may be demonstrated that the connection remains at a significantly lower temperature than the connected beam.

It has been suggested that the fire protection of columns is necessary to ensure the maintenance of structural integrity, with the encasement of columns also often desirable for architectural reasons. Initial tests on the Cardington frame investigating the influence of curtailing column fire protection at the underside of a false ceiling using a boarded system, resulted in failure in the unprotected region. As such it may be advantageous to extend column protection to the full storey height, resulting in a reduction in connection temperature; although this may present some complexities with regard to detailing due the levels of rotation experienced.

As described in Chapter 4, a number of equations exist capable of representing the fully non-linear connection response in a form suitable for incorporation within numerical analysis. The requirements of curve-fitting at elevated-temperatures differ from those associated with ambient-temperature analysis due to the levels of rotation permissible. It was observed that the incorporation of linear-elastic connection characteristics corresponding to the initial secant-stiffness result in a response more appropriate to rigid connections, due to the over-estimate of connection capacity. However, the use of a bi-linear form of curve-fit generated results which were comparable with those obtained using a full non-linear form of curve-fit expressed using the Ramberg-Osgood equation. This highlights the insensitive nature of frame-response to the accuracy with which moment-rotation characteristics are defined due to the levels of rotation experienced. It was demonstrated that rotations significantly greater than 100 millirads may be anticipated. Due to the levels of rotation permissible it is suggested that a limiting capacity should be applied to all forms of curve-fit for levels of rotation greater than those considered in the application of the expression as the adoption of a constant plastic-stiffness may result in a significant overestimate of moment capacity.

The use of the Ramberg-Osgood expression to define moment-rotation characteristics facilitated the scaling of connection stiffness and capacity, whilst still maintaining a curve of comparable shape. It was observed for both the bare-steel and composite arrangements analysed that whilst the resultant failure-temperature was highly sensitive to the assumed capacity of the connection (an almost linear relationship), any further increases in stiffness did not significantly affect the observed calculated failure-temperature. Further studies conducted based on the concept of connection classification for alternative bare-steel arrangements supported the form of behaviour observed. This indicated that a level of stiffness 10% of that adopted for the classification as rigid within EC3 resulted in a form of response comparable with that assuming a connection of stiffness equal to the connected beam. Once more an almost linear relationship was observed relating connection capacity to failure-temperature between the limits of a pinned (no moment capacity) and rigid (capacity equivalent to that of the connected beam) connection characteristics. It was suggested that when assessing the capacity of the connection relative to that of the connected beam, the ultimate plastic capacity should be adopted rather than the elastic capacity.

As described in Chapter 4, the use of connection models is desirable due to the broad range of arrangements which exist and the expense of testing. The influence of the use of a number of forms of connection model of varying complexities has been considered in comparison with the use of experimental results.

One of the simplest forms of elevated-temperature connection model is the degradation of existing ambient-temperature connection characteristics. Based on the recommendations of Chapter 3 connection characteristics were incorporated within the analysis based on degraded ambient-temperature results for the bare-steel and composite arrangements tested. The incorporation of degraded bare-steel characteristics resulted in a form of response comparable with that assuming true connection response, as may be anticipated due to the accuracy with which degradation may be predicted. More surprisingly, the form of response observed incorporating degraded composite characteristics also closely followed the true behaviour despite significant inaccuracies in the rate of degradation of connection stiffness and capacity based on the studies presented in Chapter 3. This suggests that an acceptable analysis of frame response may be achieved based on the use of approximate rates of degradation. An alternative simplified method of connection modelling is the extrapolation of connection characteristics for alternative geometric arrangements from existing test data for a connection of similar form. Based on recommendations presented by El-Rimawi[163] the response of the bare-steel arrangement tested was predicted based on a series of tests by Lawson[44]. The incorporation of these results within the analysis resulted in a form of response closely following that assuming true connection characteristics, although further validation would be necessary to establish the suitability of this form of model for different arrangements.

The use of the bare-steel spring-stiffness model presented in Chapter 4 resulted in a form of response which was comparable to that obtained incorporating experiment results, whilst the use of the composite connection model failed to accurately predict the true behaviour. This was observed to be as a result of the composite spring-stiffness model predicting failure of reinforcement at low levels of rotation, a form of failure not observed from experimentation. This highlights the need to consider further the deformation of composite connections in the compression zone, and the de-bonding of reinforcement acting in tension. The findings of these initial studies also suggest that it is not necessary to make an accurate assessment of initial connection stiffness within connection modelling. The incorporation of bare-steel connection results predicted by Liu[116] would result in a form of response indiscernible from that obtained incorporating experimentally derived connection characteristics, although it has been demonstrated that an acceptable representation of frame response may be achieved through the use of simplified methods of connection modelling.

7. CARDINGTON TEST FRAME STUDIES

7.1. INTRODUCTION

The influence of realistic connection characteristics on frame response has been considered within Chapter 6. Both bare-steel and composite elevated-temperature connection characteristics obtained from experimentation have been incorporated within isolated sub-frame analysis, and parameters including connection temperature, stiffness and capacity varied, providing information of the sensitivity of frame response to aspects of connection behaviour. The findings of Chapter 6 are limited in that they are restricted to a single beam-to-column arrangement (although the sensitivity of bare-steel arrangements to non-dimensionalized connection stiffness and capacity is considered in Section 6.6). As such it is desirable to extend the scope of studies to include a 'typical structure'.

A series of elevated-temperature frame tests has recently been undertaken by the Building Research Establishment and British Steel at the Cardington Large Building Test Facility (LBTF)[12] on a structure designed to be representative of current practice. Connections have been designed as 'simple', although it may be appreciated that in reality these will act as 'semi-rigid'. As such the 8 storey composite steel structure erected presents an ideal structure for analysis, and presents the additional advantage that experimental results will become available in due course.

The validity of the analysis is limited by the fact that fully non-linear elevated-temperature connection characteristics have only been established for the 254x102x22UB(43) to 152x23UC(43) arrangement described in Chapter 3. However, ambient-temperature tests have been conducted for typical connections contained within the Cardington test-frame by Boreman[47],and based on the findings of studies to date a reasonable approximation of the degradation of connection characteristics should be possible.

7.2. THE CARDINGTON LBTF TEST FACILITY

Large Building Test facility (LBTF) was developed by the Building Research Establishment during 1992 to extend research facilities available within Europe to include the provision of resources for full-scale structural and fire testing[13]. This resource allows the construction of full-sized buildings up to ten storeys high on a foundation 70m by 50m within a weatherproof envelope, being located within an existing airship hanger. Other structures such as bridges, towers, pylons and significant sections of offshore oil rigs can also be accommodated.

The first structure erected on the strong floor was an eight-storey steel-framed building designed by Peter Brett and Associates and constructed by Caunton Engineering Limited early in 1993[12]. It was required that the steel framed structure should resemble a typical office building, modelling a city centre infill development of eight storeys with roof-mounted services. Floor slabs are 45 x 21m, providing a gross square footage of 91,000ft^2. A braced frame with composite 'simply-supported' beams was selected as typical of buildings of this form. The frame was designed in accordance with BS 5950[161] with

Eurocode[58,165] checks being carried out where applicable. Levels of imposed loadings have recently been the subject of debate. Loads adopted in the design were 2.5 + 1.0kN/m^2 on all floors except at roof plant level, which was 7.5kN/m^2.

The fabricator was given the choice to adopt any of the three simple connection types detailed in the SCI/BCSA publication: *Design Methods for Joints in Simple Construction, Volumes 1*[63] *and 2*[168]. An arrangement of flexible end-plate for beam-to-column connections and fin-plate connections for beam-to-beam connections was adopted.

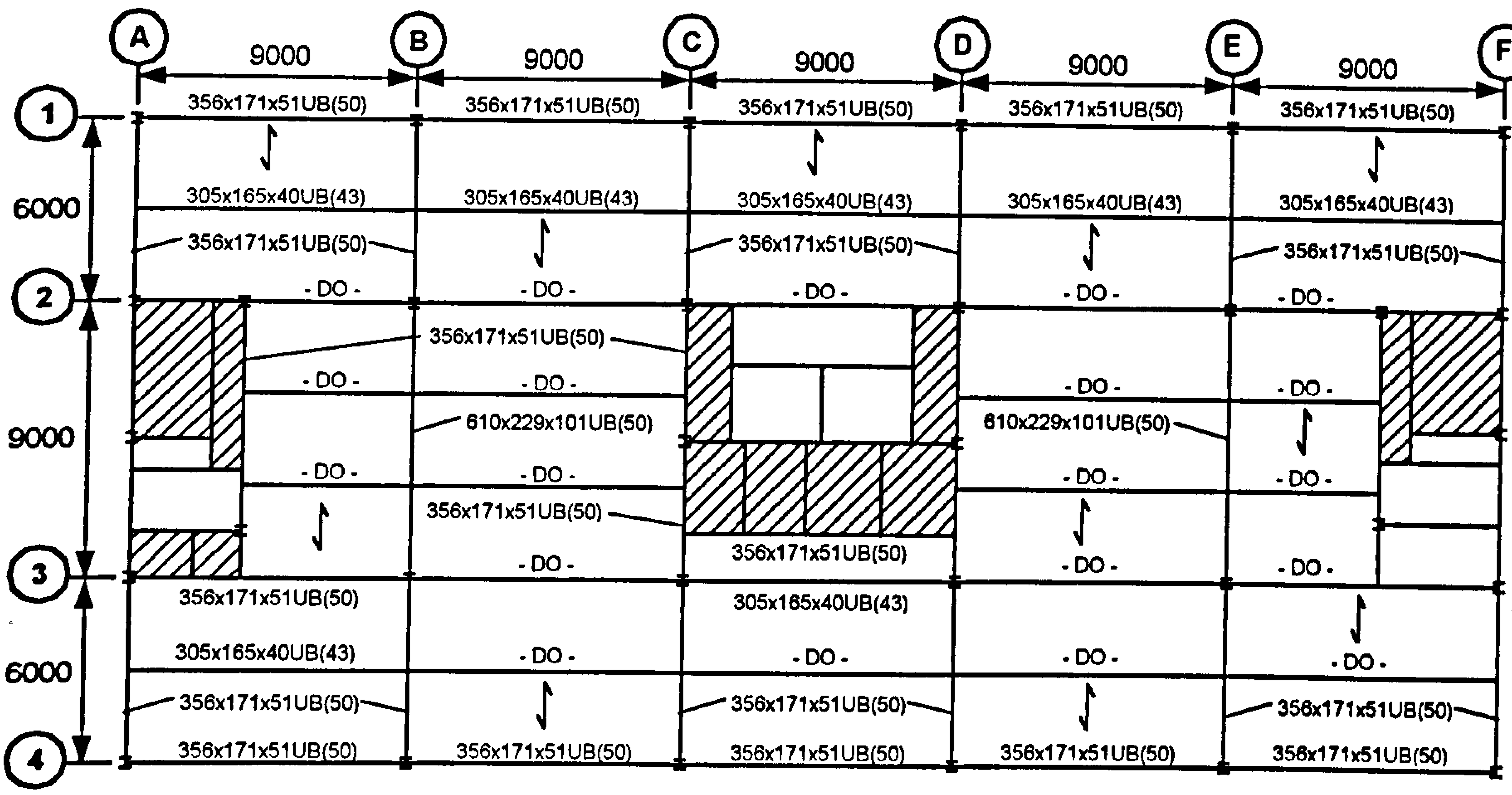
A total of 8 fire tests have been conducted by the Building Research Establishment and British Steel on the composite frame to date as summarised:

1. Column tests[69,70] were conducted using portable barrel-furnaces (which form part of the furnace arrangement used for testing connections as detailed in Chapter3) capable of being wrapped around columns. Initial testing was restricted to low temperatures (below 500°C). Further tests are scheduled upon completion of the Cardington test program, testing columns to failure.
2. A restrained beam test was conducted on the 7th floor using a gas fired furnace to heat the beam over a length of 8m.
3. A two-dimensional cross-frame test was conducted using a gas-fired furnace located between the third and fourth floors, with columns and beams being heated across the entire width of the building.
4. A corner test was conducted using a gas-fired furnace within a corner bay between the third and fourth floors.
5. A corner test was conducted being fuelled by wooden cribs within a corner bay between the second and third floors.
6. A demonstration tests was conducted, with standard office furniture being placed within an area occupying a corner section of the building for one storey height, and starting a fire from an ignition point. The development of the fire along with steel temperatures was monitored.
7. A large scale test located at one end of the structure, and occupying approximately 400m^2 of floor area, for one storey height. The tests was fuelled by wooden cribs.

Tests 3 and 7 have been selected for further studies investigating the influence of semi-rigid connection characteristics on frame response. The structural arrangement for both Tests 3 and 7 was comparable. The general arrangement of structural steelwork (including dimensions of elements) is shown in Fig. 7.1.

Test 3 was restricted to a gas-fired compartment approximately 2.0m wide running along grid-line B, representing an essentially two-dimensional plane-frame test. As such this test has been adopted for initial two-dimensional bare-steel and composite analysis. All beams running along grid-line B are connected to the major-axis of columns with flexible end-plate connections.

Analysis assuming two-dimensional response neglects the potentially significant influence of membrane action within the composite slab. Whilst this may be expected to enhance the fire-resistance of a given structure, it may also diminish the relative influence of the incorporation of semi-rigid connection characteristics. Test 7 has been selected for analysis into the three-dimensional response of the structure. Test 7 extended the heated area of Test 3 to include the full width of the structure between grid-lines A and C, and was heated using wooden cribs. This provides a test area which is comparable with the plane-frame analysis of Test 3, and incorporates an extensive floor area from which to study the influence of membrane action.



NOTES: Columns A1, A4, F1 and F4 254x89UC(50)
All other columns 305x137UC(50)
PMF CF70 (0.9mm) decking to be used with 1 layer A142 mesh - top face
130mm thich slab - Grade 35 lightweight aggregate

Figure 7.1. General Arrangement of the Cardington Test Frame (Tests 3 and 7)

7.3. AMBIENT-TEMPERATURE CONNECTION TESTS

The validity of studies into the influence of semi-rigid connection characteristics on the Cardington test frame at elevated-temperatures is limited by the fact that elevated-temperature characteristics have not yet been developed. However, a number of tests have recently been conducted by Boreman[47] to develop ambient-temperature characteristics for typical connections within the Cardington test frame (as bare-steel).

Based on the recorded ambient-temperature moment-rotation response, and a knowledge of the rate of degradation of both bare-steel and composite connection characteristics from the studies of Chapter 3, it is anticipated that an acceptable representation of elevated-temperature connection response may be obtained. This is supported by the findings of Chapter 6 in which it was indicated that overall structural response is not highly sensitive to the rate of degradation adopted.

A total of 9 bare-steel tests were conducted by Boreman[47] on both major and minor-axis connections as detailed in Table 7.1. The arrangement of connections tested and recorded moment-rotation response is included in Appendix D. Connection arrangements tested were chosen to be representative of all standard connection types contained within the test frame below 4th floor, with columns reducing to 254x89UC(50) above 4th floor.

Test:	*Connection Type:*	*Arrangement & Orientation:*	*Connected Beam(s):*	*Column / Beam:*
CANT1	Flexible End-plate	Minor-axis Cantilever	356x171x51UB(50)	254x89UC(50)
CANT2	Flexible End-plate	Major-axis Cantilever	356x171x51UB(50)	254x89UC(50)
CANT3	Flexible End-plate	Major-axis Cantilever	356x171x51UB(50)	305x137UC(50)
CANT4	Flexible End-plate	Major-axis Cantilever	610x229x101UB(43)	305x137UC(50)
CRUC1	Flexible End-plate	Minor-axis Cruciform	356x171x51UB(50)	254x89UC(50)
CRUC2	Flexible End-plate	Minor-axis Cruciform	305x165x40UB(43)	305x137UC(50)
CRUC3	Flexible End-plate	Minor-axis Cruciform	305x165x40UB(43) 356x171x51UB(50)	305x137UC(50)
CRUCB4	Fin-plate	Beam-to-Beam Cruciform	305x165x40UB(43)	356x171x51 UB(50)
CRUCB5	Fin-plate	Beam-to-Beam Cruciform	305x165x40UB(43)	610x229x101 UB(43)

Table 7.1. Ambient-Temperature Cardington Connection Tests

Connections contained within the Cardington test were designed assuming pinned response, with the fabricator being given the choice to adopt any of the three simple connection types detailed in the SCI/BCSA publication: *Design Methods for Joints in Simple Construction, Volumes 1*[63] *and 2*[168]. An arrangement of flexible end-plate for beam-to-column connections and fin-plate connections for beam-to-beam connections was adopted.

Tests CANT1 to CANT4 and CRUC1 to CRUC3 (Figs. D.1 to D.7) considered the response of both major and minor-axis flexible end-plate connections. A combination of cruciform and cantilever test arrangements was adopted, corresponding with the relevant location of connections within the structure. The typical test arrangement for both cantilever (CANT3) and cruciform (CRUC2) ambient-temperature tests is shown in Figs. 7.2 and 7.3 respectively.

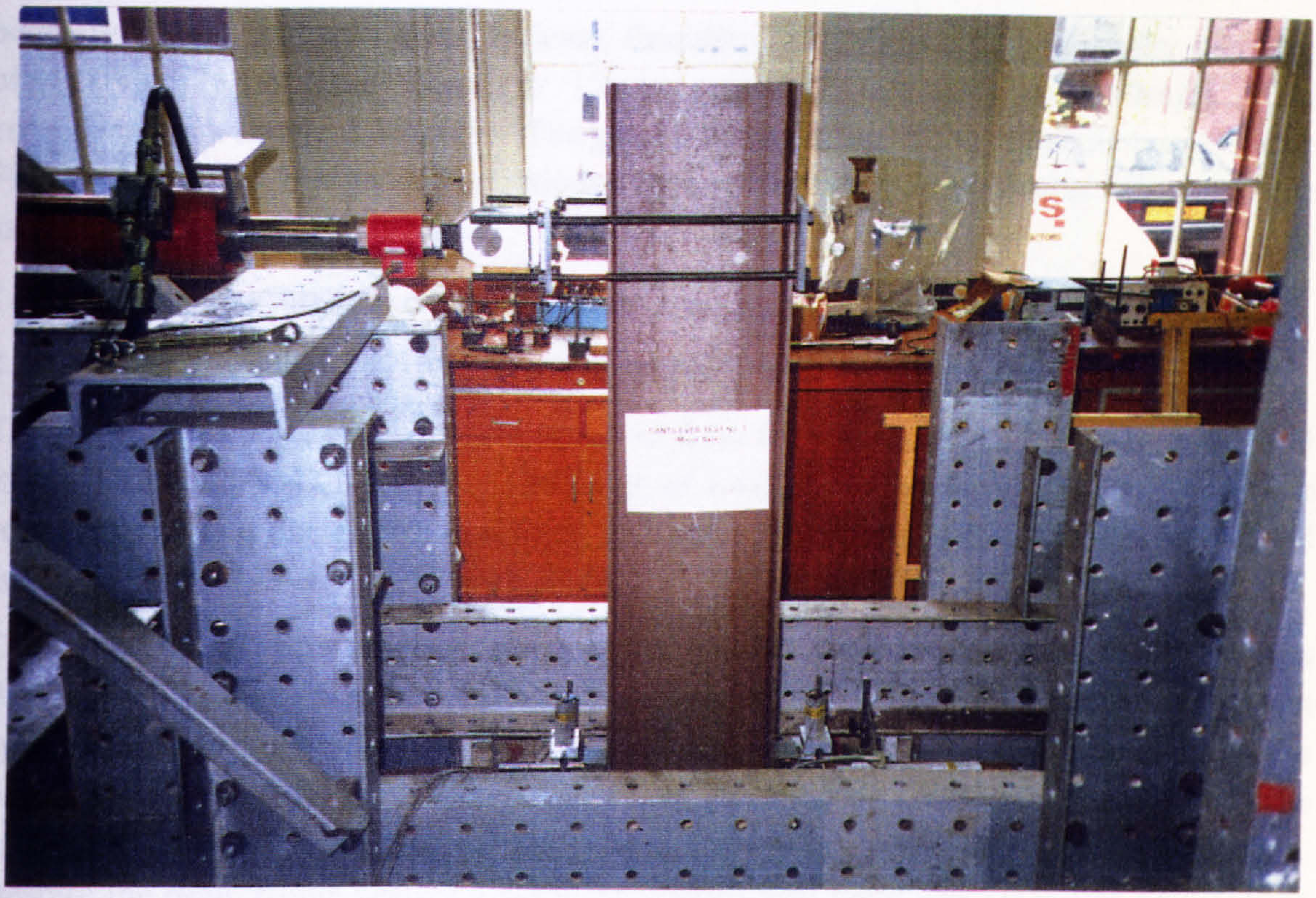


Figure 7.2. Ambient-Temperature Cantilever Beam-to-Column Test Arrangement

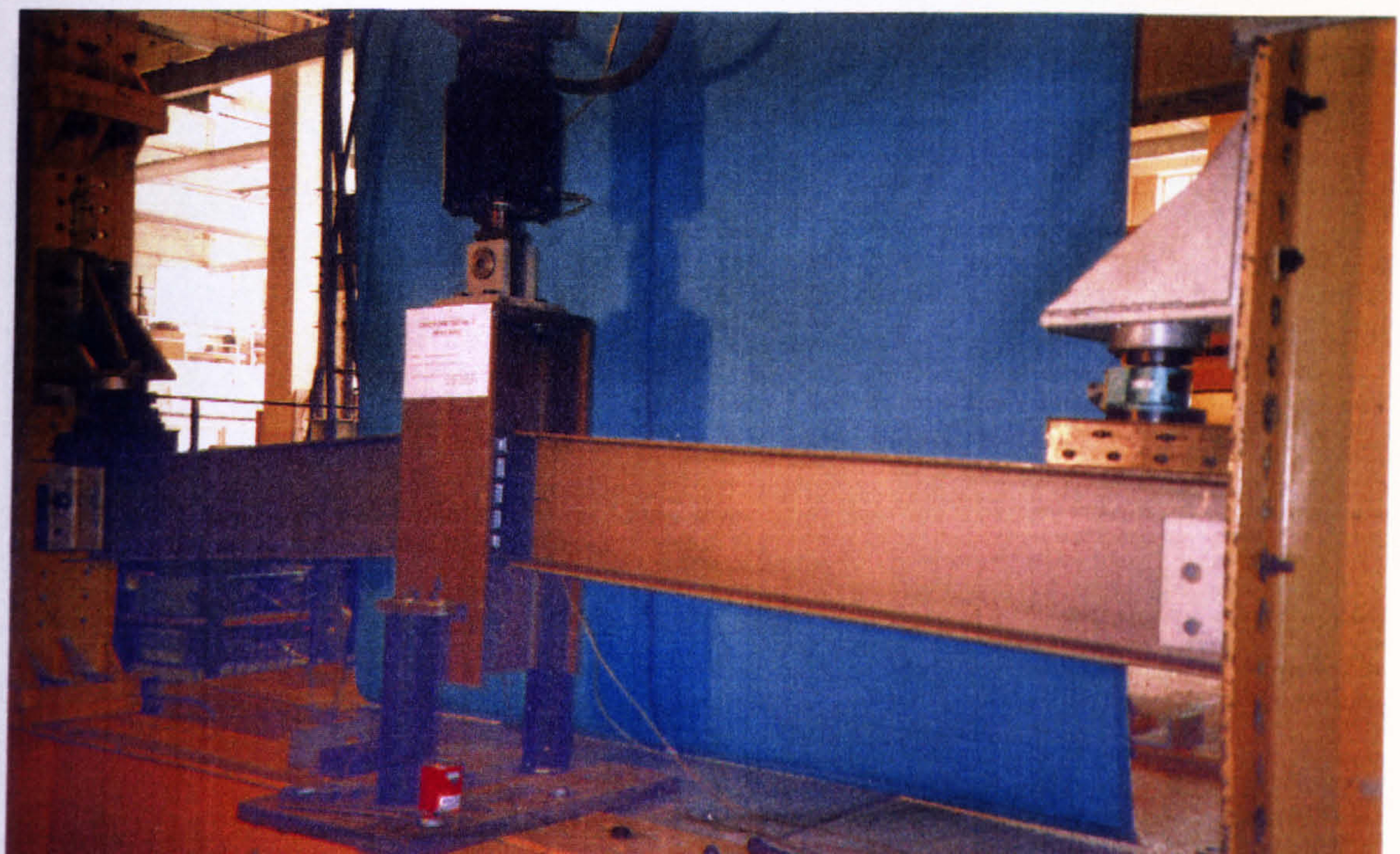


Figure 7.3. Ambient-Temperature Cruciform Beam-to-Column Test Arrangement

Partial-depth flexible end-plate connections consist of a single plate fillet welded to the end of the beam and is site bolted to the supporting member. The end-plate is welded to the beam web only, and thus gains sufficient flexibility from the use of a relatively thin end-plate (typically no more than 8 or 10mm) combined with large gauge length to be considered as a simple connection. The general arrangement of the connection is shown in Figs. D.1 to D.7. The general behaviour of the connection may be idealised in two stages as follow:

1. the unhindered rotation of the connection, until;
2. the lower beam flange bears against the support, resulting in an increase in stiffness.

This form of response may be clearly observed from the results presented for Tests CANT1 to CANT3 in Figs. D.1 to D.3. The range of rotation for subsequent flexible end-plate connection tests is limited to 60 millirads, and hence results are only available for stage 1 of the response.

The observed failure mechanism for a typical flexible end-plate connection (CANT3) is shown in Fig. 7.4. It may be seen that significant deformation of the end-plate occurred in the tension zone, as would be desirable designing the connection as pinned. For the connection shown the lower beam flange was observed to come into bearing with the column flange resulting in a significant enhancement in capacity at high levels of rotation. Despite the beam flange bearing against the column web there was no visible deformation of either the beam or column flange, with increased rotations being accommodated by further deformation of the end-plate in the tension zone.

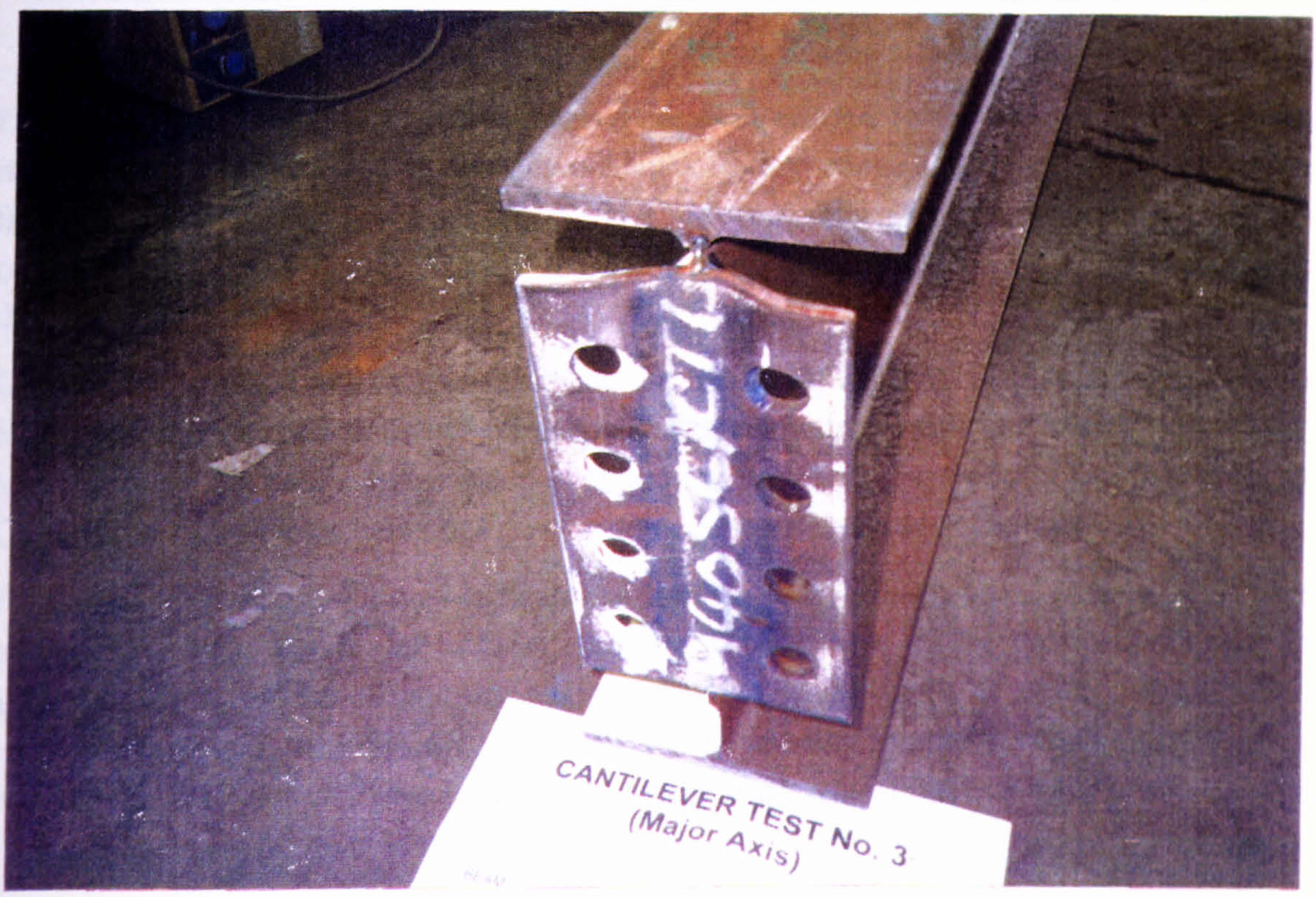


Figure 7.4. Failure Mechanism for Flexible End-Plate Connection (CANT3)

Tests CRUCB4 and CRUCB5 (Figs. D.8 and D.9) considered the response of fin-plate beam-to-beam connections. The typical test arrangement is shown in Fig. 7.5.

Figure 7.5. Ambient-Temperature Cruciform Beam-to-Beam Test Arrangement

Fin-plate connections consist of a single plate fillet welded to the web of the supporting member and is site bolted to the beam. Unlike other connections where the two mated faces are at right angles to each others, fin-plate connections are joined parallel to the line of the beam. This results in only the beam web being available to transmit moments through the fin-plate.

Considerable unease has existed regarding the rotational capacity of fin-plate connections. However, recommendations have been presented[63] to enable sufficient rotational capacity to be derived from bolt deformation in shear and bolt hole distortion in bearing, with the Cardington connections being designed in accordance with these guidelines.

From Figs. D.8 and D.9 it may be seen that the fin-plate beam-to-beam connections tested possessed a very low initial-stiffness, and that the stiffness of the connection remained almost constant for the duration of testing. For increasing levels of rotation the fin-plate connections tested were observed to be capable of resisting moments approaching 40kNm. No failure was observed in terms of rotation capacity within the range of rotations considered (up to 80 millirads).

7.4. BARE-STEEL TWO-DIMENSIONAL ANALYSIS OF FRAME RESPONSE

Initial studies of the influence of connection characteristics on the response of the Cardington test frame will be restricted to the two-dimensional analysis of Test 3 neglecting the influence of the composite slab. Test 3 consisted of heating a strip 2.00m wide running along grid-line B for the entire width of the structure. The position of the test is indicated in Fig. 7.6 below. To reduce the extent of analysis advantage was taken of symmetry of the structure along the assumed grid-line 2.5.

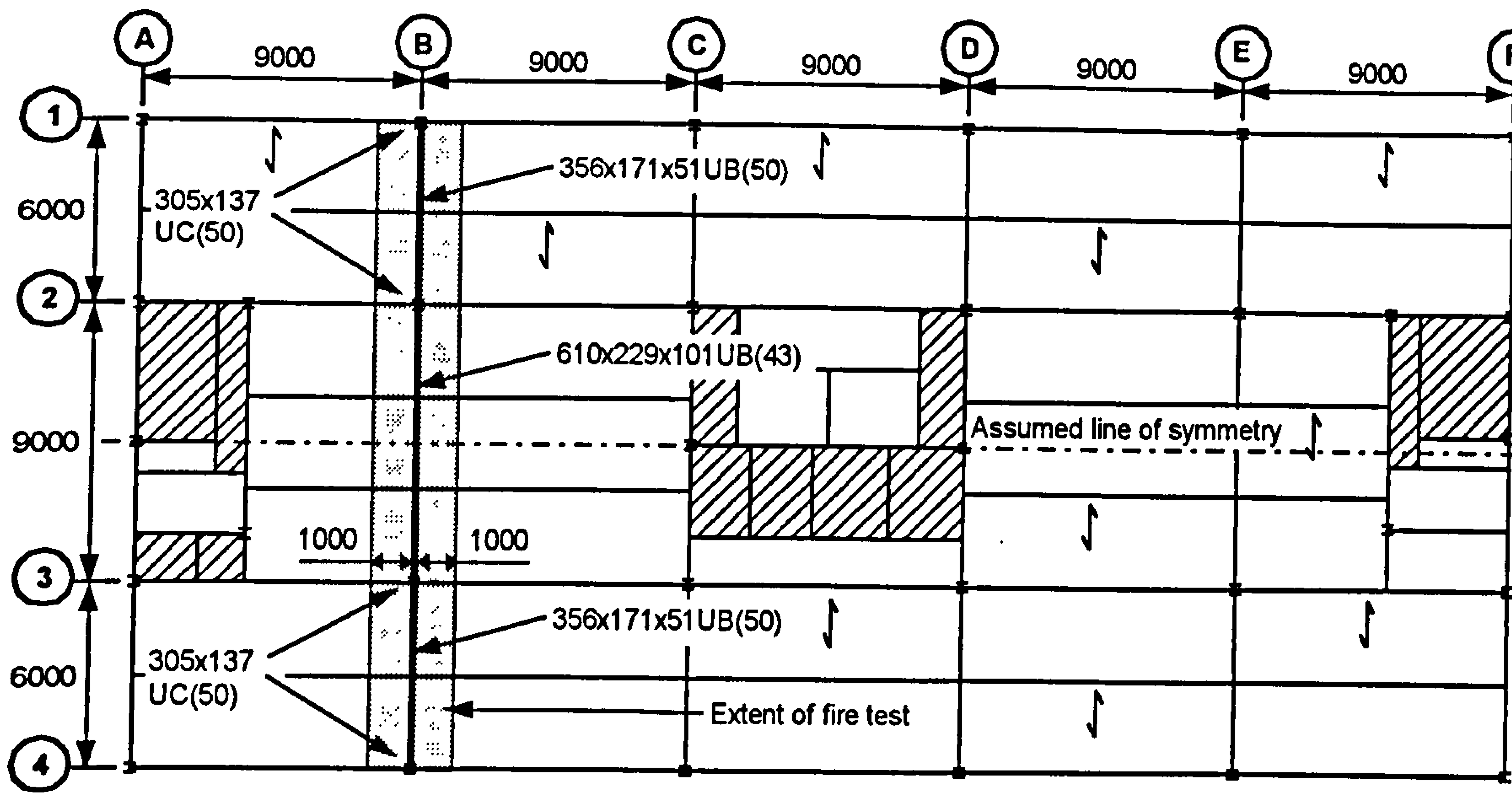


Figure 7.6. Position of Two-Dimensional Cardington Cross-Frame Test (Test 3)

It may be seen that the extent of the furnace encloses the 9000mm internal spanning 610x229x101UB(43) and the 356x171x52UB(50) 6000mm edge spans, with beams framing into the flanges of 305x137UC(50). Connection between beams and columns is by flexible end-plate connections CANT3 (356UB) and CANT4 (610UB), moment-rotation characteristics for which are presented in Figs. D.3 and D.4 of Appendix D.

The furnace was gas fired by a series of burners following the ISO[24] heating regime. Beams were left exposed (composite slab providing insulation of top flange), whilst columns were protected using a system of ceramic fibre. Column protection extended to the underside of an assumed suspended ceiling, approximately 500mm below the level of the lower flange of the 610UB. Connections remained unprotected.

7.4.1. Degradation of Bare-Steel Connection Characteristics

To allow the incorporation of semi-rigid connection characteristics within the analysis it is necessary to consider the expected rate of degradation of both connection stiffness and capacity (although as discussed in Chapter 6, it would be expected that overall frame response would not be very sensitive to inaccuracies in the assumed initial-stiffness).

Connection characteristics have once more been degraded by varying the parameters A and B contained within the modified Ramberg-Osgood expression (Eq. 4.1), where these parameters control initial-stiffness and capacity of the connection respectively. To allow the degradation of connection characteristics it is necessary to firstly consider the application of the Ramberg-Osgood expression to ambient-temperature test data.

Ambient-temperature moment-rotation characteristics for flexible end-plate connections CANT3 and CANT4 are shown in Figs 7.7 and 7.8 below. As discussed in Section 7.3, the response of flexible end-plate connections may be idealised assuming the unhindered rotation of the connection, until the lower beam flange bears against the support, resulting in an increase in stiffness.

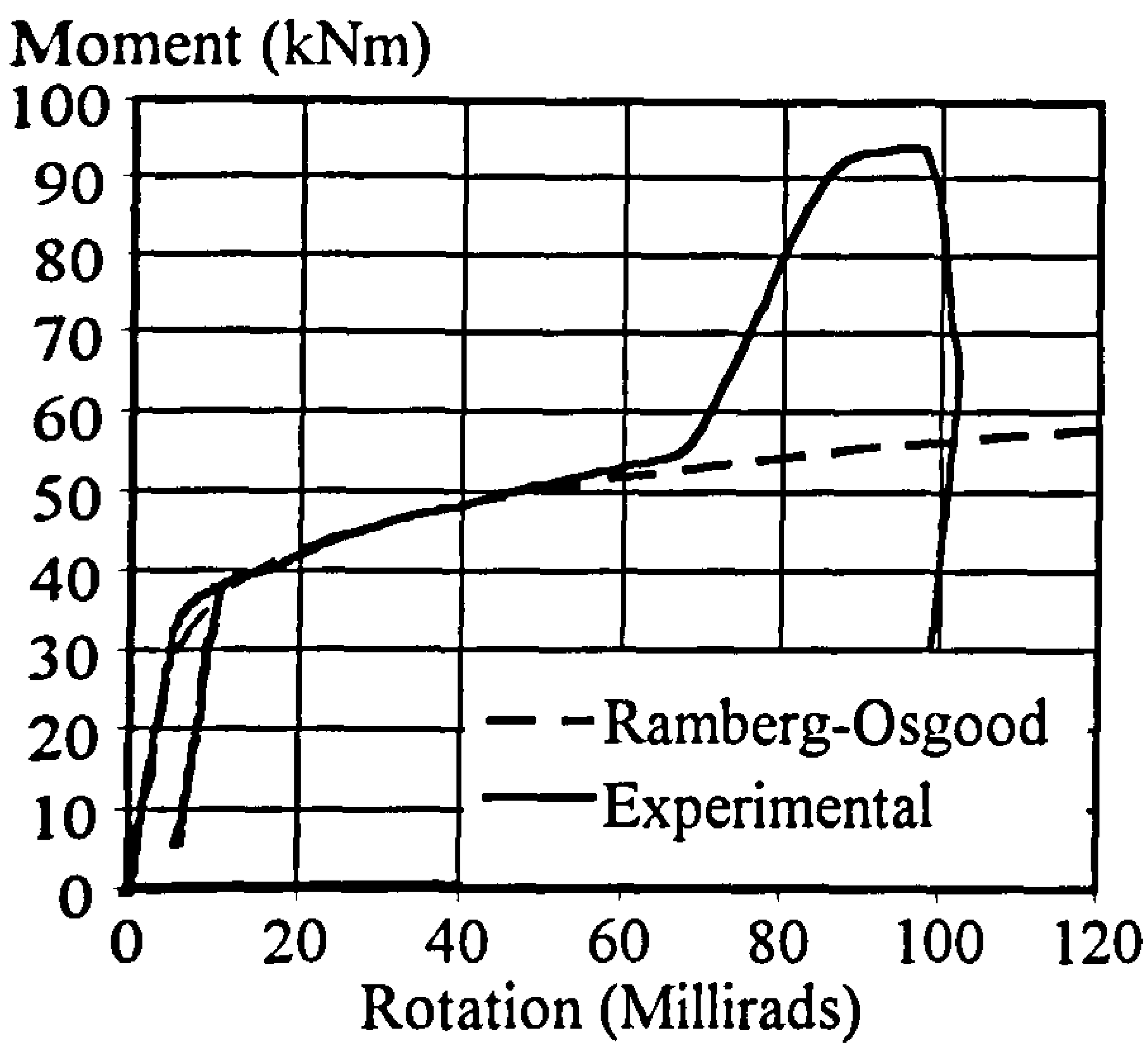


Figure 7.7. Ambient-Temperature Ramberg-Osgood Curve-Fit to Test CANT3

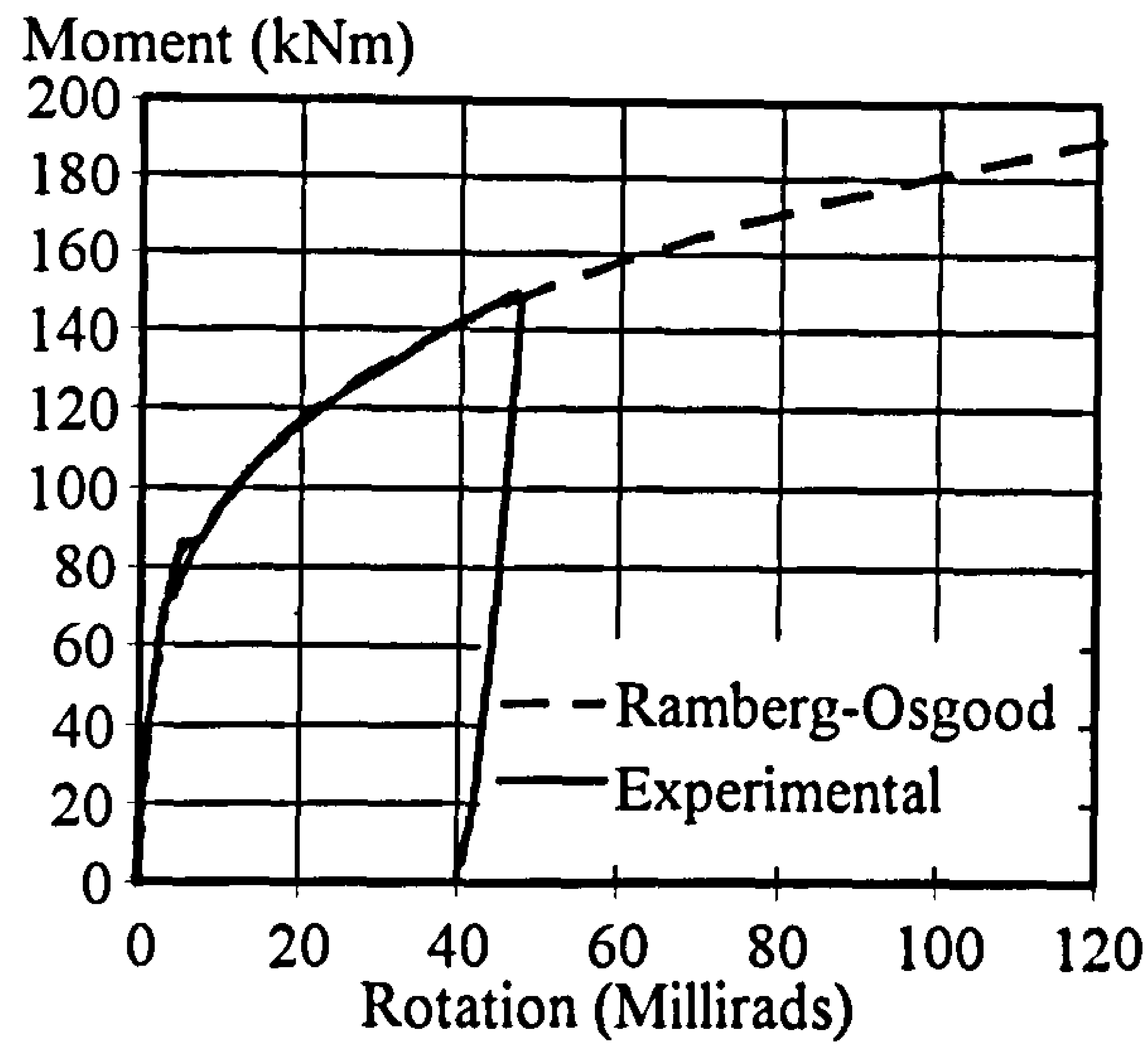


Figure 7.8. Ambient-Temperature Ramberg-Osgood Curve-Fit to Test CANT4

For CANT3 the initial connection stiffness is followed by a plastic plateau representing the free rotation of the connection up to a moment of approximately 55kNm ($M_c \approx 0.16M_p$), at which point the beam lower flange comes into bearing with the column flange ($\phi_c \approx 68$ millirads). For increased levels of rotation the bearing of the beam lower flange results in a significant increase in stiffness until the onset of plastification for a moment approaching 95kNm ($M_c \approx 0.27M_p$). Results for test CANT4 are restricted to a maximum rotation of approximately 50 millirads corresponding with a capacity of approximately 150kNm ($M_c \approx 0.17M_p$), and as such the information presented does not include the subsequent increase in capacity from the bearing of the beam lower flange.

Application of the Ramberg-Osgood expression to moment-rotation characteristics for flexible end-plate connections is complicated by the increase in stiffness as the beam lower flange comes into bearing, with the form of expression described in Eq. 4.1 describing a single curve with reducing stiffness as rotations increase. As such (and as no results are available for stage 2 for Test CANT4) initial connection characteristics have been postulated assuming the form of response for stage 1 in isolation.

Moment-rotation characteristics obtained form the application of the Ramberg-Osgood form of curve-fit are compared with experimental results at ambient-temperatures in Figs. 7.7 and 7.8 for tests CANT3 and CANT4 respectively. The associated terms are tabulated for increases in temperature in Tables 7.2 and 7.3. It may be seen from Fig. 7.7 that the curve defining Test CANT3 closely follows the form of response obtained experimentally, and that for rotations greater than 68 millirads (onset of stage 2) there is little resultant increase in moment. The application of the Ramberg-Osgood curve-fit applied to Test CANT4 closely follows the recorded response within the range that test data is presented (up to 50 millirads). For increased levels of rotation it may be seen that the postulated curve-fit predicts a significant increase in capacity ($M_c \approx 0.20M_p$ for $\phi_c = 100$ millirads), however this is felt to be acceptable as the moment resistance of the connection would be expected to increase significantly with increased rotations.

Temperature	*A*	*B*	*n*
20°C/100°C	*6.900*	*14.700*	*6.800*
200°C	*6.201*	*13.509*	"
300°C	*5.513*	*12.289*	"
400°C	*4.825*	*11.143*	"
500°C	*4.138*	*8.923*	"
600°C	*2.123*	*5.116*	"
700°C	*0.897*	*2.411*	"

Table 7.2. Predicted Elevated-Temperature Characteristics for CANT3

Temperature	*A*	*B*	*n*
20°C/100°C	*55.000*	*17.000*	*3.880*
200°C	*49.463*	*15.742*	"
300°C	*39.927*	*14.416*	"
400°C	*31.068*	*13.175*	"
500°C	*26.085*	*10.506*	"
600°C	*13.719*	*6.069*	"
700°C	*5.968*	*2.873*	"

Table 7.3. Predicted Elevated-Temperature Characteristics for CANT4

Experimentally observed rates of degradation for the bare-steel flush end-plate connection tested were compared with the rates of degradation of material properties (for an appropriate level of strain) in accordance with the recommendations of EC3: Part 1.2[8], as presented in Section 3.4. The temperature of the observed critical element of the connection was adopted in the degradation of material properties. It was observed that for the bare-steel arrangement tested an acceptable approximation of rates of degradation was achieved assuming levels of strain contained within the proportional limit and of 0.5% for the degradation of connection stiffness and capacity respectively. Results are compared in Fig. 3.42.

The ambient-temperature Ramberg-Osgood expressions for tests CANT3 and CANT4 presented have been degraded for increasing temperatures based on the levels of strain suggested, and the rates of degradation presented in EC3: Part 1.2[8]. A uniform temperature distribution was assumed, and the grade of steel for the connection was assumed to correspond to that of the connected beam. This represents a conservative approximation as according to EC3: Part 1.2, Grade 50 steel degrades as a slightly higher rate than Grade 43. All end-plates were Grade 43, but deformation of the column web in the compression zone would contribute to overall connection response. The terms A and B contained within the Ramberg-Osgood expression have been degraded for temperature as shown in Tables 7.2 and 7.3. A uniform shape function n was adopted for all temperatures.

7.4.2. Bare-Steel Plane-Frame Analysis

Test 3 has been modelled as a two-dimensional plane-frame structure incorporating beams and columns along grid-line B, but neglecting the existence of the composite slab. Columns have been assumed to extended from the floor enclosing the fire compartment (rigidly-fixed) to one full storey height above the fire compartment (free to expand), resulting in a sub-frame arrangement comparable with the outer beam sub-frame of Chapter 6 (Fig. 6.4). The structure has been analysed using the program developed by Bailey[22]. The following assumptions have been adopted in the analysis:

1. Material properties incorporated within the analysis are based on those presented in Appendix A for the Cardington test frame ($f_{y,43}$ = 308N/mm^2; $f_{y,50}$ = 389N/mm^2), with an elastic-modulus of 210,000N/mm^2 being assumed.

2. The heating regime adopted within the analysis was comparable with that adopted in the studies of Chapter 6 (Fig. 6.4), with the end-sixth of the beam length remaining at a reduced temperature and columns within the fire compartment remaining at 50% of the beam lower flange temperature. No account has been taken of the exposure of the column heads.

3. A uniform floor load of 5.48kN/m^2 was applied. This results in load ratios of 0.56 and 0.64 for the 610UB and 356UB respectively analysing the structure as bare-steel.

4. Moment-rotation characteristics postulated above have been incorporated as rotational spring elements. A connection temperature 80% of the beam lower flange temperature was adopted corresponding with the temperature of the web of the connected beam.

The analysis has been conducted assuming the actual postulated connection characteristics and ratios of 50%, 200% and 400% of connection characteristics, and compared with the limiting cases of pinned and rigid connection characteristics. Results are presented in Figs. 7.9 and 7.10 below in terms of residual central deflections of the 356UB and 610UB and corresponding rotations for connections CANT3 and CANT4. Rotations presented for the connection CANT3 are those of the internal connection. Similar levels of rotation were experienced for the edge connection.

It may be seen from Fig. 7.9 that the incorporation of semi-rigid connection characteristics within the analysis results in only a slight increase in fire resistance for the 356UB when compared with the assumption of pinned characteristics. This may have been anticipated as the moment capacity of the connection is low relative to that of the connected beam ($M_c \approx 0.16M_p$). For increased ratios of connection capacity an incrementally increasing influence is observed for temperatures up to 700°C. For higher temperatures corresponding deflections converge towards a common point irrespective of the assumed connection characteristics. Whilst results are not available assuming fully rigid characteristics for temperatures greater than 700°C, extrapolation suggests a form of response converging towards that assuming pinned characteristics at higher temperatures.

Results presented in Section 6.6 considered the influence of non-dimensionalized connection characteristics on the resultant failure-temperature for a 6000mm spanning

356UB. Fig. 6.17*(b)* indicates an almost linear relationship between connection capacity and resultant failure-temperature between the limits of pinned and rigid characteristics. The results presented in Fig. 7.9 seem somewhat contrary, with the incorporation of connection characteristics 4 times the actual characteristics ($M_c \approx 0.64M_p$) resulting in an increase in temperature at span/30 of approximately 50°C compared with pinned characteristics. Although results are not available assuming rigid characteristics the resultant increase in temperature for a deflection of span/30 would be anticipated to be approximately 120°C higher than that assuming pinned characteristics. As such the inclusion of characteristics $M_c = 0.64M_p$ results in an increase in response of approximately 40% over pinned characteristics (based on rigid characteristics representing 100%).

It is suggested that the influence of connection characteristics on frame response may be dictated by the convergence of deflections towards a common point, irrespective of the assumed connection characteristcs, at relatively low levels of deflection. The reason for this convergence is unknown, although it is felt that the relative stiffness of the column may be influential as discussed in Section 6.3. This is supported by the fact that for increasing temperatures (greater than 700°C) there is a reduction in the associated rate of deflection. This is typical of the point at which the direction of the horizontal displacement of the column reverses, with the column being pulled inwards with increased deflections. This form of response is shown in Fig. 6.5.

Observed levels of rotation may be seen to be in excess of 120 millirads at a limiting deflection of span/20. This indicates that stage 2 of the response of flexible end-plate characteristics may be influential in the response of steel framed structures at elevated-temperatures, with the beam lower flange coming into contact with the column flange at a rotation of 68 millirads for connection CANT3. The resultant capacity of the connection increases significantly from $M_c \approx 0.16M_p$ to $M_c \approx 0.27M_p$.

CANT4 connecting the 610UB possesses a similar relative capacity to CANT3 ($M_c \approx 0.17M_p$). However, inspection of Fig. 7.10 shows that the incorporation of connection characteristics within the analysis results in a more pronounced enhancement in response than for the 356UB. For a deflection of span/30 semi-rigid characteristics represent a failure-temperature approximately 20°C higher than that assuming pinned characteristics (100°C assuming 4 times actual characteristics).

Whilst deflections for the 610UB do once more tend towards a common point, this is not until far higher levels of deflection than for the 356UB, and as such seems less significant in the assessment of the influence of the inclusion of semi-rigid characteristics within the analysis. However, Fig. 7.10 still clearly indicates the diminishing influence of connection characteristics with increased rotations.

Rotations for the connection CANT4 are once more seen to be greater than 120 millirads. It is anticipated that this would represent a level of rotation within stage 2 of the connection response, but unfortunately ambient-temperature testing did not consider response for rotations greater than 50 millirads.

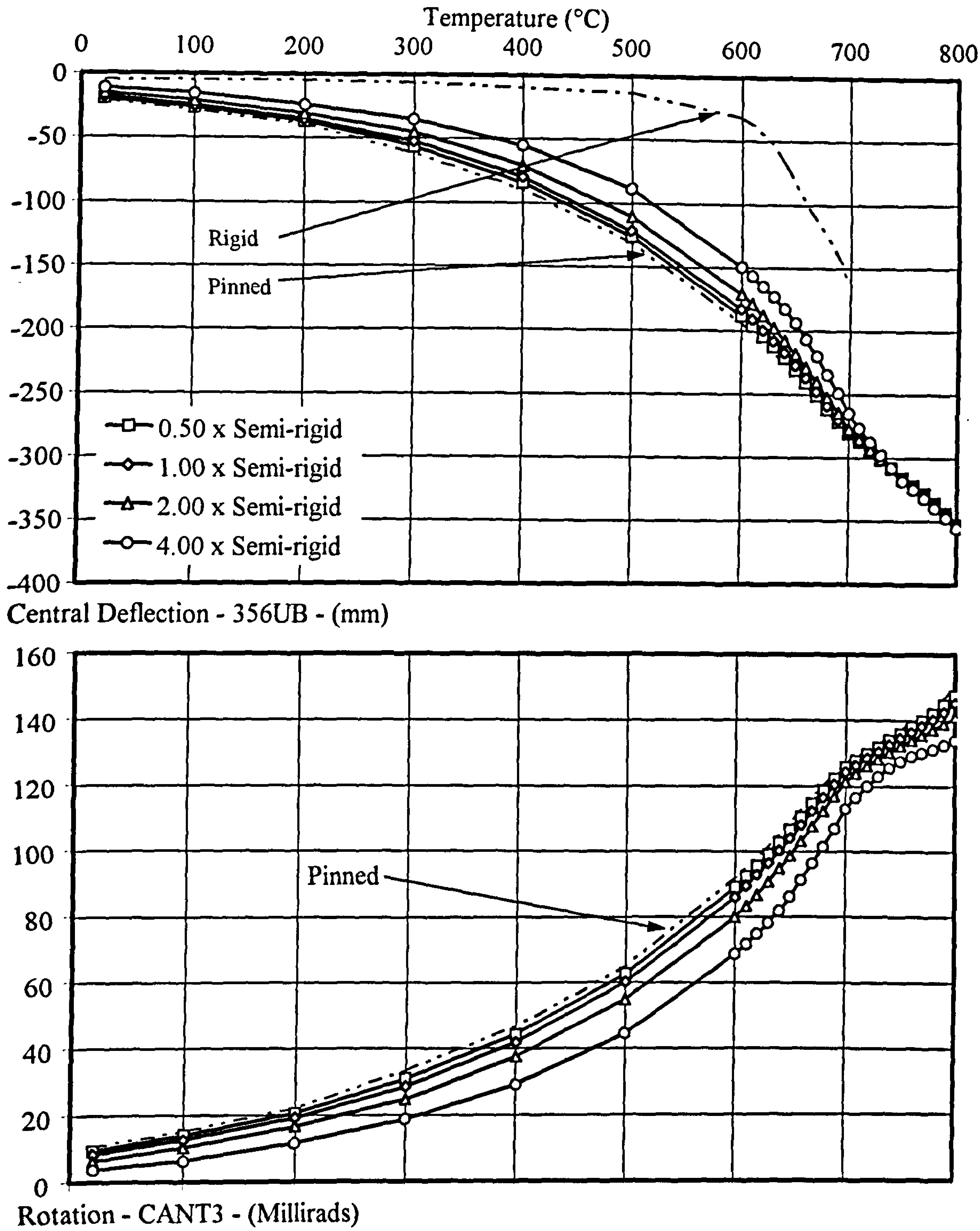


Figure 7.9. Deflections and Corresponding Rotations for 356UB (CANT3)
- Analysis of Cardington Test 3 as 2D Bare-Steel -

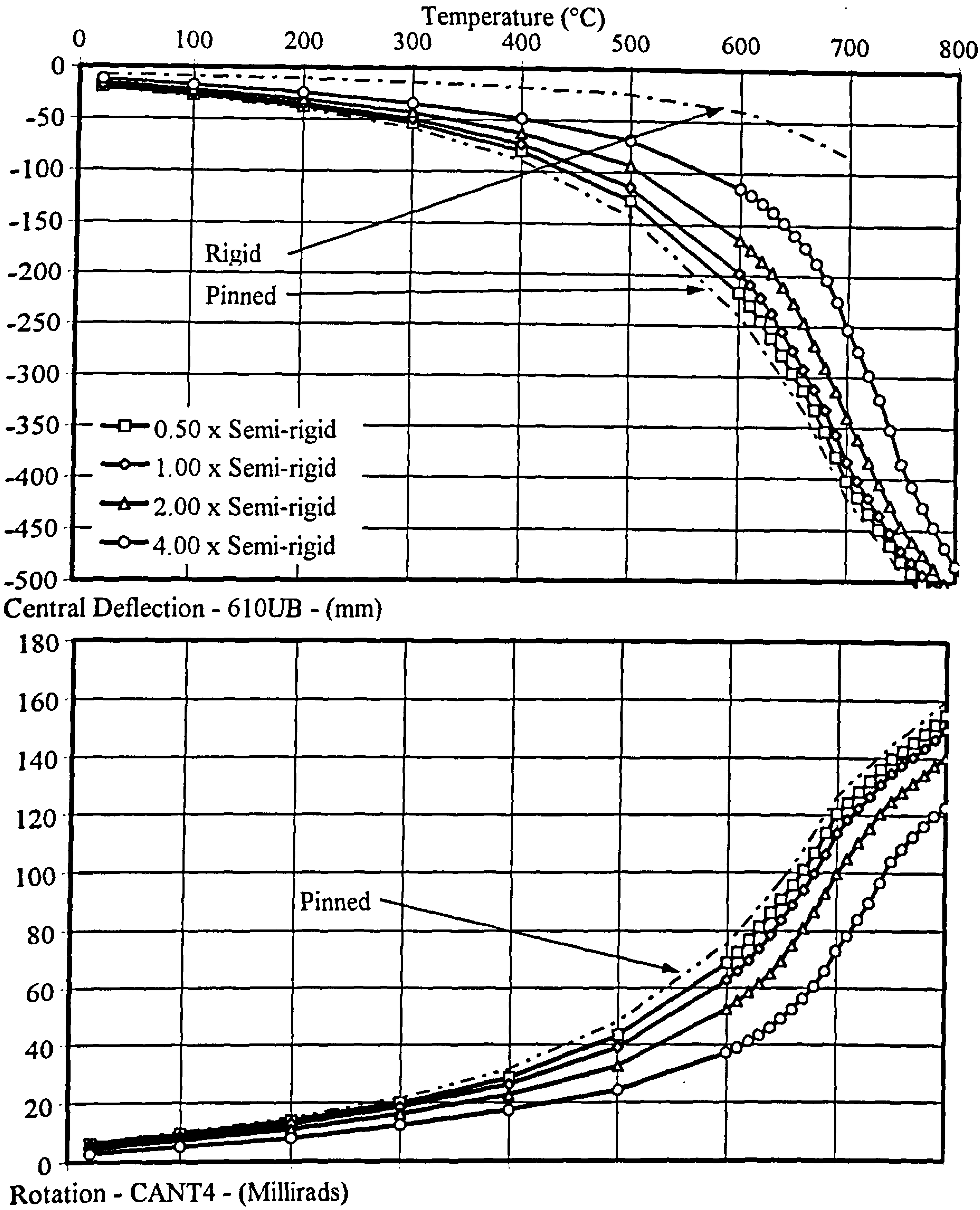


Figure 7.10. Deflections and Corresponding Rotations for 610UB (CANT4)
- Analysis of Cardington Test 3 as 2D Bare-Steel -

7.4.3. Refinement of Flexible End-Plate Characteristics

Rotations experienced at elevated-temperatures are significantly higher that those associated with the ambient-temperature analysis of semi-rigid connections. It can be seen from Figs. 7.9 and 7.10 that rotation experienced incorporating postulated characteristics for the flexible end-plate connections contained within the Cardington test frame were in the region of 90 millirads for a deflection of span/30, increasing to approximately 140 millirads for a limiting deflection of span/20. This indicates that stage 2 of the response of flexible end-plate connections may become influential in the performance of semi-rigid structures at elevated-temperatures.

Consideration of the ambient-temperature moment-rotation response of the connection CANT3 (Fig. 7.7) shows that the beam lower flange came into bearing with the column flange at a rotation of approximately 68 millirads (corresponding with a central deflection of just 150 millimetres - Span/40). This would suggest that a significant enhancement in the influence of the semi-rigid connection characteristics on frame response may be obtained by incorporating stage 2 of the flexible end-plate characteristics within the analysis. This results in an increase in the ultimate moment capacity of the connection at ambient-temperature to approximately 95 kNm ($M_c \approx 0.27M_p$).

As discussed above the Ramberg-Osgood form of expression is only capable of describing a single curve of decreasing stiffness with increasing rotation. To facilitate the incorporation of flexible end-plate characteristics within analysis it is necessary to firstly redefine the Ramberg-Osgood equation to allow for the subsequent increase in stiffness.

This may be achieved by superimposing a second Ramberg-Osgood curve at an artificially introduced origin (ϕ_l, M_l) corresponding with the location at which the beam comes into bearing with the supporting member. For increasing temperatures the location of the origin in terms of rotation would be anticipated to remain similar (slight deviation due to movement of the centre of rotation), and as such for increasing temperatures the value of ϕ_l is assumed constant, with M_l being the moment at which the curve defining stage 1 of the response intercepts ϕ_l.

The resultant Ramberg-Osgood expression may be defined in terms of rotation and associated tangent-stiffness as described in Eqs. 7.1 to 7.4 below. Values of corresponding moment may be obtained by applying an iterative solution. The resultant form of curve-fit has been applied to connection CANT 3 as shown in Fig. 7.13.

If $\phi_c \le \phi_l$ then:

$$\phi_c = \frac{M_c}{A_1} + 0.01\left\{\frac{M_c}{B_1}\right\}^{n_1} \qquad \text{Eq. 7.1.}$$

$$\frac{dM_c}{d\phi_c} = \left\{\frac{1}{A_1} + 0.01\left(\frac{M_c}{B_1}\right)^{n_1-1}\frac{1}{B_1}\right\} \qquad \text{Eq. 7.2.}$$

If $\phi_c > \phi_l$ then:

$$\phi_c = \phi_1 + \frac{(M_c - M_1)}{A_2} + 0.01\left\{\frac{(M_c - M_1)}{B_2}\right\}^{n_2} \qquad \text{Eq. 7.3.}$$

$$\frac{dM_c}{d\phi_c} = \left\{\frac{1}{A_{21}} + 0.01\left(\frac{(M_c - M_1)}{B_1}\right)^{n_{21}-1}\frac{1}{B_2}\right\} \qquad \text{Eq. 7.4.}$$

Where ϕ_c is the connection rotation,
M_c is the corresponding level of moment,
ϕ_l is the rotation at which the beam flange comes into bearing with the column,
M_l is the moment corresponding with ϕ_l,
A_1, B_1 and n_1 are temperature dependent factors for stage 1 of response,
A_2, B_2 and n_2 are temperature dependent factors for stage 2 of response.

For the connection CANT 3 it may be seen that the modified Ramberg-Osgood expression closely follows the form of response recorded. The modified expression remains simple, following the form of the original equation, with the incorporation of an additional term. The terms A_1, B_1 and n describing the response up to a rotation of 68 millirads may be read as those adopted previously (A, B and n - Table 7.2), whilst the terms defining stage 2 are included in Table 7.4.

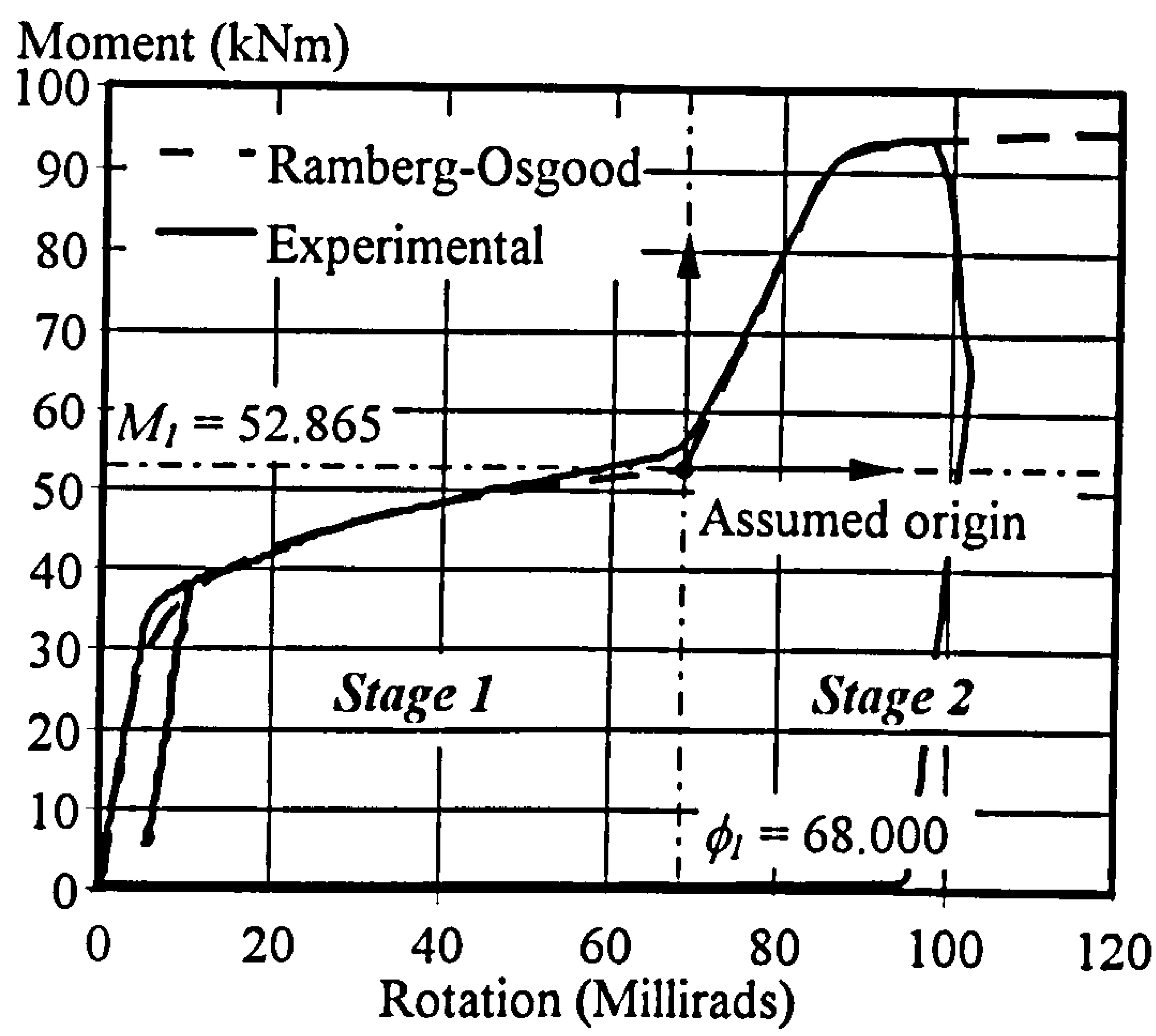


Figure 7.11. Refined Ambient-Temperature Ramberg-Osgood Curve-Fit to Test CANT3

The effects of temperature have been included based on the assumptions adopted above. For stage 1 degraded characteristics are as detailed in Table 7.2. For stage 2 it was once more assumed that connection characteristics degraded based on levels of strain contained within the proportional limit and of 0.5% in accordance with the recommendation of EC3: Part 1.2[8]. The grade of the connected beam was once more adopted in the degradation as a conservative assumption, although deformation would be expected to be mainly limited to the flexible end-plate in stage 2. Resultant terms describing stage 2 characteristics for increasing temperatures are included in Table 7.4.

The structure has been reanalysed based on the assumptions described above, and incorporating the refined representation of the flexible end-plate connection CANT3. Moment-rotation characteristics for CANT4 are assumed to remain as previous (stage 1 only) as no data is available for stage 2 of the connection response. Results from analysis in terms of deflections and corresponding deflections for the 356UB (CANT3) are compared with those obtained neglecting the influence of stage 2 (for actual characteristics and a value twice that) in Fig. 7.12. Results have not been presented for the 610UB (CANT4) as these were not affected noticeably by the inclusion of refined characteristics for the connection CANT3.

Temperature	A_2	B_2	n_2
20°C / 100°C	*2.300*	*35.200*	*38.600*
200°C	*2.067*	*32.349*	"
300°C	*1.838*	*29.427*	"
400°C	*1.608*	*26.682*	"
500°C	*1.379*	*21.366*	"
600°C	*0.711*	*12.250*	"
700°C	*0.299*	*5.773*	"

ϕ_1 = 68 millirads

Table 7.4. Predicted Elevated-Temperature Characteristics for CANT3 - Stage 2

It may be seen from Fig. 7.12 that for temperatures below 500°C deflections incorporating the revised representation of connection characteristics for connection CANT3 remain unchanged. Corresponding rotations at a temperature of 500°C are approximately 60 millirads, and as such connection response remains within stage 1. For the subsequent temperature step increasing from 500°C to 600°C it may be seen that the corresponding rotations increase to 80 millirads, with the connection entering stage 2 of the response. This results in a reduction in both connection rotation and central deflection of the beam due to the significant increase in the moment capacity of the connection. Considering the resultant influence on deflections it may be seen that these increase to a level similar to that assuming the incorporation of connection characteristics twice those recorded considering stage 1 in isolation. This may be expected as the moment capacity of the connection increases from $M_c \approx 0.16M_p$ to $M_c \approx 0.27M_p$ as the response moves from stage 1 to stage 2. For increased levels of rotation deflections once more converge towards a common point.

It would be expected that the level of rotation at which typical flexible end-plate connections would enter stage 2 of response would be within the range of rotations experienced under fire conditions, and as such it would be anticipated that a similar enhancement would be arise from the incorporation of refined characteristics for the connection CANT4. Unfortunately experimental data is not available describing the response of stage 2 for this connection.

The observed response suggests that flexible end-plate connection tests conducted in the development of elevated-temperature connection characteristics should follow the connection response through to stage 2 as this contributes significantly to the influence of semi-rigid connection characteristics on the performance of steel framed structures.

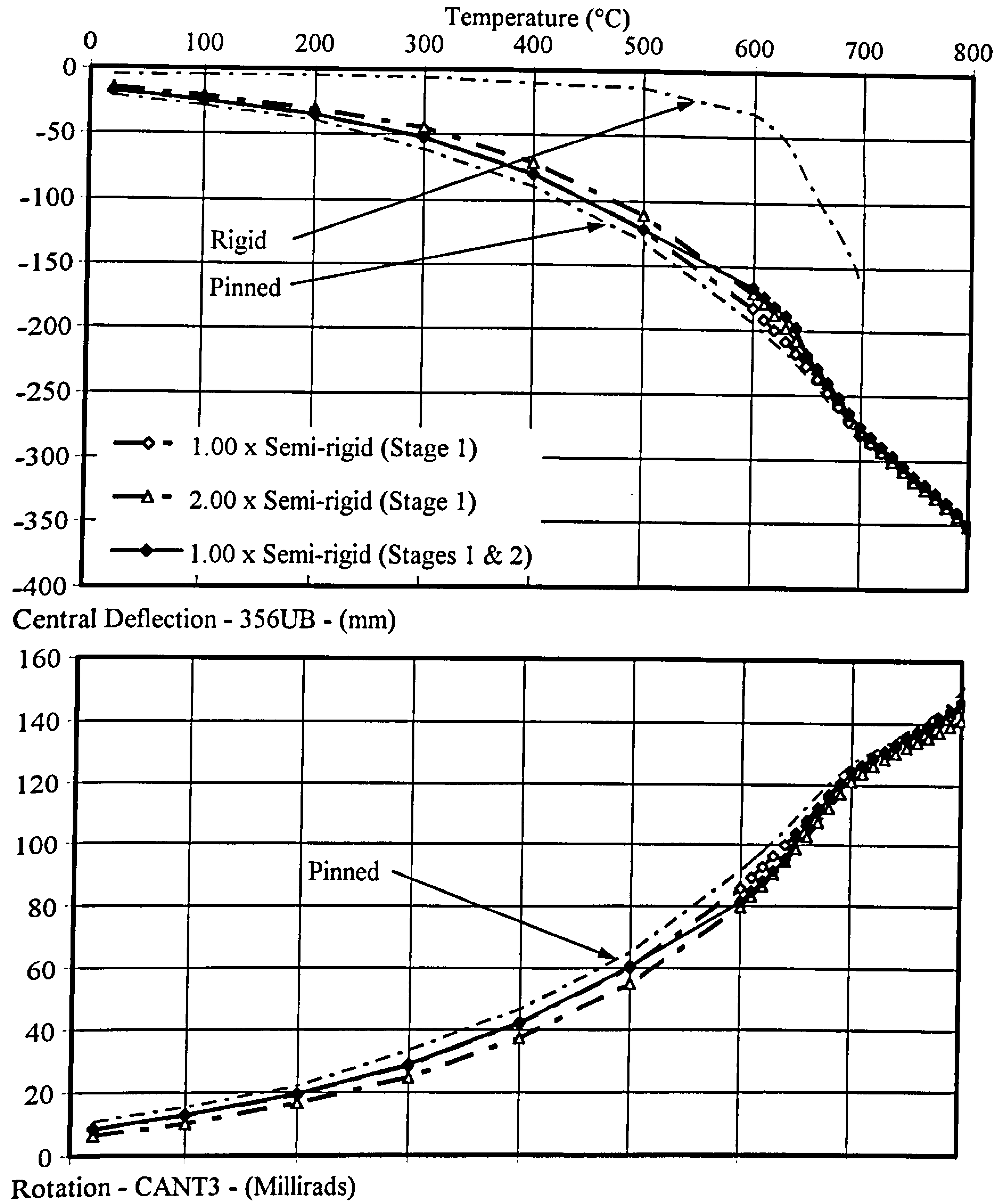


Figure 7.12. Deflections and Corresponding Rotations for 356UB (CANT3) Incorporating Refined Bare-Steel Flexible End-Plate Connection Characteristics

7.5. COMPOSITE TWO-DIMENSIONAL ANALYSIS OF FRAME RESPONSE

The response of the Cardington test frame at elevated temperatures is significantly influenced by the existence of a concrete slab acting compositely with the steel beams. With increasing temperatures the temperature, and reduction in capacity of the concrete slab increases at a significantly slower rate compared to the exposed steel. As such the capacity of the composite beam in sagging reduces at a reduced rate compared to an equivalent bare-steel section. Similarly in consideration of the response of composite connections at elevated-temperatures, the capacity of the connection is enhanced by the existence of reinforcement acting in tension at a lower temperature. Although only nominal top reinforcement was used in the Cardington test frame (A142 mesh), as the reinforcement remains at a temperature approximately 20% of the beam lower flange temperature, its influence may become significant at high temperatures.

Ambient-temperature connection characteristics developed for the Cardington test frame[47] have been limited to bare-steel arrangements, and as such it is necessary to consider the influence of the composite slab on connection response.

7.5.1. Development of Composite Connection Characteristics

The ability with which composite conditions may be imposed on the response of bare-steel flush end-plate characteristics was considered in Chapter 5 in the development of the proposed composite spring-stiffness model. The form of model adopted was based around the formulation presented by Anderson and Najafi[27], and accounted for the influence of slip at the beam-slab interface, an effect which has been observed to be influential in studies by others. Based on the recommendations of Anderson and Najafi, overall composite connection stiffness may be expressed as:

$$S_{cj} = \left\{ \frac{K_r K_s D_r D_s}{K_r + K_s} \right\} + S_j \qquad \text{Eq. 7.5.}$$

Where S_{cj} is the rotational stiffness of the composite connection;
S_j is the rotational stiffness of the bare-steel connection;
K_r is the stiffness of the spring representing the reinforcement;
K_s is the stiffness of the spring representing shear connection;
D_r is the distance from the centre of rotation to the centre of the reinforcement;
D_s is the distance from the centre of rotation to the top face of the beam flange.

Comparison of experimentally recorded composite connection response for the flush end-plate tested at ambient-temperatures showed that a close correlation existed with the response predicted using this simplified expression. However, for the flush end-plate tested the centre of rotation would be expected to be located close to the centre of the beam lower flange at ambient-temperatures. For increasing temperatures the ability of the model to follow the experimentally observed response diminished, presumably due to the relocation of the neutral axis into the depth of the beam as the column web deformed significantly in compression.

The development of composite characteristics for flexible end-plate connections is complicated by the two-stage form of response observed, and the movement of the centre of rotation.

In the early stages of response, deformation of the bare-steel connection is attributable in part to deformation of the 'flexible' end-plate in tension and in part to the deformation of the beam web in compression. As such stresses in the compression zone are resisted purely by the column web, and the resultant plastic stress block may be expected to extend a considerable distance up the height of the web, significantly influencing the location of the centre of rotation. When the flexible end-plate connection acts compositely with reinforcement in the tension zone, it may be anticipated that this would generate a higher concentration of stresses in the compression zone, resulting in the centre of rotation moving further up the beam web. Incorporating the effects of increasing temperature, the capacity of the beam web would diminish at a far higher rate than the reinforcement, and as such the composite connection would tend to rotate about the centre of the reinforcement until a point where the beam lower flange comes into bearing with the column flange.

Observation of bare-steel (ambient-temperature) and composite (elevated-temperature) specimens has demonstrated that little deformation of either the column flange or beam flange in compression occurred. It therefore seems reasonable to assume that within stage 2 of the response the connection effectively rotates about the lower flange of the beam, and the existence of reinforcement at a reduced temperature would be influential in the rate of degradation of connection characteristics.

For composite flexible end-plate connections at elevated-temperatures it may be expected that the beam lower flange would come into bearing with the column flanges at a far lower rotation than for the bare-steel ambient-temperature connection. Assuming rotation about the top flange of the beam for the 356UB (mid-point between reinforcement and top row of bolts acting in tension), the beam may be expected to bear against the column flange for a rotation as low as 20 millirads.

In considering the influence of connection characteristics on frame behaviour, it has been shown that connection response at low levels of rotation has a limited influence on the resultant failure-temperature of any given arrangement. It is therefore suggested that as no experimental data is available accurately defining the response of the composite Cardington connections at elevated-temperatures, stage 1 of the response should be omitted from analysis.

Development of composite characteristics is complicated further by fact that results for stage 2 are only available for 2 of the 7 flexible end-plate connections tested. It was thus decided to adopt the conservative approach of assuming the connection response to be defined by a single curve extrapolated from stage 1 (previously defined Ramberg-Osgood expression), assuming these reduced connection characteristics to prevail after the point that the beam lower flange has come into bearing with the column flange. It should be realised that this would not be expected to generate results directly comparable with those for the true connections, but it would be expected that the postulated characteristics would present an acceptable lower bound approximation of true characteristics.

The slab detailing adopted within the Cardington test frame was as used in the Composite flush end-plate tests described in Chapter 3, i.e. 130mm thick Lytag Grade 35 concrete slab on PMF COMFLOR 70 decking with an A142 mesh. Connection between beam and slab was by 100x19mm diameter shear studs on 300mm centres.

Non-linear composite connection characteristics have been developed at ambient-temperatures for connections CANT3 and CANT4 based on the expression described in Eq. 7.5, and the following assumptions:

1. Bare-steel characteristics have been assumed to defined by the Ramberg-Osgood expression described for stage 1 only (Tables 7.2 and 7.3).
2. Material properties incorporated within the analysis are based on those presented in Appendix A (f_y = 629N/mm^2; f_u = 669N/mm^2), with an elastic-modulus of 210,000N/mm^2 being assumed.
3. Rotation of the connection is assumed about the centre-line of the lower beam flange.
4. Slip at the beam slab interface has been accounted for, with the stiffness of shear studs being taken as 200kN/mm based on tests by Mottram and Johnson[60] as described in Section 5.4.2.
5. The effects of shear-lag have been neglected, assuming an effective width of slab of 1000mm. This equates to 4 No. 6mm diameter bars acting in tension (5th bar omitted as assumed to coincide with column centre-line).
6. In the assessment of stiffness a de-bonded length corresponding with the location of the first shear stud has been assumed (i.e. 300mm from column centre-line).
7. No limiting elongation is imposed on the reinforcement due to observation of the Cardington frame after testing demonstrating that reinforcement over the tension zone remained intact. This may be considered to equate to the gradual de-bonding of reinforcement in tension with increasing levels of rotation.
8. Capacity of concrete in tension has been neglected.

Resultant composite moment-rotation response is compared with experimental bare-steel results and the Ramberg-Osgood form of curve-fit adopted at ambient-temperatures in Figs. 7.12 and 7.13.

It may be seen from Fig. 7.13 that the incorporation of composite conditions results in a significant enhancement in moment-capacity for the connection CANT3. For a rotation of 100 millirads the contribution arising from the composite slab steel is approximately 32kNm (one-third of the overall composite connection capacity), resulting in an increase in moment capacity from 57kNm to 89kNm. The relative capacity of the composite connection reduces to $M_c \approx 0.14M_p$ ($M_c \approx 0.16M_p$ - bare-steel). The resultant composite response remains below that for the bare-steel connection incorporating stage 2 of the response at ambient-temperatures. However, with increasing temperatures the capacity of the connection would reduce at a lower rate as the reinforcement would remain at a temperature approximately 20% of the beam lower flange temperature.

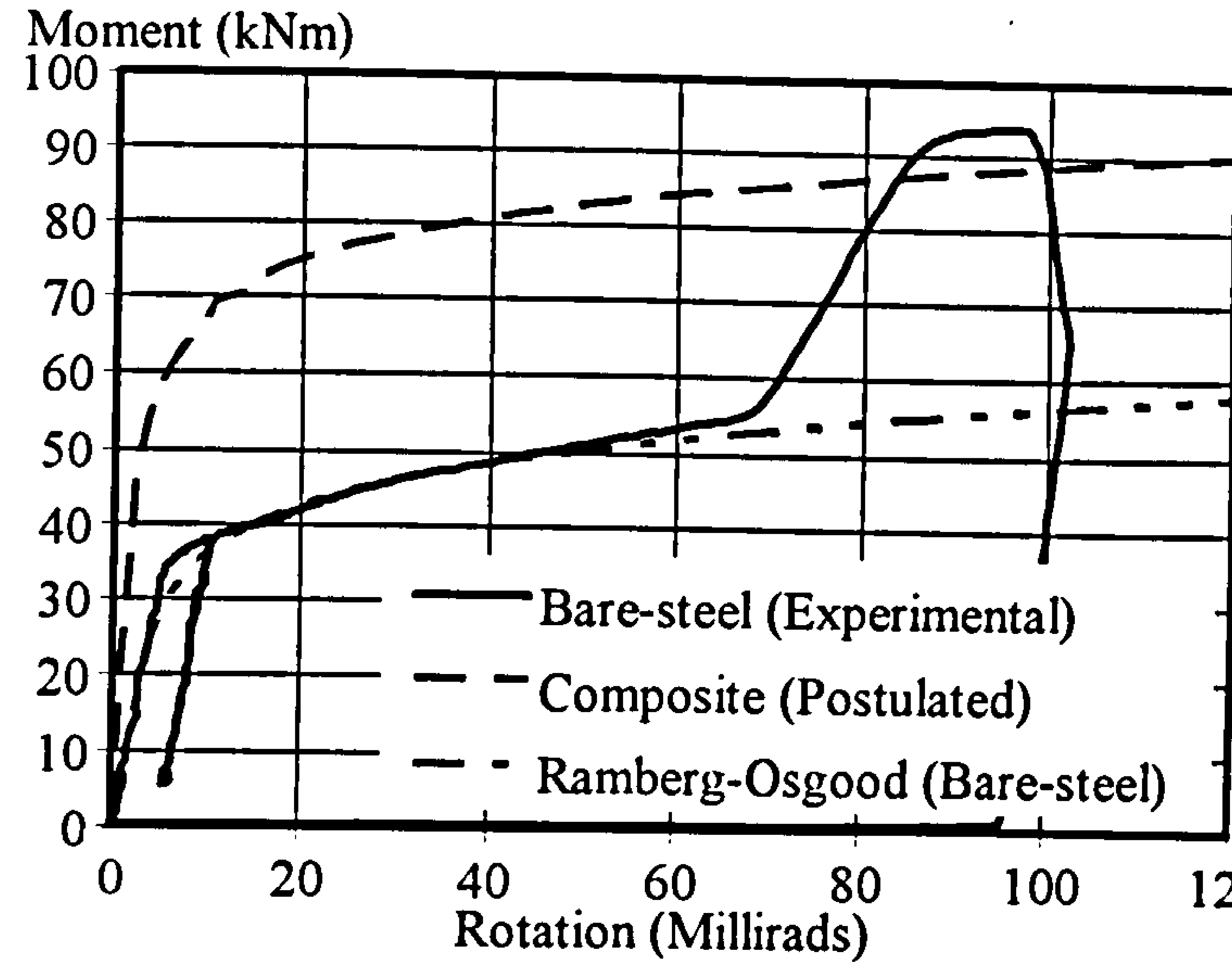


Figure 7.13. Postulated Composite Response (CANT3)

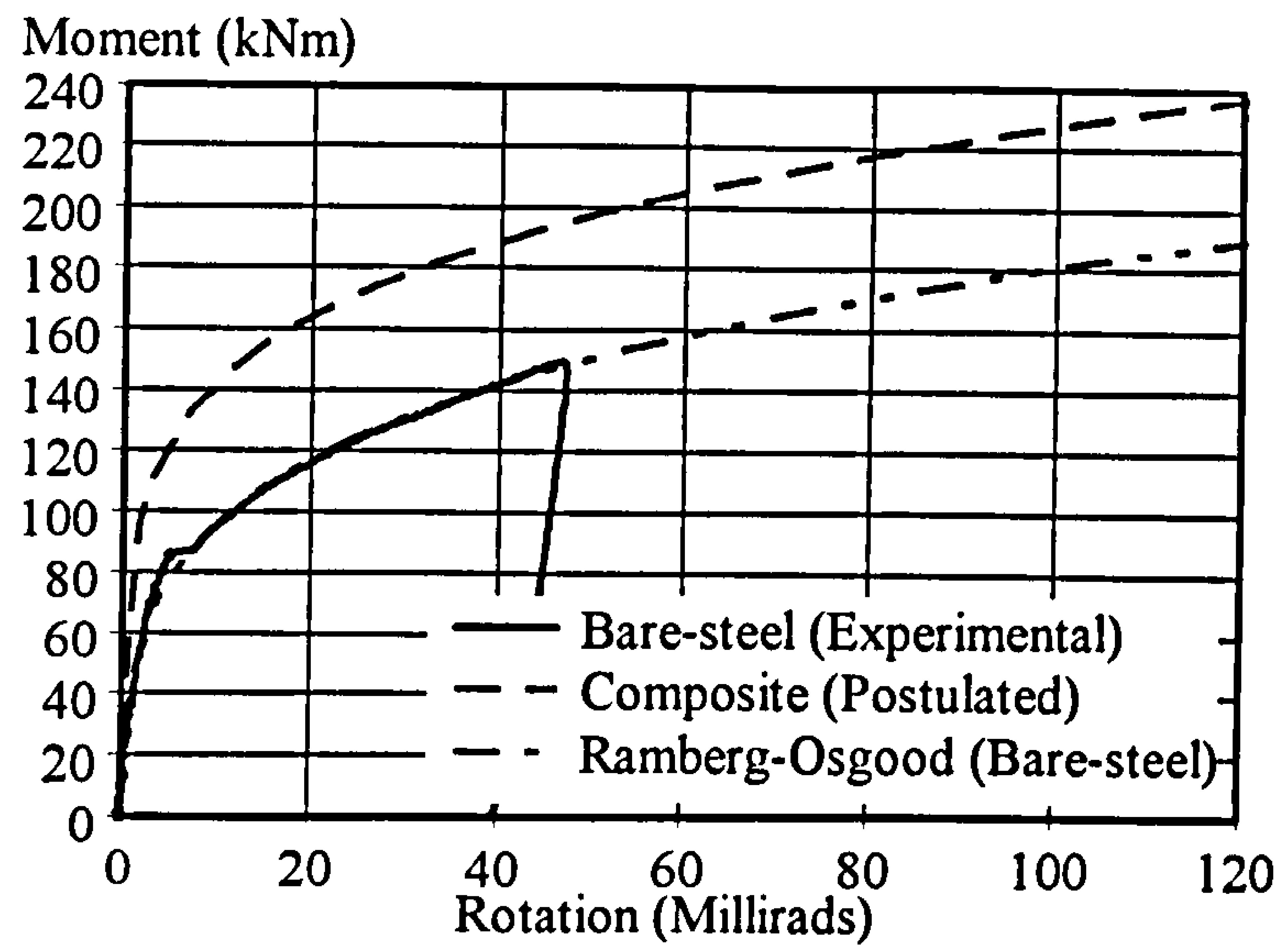


Figure 7.14. Postulated Composite Response (CANT4)

The increase in moment capacity for the connection CANT4 from the inclusion of composite action is somewhat higher due to the greater lever arm to the reinforcement. The resultant increase in moment capacity at ambient-temperature may be seen to be approximately 50kNm. However, due to the higher capacity of the bare-steel connection this relates to an increase of only 20% in overall capacity. Relative capacity of the connection reduces to $M_c \approx 0.16M_p$, being only slightly below that for the bare-steel connection ($M_c \approx 0.17M_p$).

The Ramberg-Osgood expression has once more been applied to the ambient-temperature moment-rotation curve, with the parameters being described in Tables 7.5 and 7.6.

7.5.2. Degradation of Composite Connection Characteristics

Ambient-temperature moment-rotation characteristics for the composite connections have been degraded based on the recommendation of Section 3.4.2, accounting for the fact that the reinforcement remains at a temperature approximately 20% of the beam lower flange temperature. Degradation of connection characteristics was once more achieved by varying the terms A, B and n contained within the Ramberg-Osgood expression.

In the degradation of stiffness, it is conservatively assumed that deformation of the connection in the compression zone controls, and as such the rate of degradation is based on that of the connected beam for a level of strain contained within the proportional limit according to the rates of degradation presented in EC3: Part 1.2[8]. In the degradation of connection capacity the proportion of connection capacity arising from the bare-steel connection and that arising from the existence of the composite slab were degraded independently based on their relative temperatures. The temperature of the reinforcement was assumed to be 20% of the beam lower flange temperature. The bare steel connection was once more degraded for a strain of 0.5% according to EC3: Part 1.2[8], whilst reinforcement was degraded based on the results of a series of tests conducted by Holmes *et. al.*[54] as described in Section 2.3. Resultant elevated-temperature moment-rotation characteristics for connections CANT3 and CANT4 are described in Tables 7.5 and 7.6 below.

Temperature	*A*	*B*	*n*
20°C / 100°C	*19.300*	*33.000*	*9.200*
200°C	*17.344*	*31.210*	"
300°C	*15.420*	*29.393*	"
400°C	*13.497*	*27.681*	"
500°C	*11.573*	*24.427*	"
600°C	*5.966*	*18.890*	"
700°C	*2.510*	*14.938*	"

Table 7.5. Postulated Elevated-Temperature Composite Characteristics for CANT3

Temperature	*A*	*B*	*n*
20°C / 100°C	*74.000*	*39.200*	*5.200*
200°C	*66.550*	*36.874*	"
300°C	*53.720*	*34.435*	"
400°C	*41.801*	*32.151*	"
500°C	*35.096*	*27.289*	"
600°C	*18.459*	*19.237*	"
700°C	*8.029*	*13.424*	"

Table 7.6. Postulated Elevated-Temperature Composite Characteristics for CANT4

7.5.3. Composite Plane-Frame Analysis

The analysis has been repeated for the bare-steel plane-frame described in Section 7.4 (Test 3), incorporating the composite slab, and the elevated-temperature composite connection characteristics described above. Edge connections were assumed to behave as bare-steel as no special provision was made to allow the development of moments in the reinforcement at the edge of the slab. The structure has once more been analysed for increasing temperatures using the program developed by Bailey[22]. The following assumptions have been adopted in the analysis in addition to those described in Section 7.4.2:

1. Concrete properties have been based on those described in Appendix A for the Cardington test frame ($f_{cu,28}$ = 47N/mm^2).
2. The concrete is isotropic and linear-elastic, with an elastic modulus of 21,000N/mm^2.
3. The concrete slab is assumed to remain at 20% of the beam lower flange temperature.

4. Only the top 75mm of the slab is considered, representing the area of the slab above the top of the trapezoidal steel deck.
5. The width of the slab has been assumed to be 2000mm corresponding to the width of the fire compartment.
6. Slab elements above steel-to-column connections are reduced to 6mm thick, corresponding to the thickness of the mesh in the slab.
7. The level of loading of 5.48kN/m^2 has been maintained; this results in reduced load-ratios of 0.36 for the 356UB and 0.35 for the 610UB.

The analysis has been conducted assuming the actual postulated connection characteristics and ratios of 50%, 200% and 400% of connection characteristics, and compared with the limiting cases of pinned and rigid connections. Results are presented in Figs. 7.15 and 7.16 below in terms of residual central deflections of the 356UB and 610UB and corresponding rotations for connections CANT3 and CANT4. Rotations presented for the connection CANT3 are those for the internal connection.

It may be seen from Fig. 7.15 that a visible enhancement in fire resistance is observed by incorporating composite connection characteristics, where this enhancement is greater than that observed for the bare-steel frame as shown in Fig. 7.9. It is suggested that this is in part due to the fact that for the composite arrangement there is not a tendency for deflections to converge towards a common point. However, the fact that a noticeable increase may be seen across the range of temperatures seems to indicate that the degradation of connection characteristics was at a lower rate than the connected beam. A similar response was observed for the 610UB incorporating composite characteristics for the connection CANT4. For the beam the enhancement observed by incorporating composite characteristics was somewhat greater than for the 356UB. It would be expected that this is attributable in part to the increased relative capacity of CANT4, and in part to the fact that the external connection for the 356UB was based on bare-steel characteristics.

It may be seen that corresponding rotations are as high as 160 millirads and as such it is necessary to ensure that sufficient ductility exists within the reinforcement to prevent yielding before this point. An increase in the rotational capacity may be achieved by de-bonding reinforcement in the tension zone, although observation of the structure after testing did not indicate yielding. It is felt that further testing is desirable to assess the rotational capability of typical reinforcement.

Considering rotations for the connection CANT3 (Fig. 7.15) it may be seen that a reversal in rotations is observed for connection characteristics 4 times those postulated, indicating unloading of the connection. Unloading of connections can occur for a number of reasons including the deflection of columns or the application of lateral loads. However, as this form of response was only observed for a connection of such high strength it is suggested that unloading may have occurred as a result of a plastic hinge forming in the connected beam.

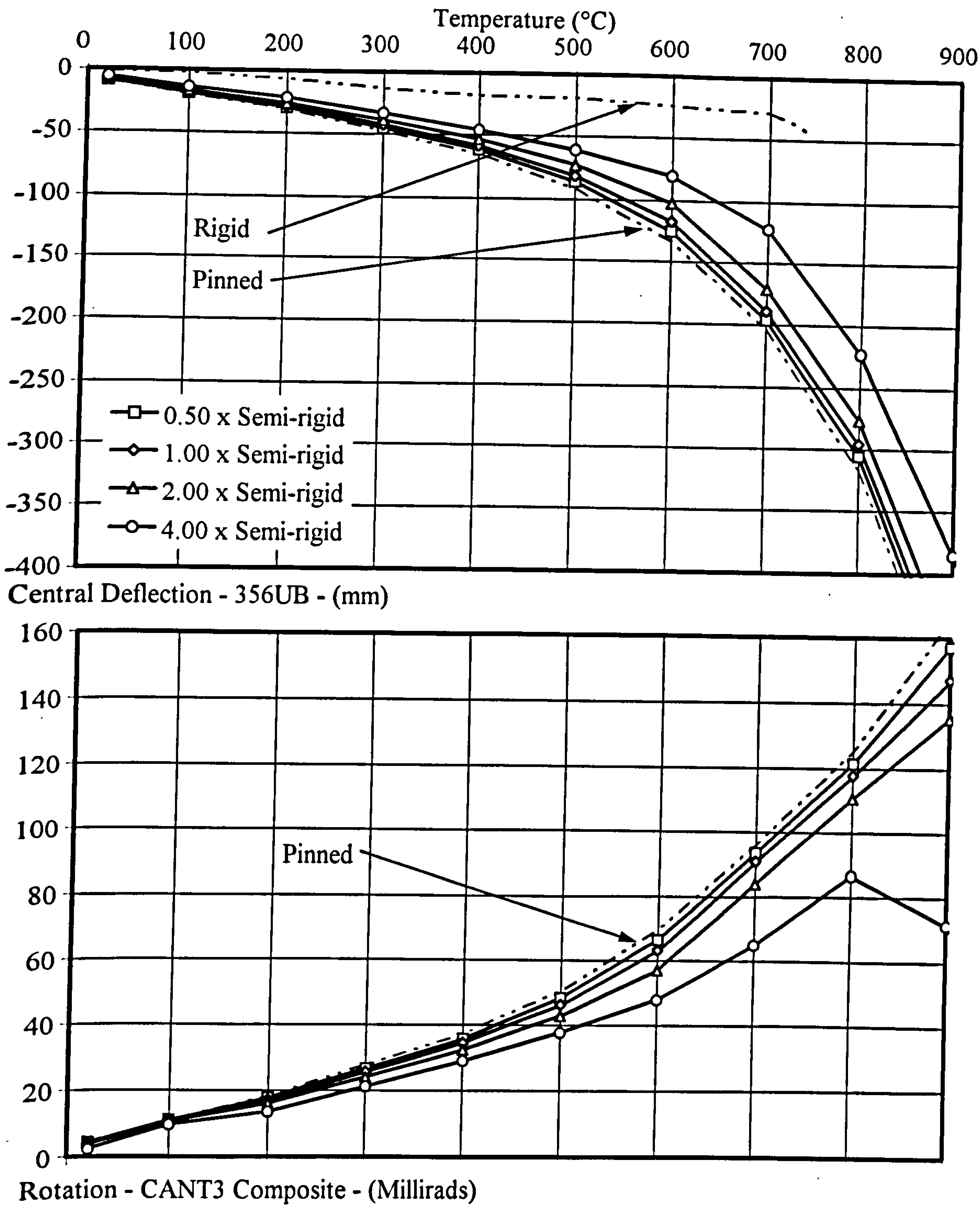


Figure 7.15. Deflections and Corresponding Rotations for 356UB (CANT3)
- Analysis of Cardington Test 3 as 2D Composite Frame -

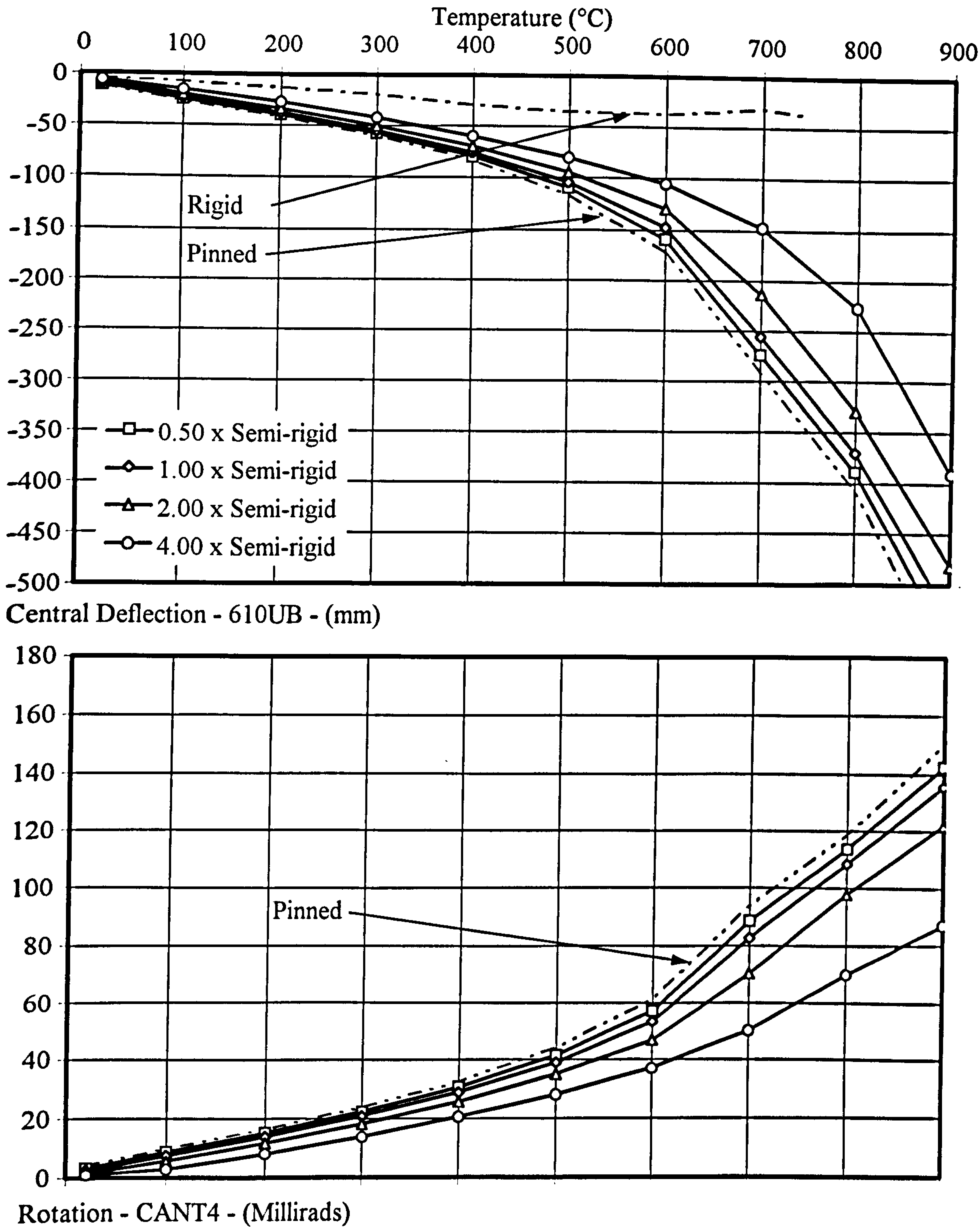


Figure 7.16. Deflections and Corresponding Rotations for 610UB (CANT4)
- Analysis of Cardington Test 3 as 2D Composite Frame -

7.6. THREE-DIMENSIONAL ANALYSIS OF FRAME RESPONSE

All studies presented so far have been restricted to the consideration of two-dimensional structures, neglecting the potentially significant influence of the composite slab. It is possible that whilst the incorporation of realistic connection characteristics within two-dimensional analysis has been demonstrated to be beneficial in the response of both bare-steel and composite structures at elevated-temperatures, that the effects of the composite slab limit the enhancement gained from the inclusion of semi-rigid connection characteristics when considering three-dimensional frame response. The analysis has therefore been repeated for an arrangement comparable with that adopted in the two-dimensional analysis of Section 7.5, considering the full three-dimensional response of the structure.

Test 7 has been selected for this purpose. The test arrangement incorporates the area of Test 3 (at a different level), but includes the full width of the structure from grid-lines A to C.

To reduce the extent of analysis advantage was once more taken of symmetry of the structure along the assumed grid-line 2.5. The extent of the fire compartment and associated analysis is indicated in Fig. 7.17.

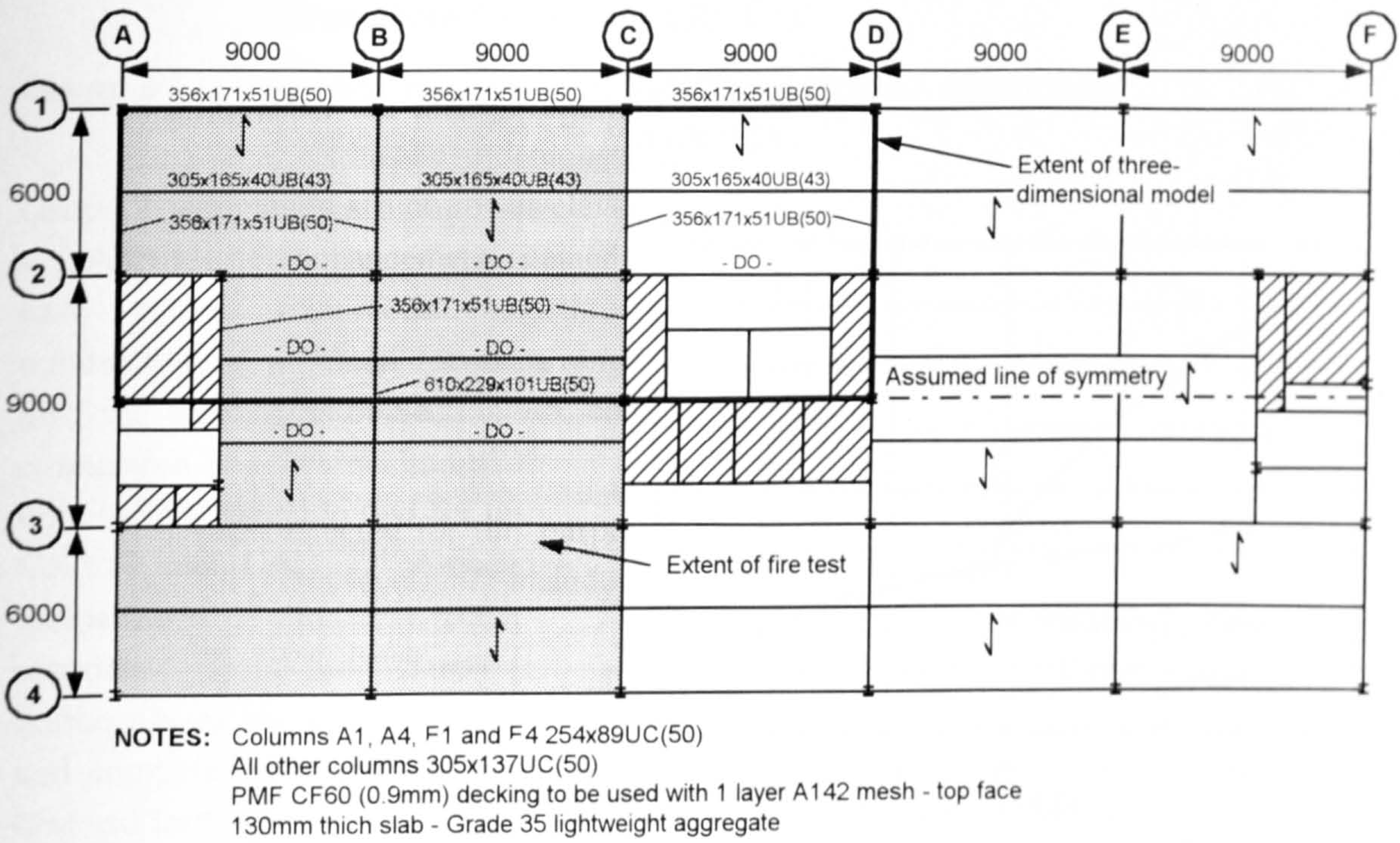


Figure 7.17. Position of Three-Dimensional Cardington Frame Test (Test 7)

It may be seen that the extent of the furnace incorporates both the major-axis framing beams running along grid-line B and minor-axis connections. Fin-plate connections are incorporated at beam-to-beam connections. The furnace was fuelled by wooden cribs. Beams were left exposed, whilst columns were protected for the full storey height. It is anticipated that this would result in the connections remaining at a significantly reduced temperature.

7.6.1. Development of Bare-Steel and Composite Connection Characteristics

As described in Section 7.3 a total of 9 bare-steel ambient-temperature connection tests have been conducted by Boreman[47], providing moment-rotation characteristics for a total of 10 connection types, being representative of the connections contained within the Cardington test frame. Inspection of the ambient-temperature moment-rotation characteristics as presented in Appendix D indicates that connection response may be grouped according to the connection type as detailed below:

Group 1 - Minor-axis flexible end-plate 356UB connection - single sided (Connection CANT1).

Group 2 - Major-axis flexible end-plate 356UB connection (Connections CANT2 and CANT3).

Group 3 - Major-axis flexible end-plate 610UB connection (Connection CANT4).

Group 4 - Minor-axis flexible end-plate 305UB connection - double sided (Connections CRUC2 and CRUC3).

Group 5 - Minor-axis flexible end-plate 356UB connection - double sided (Connections CRUC1 and CRUC3).

Group 6 - Beam-to-beam fin-plate 305UB connection - double sided (Connections CRUC4 and CRUC5).

Group 1 incorporates a single test - CANT1. This represents the case of a minor-axis edge connection of a 356UB framing into the web of a 254UC. The connection is a flexible end-plate, nominally identical to that for tests CANT2 and CANT3. Ambient-temperature moment-rotation response for the bare-steel connection is shown in Fig. 7.18, and compared with the Ramberg-Osgood form of curve-fit.

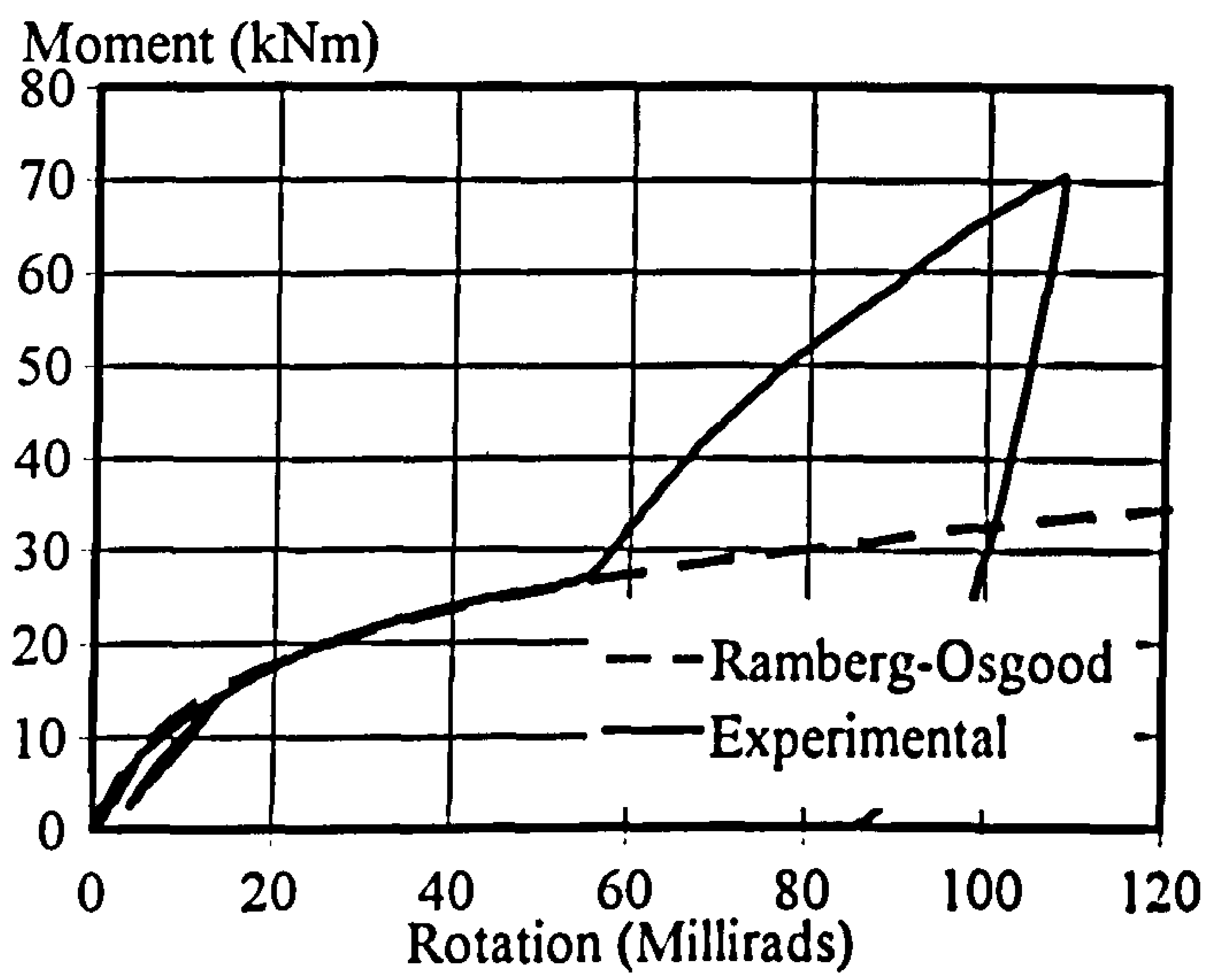


Figure 7.18. Ambient-Temperature Ramberg-Osgood Curve-Fit for Group 1

It may be seen from Fig. 7.18 that the capacity of the connection is significantly lower than that recorded from Tests CANT2 and CANT3 considering a nominally identical major axis connection, and Tests CRUC1 and CRUC3 in which the beam frames into the column web as a cruciform arrangement.

The Ramberg-Osgood curve-fit has once more been applied to the bare-steel ambient-temperature moment-rotation response, neglecting the increase in stiffness as the beam flange bears against the column. The bare-steel connection has been degraded for increasing temperatures based on the recommendations of Section 7.4.1, with the resultant terms being detailed in Table 7.7. Composite response has not been considered as no provision was made within the Cardington test frame to ensure continuity of reinforcement at edge connections.

Temperature	*A*	*B*	*n*
20°C / 100°C	*2.100*	*2.100*	*3.300*
200°C	*1.887*	*1.930*	"
300°C	*1.678*	*1.756*	"
400°C	*1.469*	*1.592*	"
500°C	*1.259*	*1.275*	"
600°C	*0.649*	*0.731*	"
700°C	*0.273*	*0.344*	"

Table 7.7. Postulated Elevated-Temperature Bare-Steel Characteristics for Group 1

Group 2 considers the case of a major-axis 356UB flexible end-plate connection (Tests CANT 2 and CANT3). These two tests are identical except for variation of the size of the connected column, with tests CANT2 and CANT3 considering the cases of a 254UC and 305UC respectively. Ambient-temperature moment-rotation response is compared for the two arrangements in Fig. 7.19 below. As can be seen the response observed in both tests compares closely, justifying the grouping of these connections. Terms describing the response of connection CANT3 are presented in Tables 7.2 and 7.5 for bare-steel and composite arrangements. The response for Group 2 has been based on these characteristics.

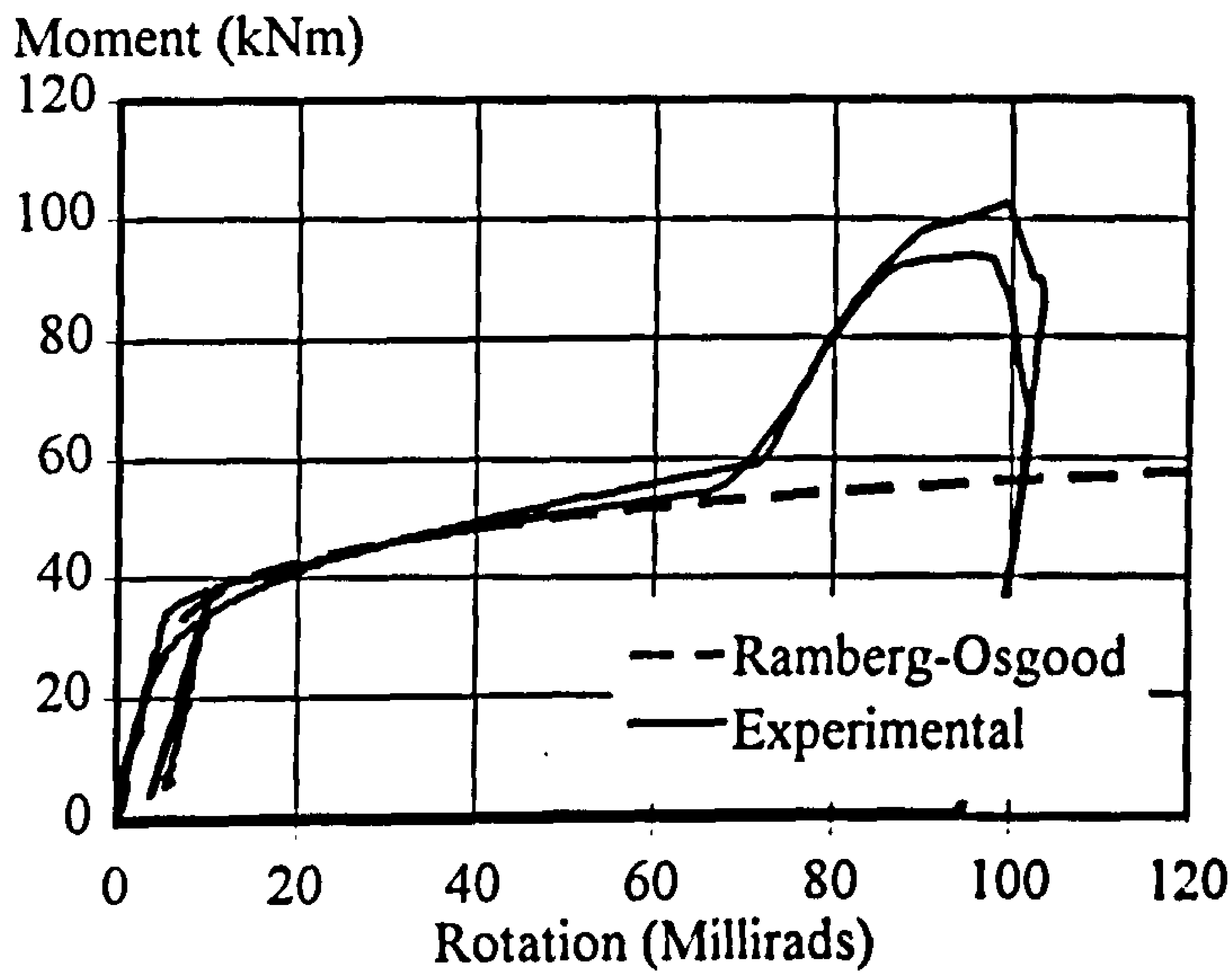


Figure 7.19. Ambient-Temperature Ramberg-Osgood Curve-Fit for Group 2

Group 3 considers the isolated case of a major-axis framing 610UB flexible end-plate connection. This arrangement has been considered as both bare-steel and composite earlier in this Chapter. Elevated-temperature response is described in Tables 7.3 and 7.6.

Group 4 represents the case of a minor-axis framing 305UB flexible end-plate connection, as adopted in Tests CRUC2 and CRUC3. Test CRUC2 considers the case of a symmetrical arrangement, whilst Test CRUC3 is of a 305UB one side and a 356UB the other. However, the ambient-temperature response for these connections compares closely as shown in Fig. 7.20.

A Ramberg-Osgood curve-fit has once more been applied to the ambient-temperature moment-rotation response, and the connection degraded for increasing temperatures based on the recommendations of Section 7.4.1. Resultant terms for the bare-steel connection are shown in Table 7.8.

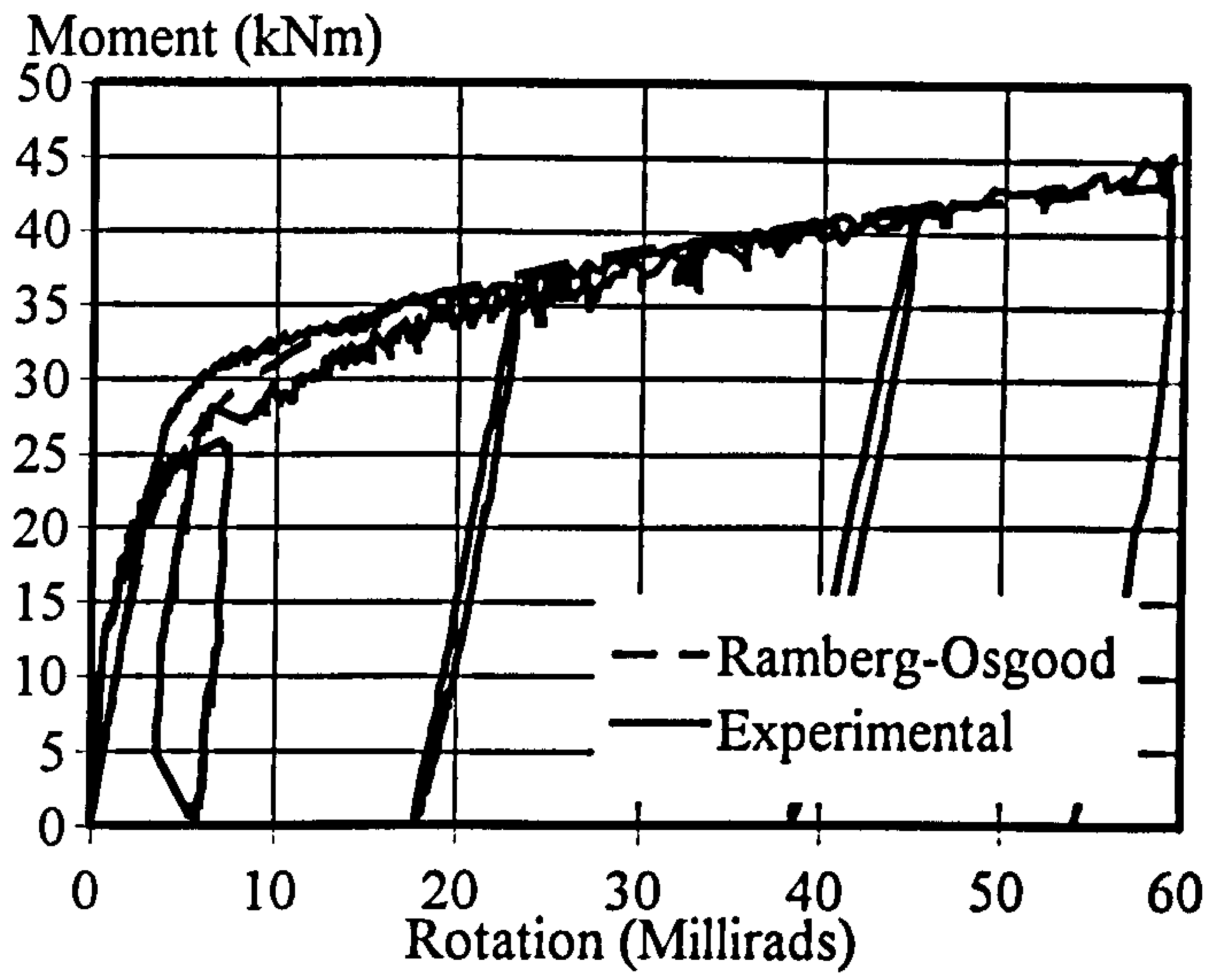


Figure 7.20. Ambient-Temperature Ramberg-Osgood Curve-Fit for Group 4

Composite conditions have been imposed on the bare-steel arrangement, and degraded for increasing temperatures based on the recommendations of Sections 7.5.1 and 7.5.2. The resultant elevated-temperature moment-rotation response is described in Table 7.9 based on the Ramberg-Osgood form of curve-fit.

Temperature	*A*	*B*	*n*
20°C / 100°C	*7.100*	*12.300*	*7.300*
200°C	*6.385*	*11.390*	*"*
300°C	*5.154*	*10.430*	*"*
400°C	*4.011*	*9.533*	*"*
500°C	*3.367*	*7.601*	*"*
600°C	*1.771*	*4.391*	*"*
700°C	*0.770*	*2.079*	*"*

Table 7.8. Postulated Elevated-Temperature Bare-Steel Characteristics for Group 4

Temperature	*A*	*B*	*n*
20°C / 100°C	*16.300*	*31.000*	*10.900*
200°C	*14.659*	*29.394*	*"*
300°C	*11.833*	*27.719*	*"*
400°C	*9.207*	*26.147*	*"*
500°C	*7.731*	*22.829*	*"*
600°C	*4.066*	*17.349*	*"*
700°C	*1.769*	*13.387*	*"*

Table 7.9. Postulated Elevated-Temperature Composite Characteristics for Group 4

Group 5 considers the case of a minor-axis flexible end-plate connection of tests on cruciform arrangements CRUC1 and CRUC3. Ambient-temperature moment-rotation response for the two tests is compared in Fig. 7.21. It may be seen once more that the response recorded from both tests compares closely. A Ramberg-Osgood form of curve-fit has again been applied to the bare-steel connection characteristics, and the enhancement in capacity arising from interaction with a composite slab has been incorporated based on the approach described in Section 7.5.1. Both bare-steel and composite characteristics have once more been degraded for increasing temperatures based on the recommendations of Sections 7.4.1 and 7.5.2. Terms describing elevated-temperature bare-steel and composite moment-rotation response are included in Tables 7.10 to 7.11 respectively.

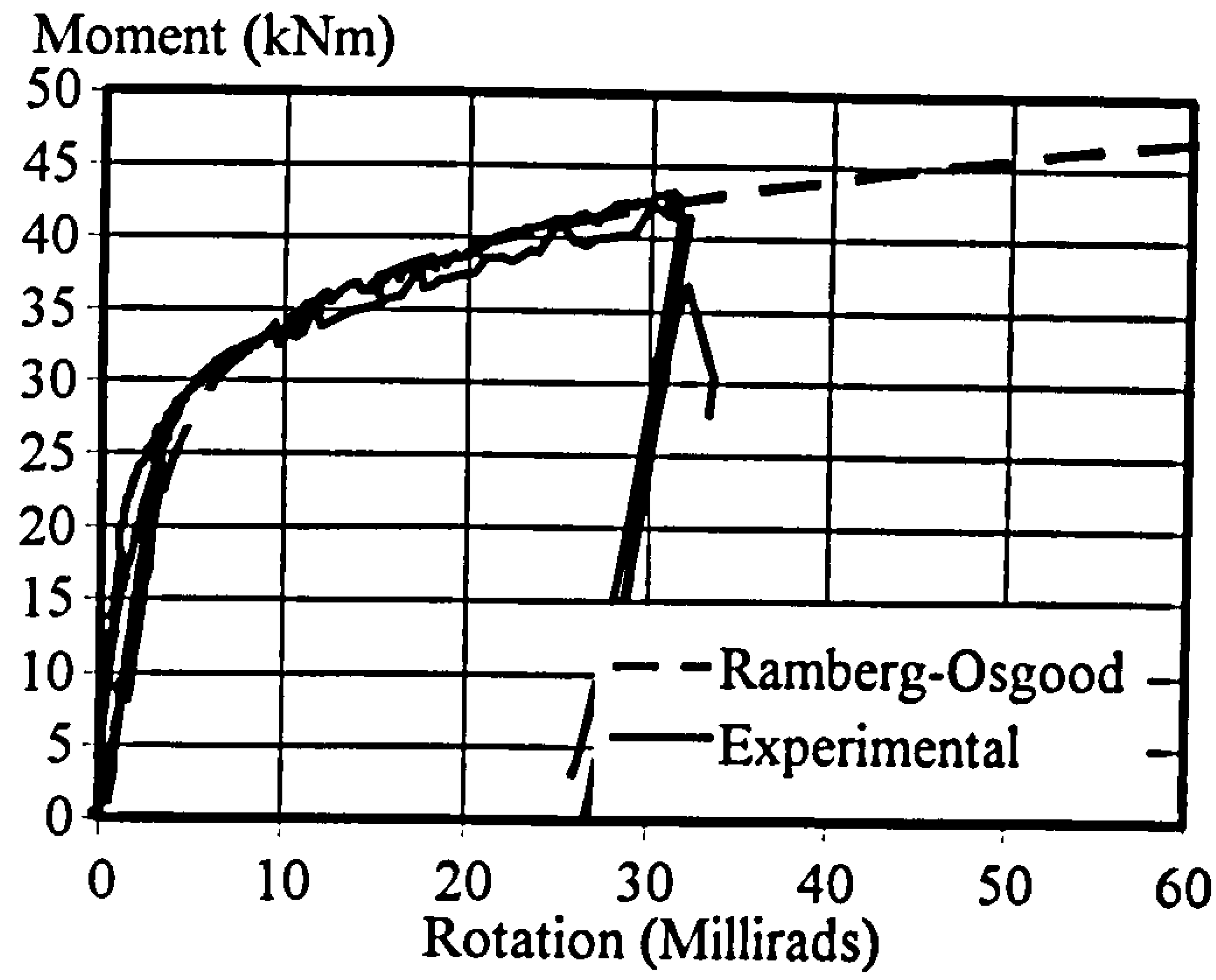


Figure 7.21. Ambient-Temperature Ramberg-Osgood Curve-Fit for Group 5

Temperature	*A*	*B*	*n*
20°C / 100°C	*7.100*	*14.500*	*7.300*
200°C	*6.380*	*13.326*	*"*
300°C	*5.673*	*12.122*	*"*
400°C	*4.965*	*10.991*	*"*
500°C	*4.258*	*8.802*	*"*
600°C	*2.195*	*5.046*	*"*
700°C	*0.923*	*2.378*	*"*

Table 7.10. Postulated Elevated-Temperature Bare-Steel Characteristics for Group 5

Temperature	*A*	*B*	*n*
20°C / 100°C	*18.700*	*36.400*	*11.100*
200°C	*16.805*	*34.496*	*"*
300°C	*14.941*	*32.565*	*"*
400°C	*13.077*	*30.746*	*"*
500°C	*11.214*	*27.294*	*"*
600°C	*5.781*	*21.427*	*"*
700°C	*2.432*	*17.237*	*"*

Table 7.11. Postulated Elevated-Temperature Composite Characteristics for Group 5

Group 6 considers the case of beam-to-beam connections in which a fin-plate is adopted to connect a 305UB to the web of a 356UB (CRUCB4) and 610UB (CRUCB5). Resultant ambient-temperature moment-rotation response is compared in Fig. 7.21 below. It may be seen that the response of these two arrangements compares closely up to moments of 25kNm. At this point loading was removed from the connection CRUCB4. Connection CRUCB5 continued to follow a consistent form of response up to a level of moment approaching 40kNm. It would be anticipated that connection CRUCB4 would be capable of withstanding moments equivalent to those for connection CRUCB5 without a significant reduction in moment. However, as data is not available within this range the Ramberg-Osgood expression has been assumed to follow the average of these two characteristics. Ambient-temperature characteristics for the bare steel arrangement have been degraded based on the recommendations of Section 7.4.1.

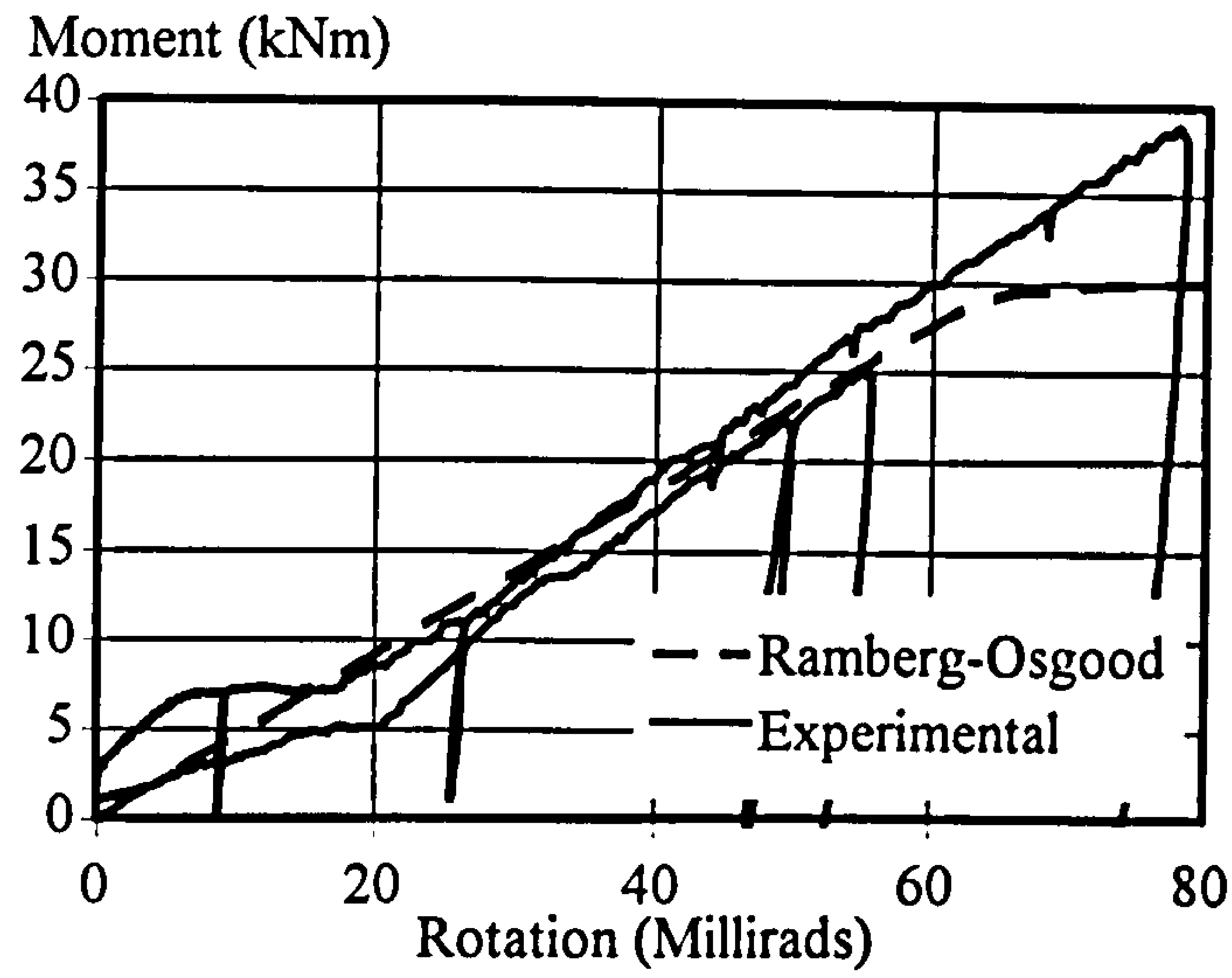


Figure 7.22. Ambient-Temperature Ramberg-Osgood Curve-Fit for Group 6

Composite conditions have been incorporated based on the assumptions of Section 7.4.1. The resultant ambient-temperature moment-rotation response is shown in Fig. 7.23. It may be seen that the inclusion of composite action results in a significant increase in connection stiffness at low levels of rotation. The level of stiffness then reduces for a moment approaching 50kNm, with the composite response then more closely following that observed for the bare-steel connection at an increased moment. It is felt that the high initial stiffness is unrealistic as this assumes the beam lower flange to be in bearing, and as such a conservative curve-fit has been applied at ambient-temperatures, lying between the bare-steel and composite behaviour, until finally reaching a capacity equivalent to that predicted for the composite arrangement. This may be seen in Fig. 7.23. Composite characteristics have once more been degraded based on the recommendations of Section 7.5.2, with the resultant moment-rotation response being described in Table 7.13 for increasing temperatures.

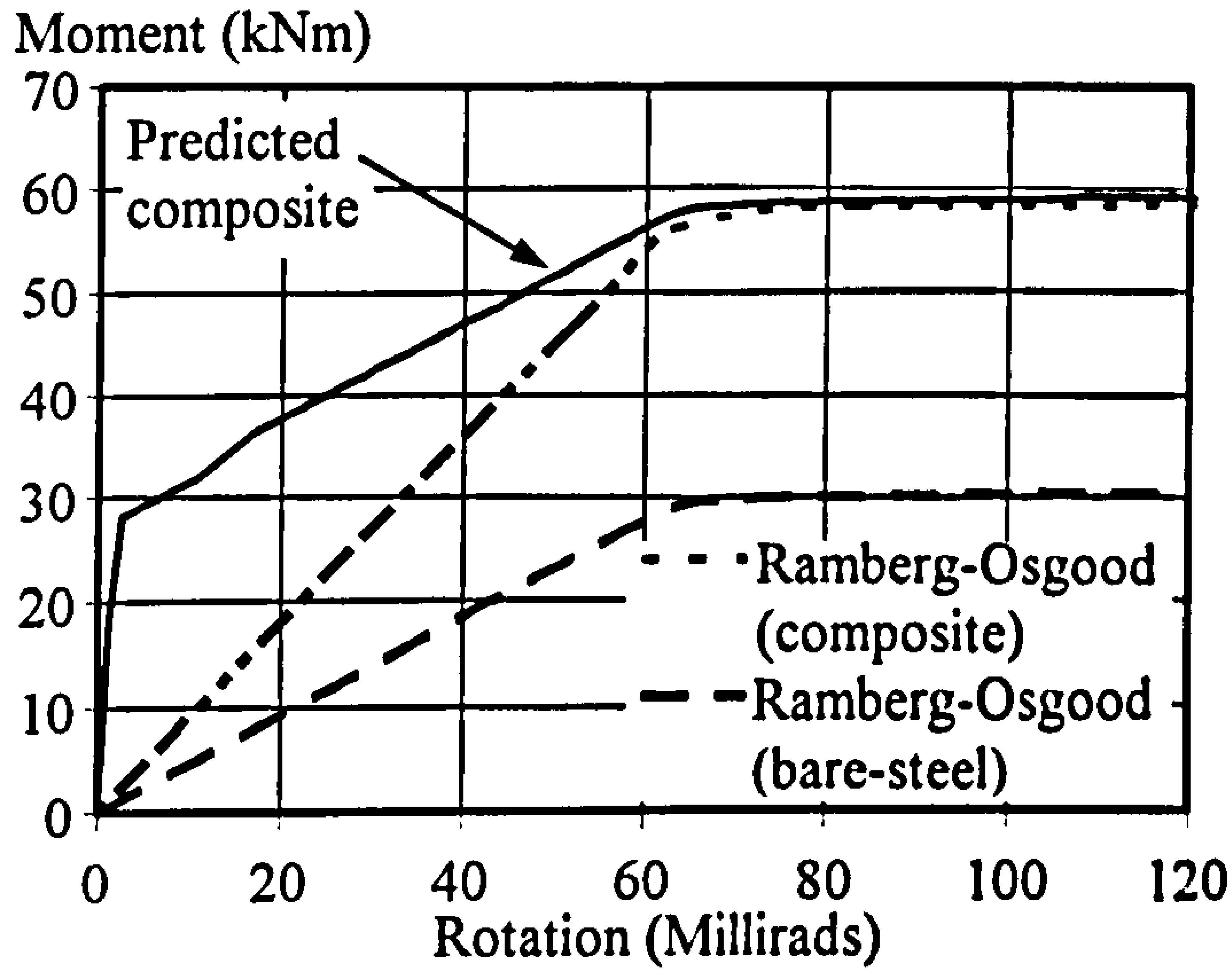


Figure 7.23. Ambient-Temperature Ramberg-Osgood Curve-Fit for Group 6 - Composite Connection

Temperature	*A*	*B*	*n*
20°C / 100°C	*0.460*	*28.000*	*100.00*
200°C	*0.414*	*25.928*	*"*
300°C	*0.334*	*23.744*	*"*
400°C	*0.260*	*21.700*	*"*
500°C	*0.218*	*17.304*	*"*
600°C	*0.115*	*9.996*	*"*
700°C	*0.050*	*4.732*	*"*

Table 7.12. Postulated Elevated-Temperature Bare-Steel Characteristics for Group 6

Temperature	*A*	*B*	*n*
20°C / 100°C	*0.460*	*54.000*	*100.00*
200°C	*0.414*	*21.761*	*"*
300°C	*0.334*	*49.444*	*"*
400°C	*0.260*	*47.267*	*"*
500°C	*0.218*	*42.743*	*"*
600°C	*0.115*	*35.315*	*"*
700°C	*0.050*	*29.926*	*"*

Table 7.13. Postulated Elevated-Temperature Composite Characteristics for Group 6

7.6.2. Composite Three-Dimensional Frame Analysis

The three-dimensional response of the Cardington test frame under fire conditions (Test 7) has been analysed using the program developed by Bailey[22], where the extent of the sub-frame includes an area representative of that incorporated within two-dimensional testing (Test 3). The extent of the structure modelled is as indicated in Fig. 7.17, with advantage once more being taken of symmetry of the structure. Elevated-temperature connection characteristics have been incorporated based on the recommendations of Section 7.6.1 (a total of 37 connections). External connections were assumed to behave as though bare-steel due to lack of continuity of reinforcement in the tension zone. assumptions adopted were as described in Section 7.4.2 and 7.5.3 (excluding point 5).

Analysis has been conducted assuming the actual postulated connection characteristics and ratios of 50% and 200% of connection characteristics, and compared with the limiting cases of pinned and rigid connection characteristics. A connection temperature 80% of the beam lower flange temperature has been adopted in analysis, and the analysis repeated for a connection temperature 50% of the beam lower flange temperature for 100% connection characteristics (reduced temperature). The reduced connection temperature assumes the provision of fire protection of columns to extend to the underside of the floor above, as was the case for Test 7.

Deflections have been plotted for the locations indicated in Fig. 7.24. Deflections at points Delta 1 and Delta 2 are comparable with those plotted previously for Test 3 (which was analysed as a two-dimensional structure), and as such deflections at these locations are plotted in relative terms (accounting for displacement of the column head). Delta 3, Delta 4 and Delta 5 represent deflections of internal spanning secondary beams. These will be

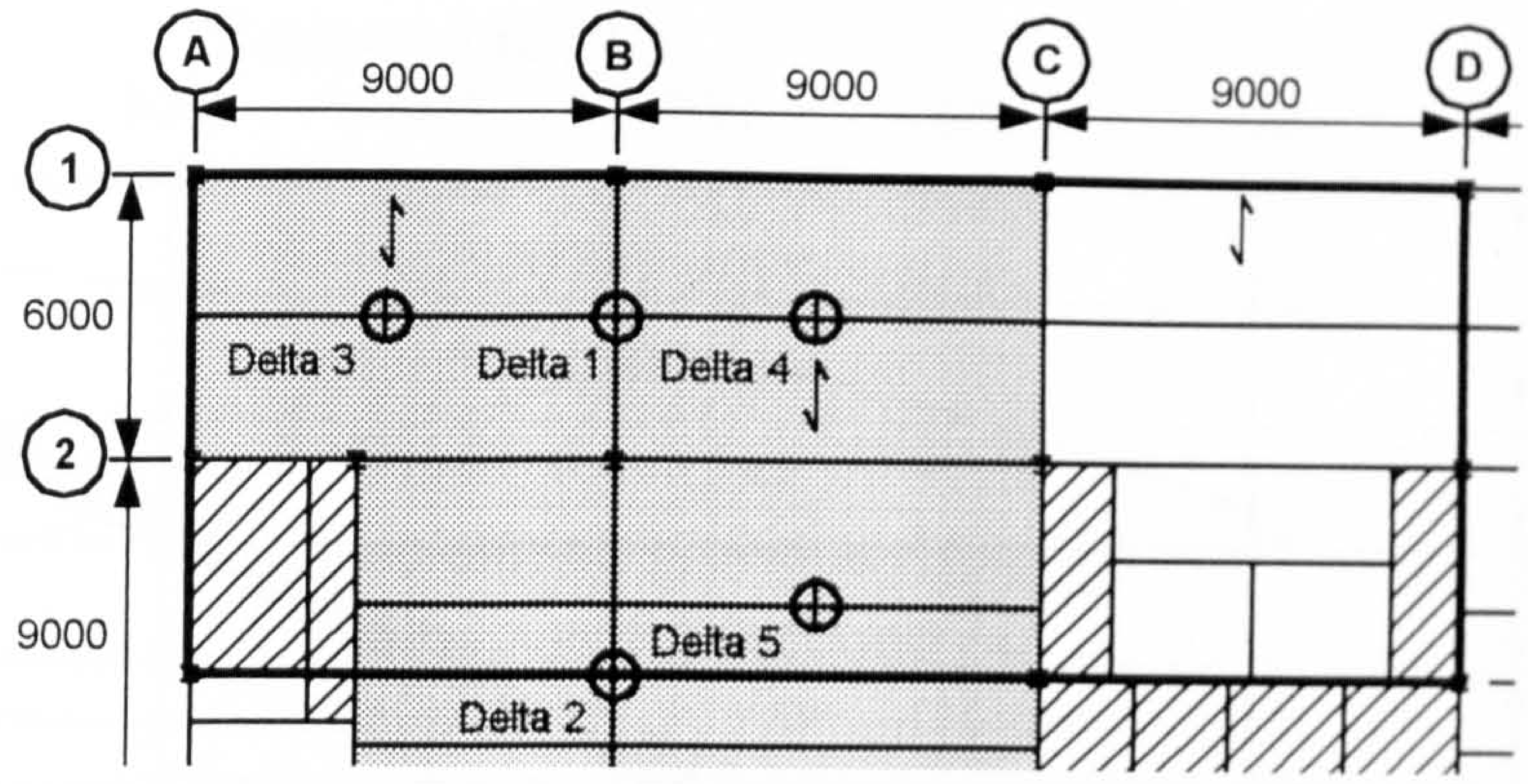


Figure 7.24. Location of Plotted Displacements

influenced by connection characteristics for the main beams in addition to the response of the end connections. As such deflections at these points have been plotted in absolute terms, indicating the cumulative effect of semi-rigid response. Resultant deflections are plotted in Figs. 7.25 to 7.29 below. Rotations are once more plotted for the internal 356UB and 610UB major-axis flexible end-plate connection.

From Figs. 7.25 and 7.26 it may clearly be seen that the incorporation of the three-dimensional response of the structure at elevated-temperatures has a significant influence on the resultant deflections. Predicted deflections for a temperature of 700°C for both the 356UB and 610UB remained below 100mm, compared with deflections in the region of 300mm analysing the structure as a two-dimensional composite arrangement, indicating the significance of slab action for increasing temperatures. Analysis terminated at comparatively low temperatures due to convergence failure. This was observed previously by Bailey, and is attributable[22] to cracking of the concrete in the tension zone. The enhancement in capacity arising from the incorporation of major axis connections for the 356UB and 610UB is comparable with that experienced from the two-dimensional analysis, and may be seen to increase for similarly increasing temperatures. Analysis of the structure for reduced connection temperature results in a slight enhancement in performance. However, whilst initial indications suggest that a similar increase in performance is observed incorporating semi-rigid connection characteristics within three-dimensional composite frame analysis, the low failure-temperature (and associated low levels of deflection experienced) obviate a direct comparison of response at the point where beam deflections begin to run away, and it is within this range of response that we are primarily concerned. It may be seen that maximum connection rotations for the 356UB and 610UB are limited to 80 millirads. This is significantly lower than for the two-dimensional composite frame analysis, but is comparable for the level of deflection experienced.

The influence of 'flexible' beam-to-beam connections has been considered at locations Delta 3, Delta 4 and Delta 5 as shown in Figs. 7.27, 7.28 and 7.29. It may be seen that far greater levels of deflections were experienced than for the major axis framing 356UB and 610UB. This conforms with observation of the fire damaged structure. It may be seen that a slight increase in performance is observed incorporating semi-rigid connection characteristics. However, it must be remembered that these represent absolute deflections, and as such are influenced by deflections of connected members. Thus, although an enhancement of approximately 25mm is seen including realistic connection characteristics, some of this will be attributable to the reduced deflection of the connected members.

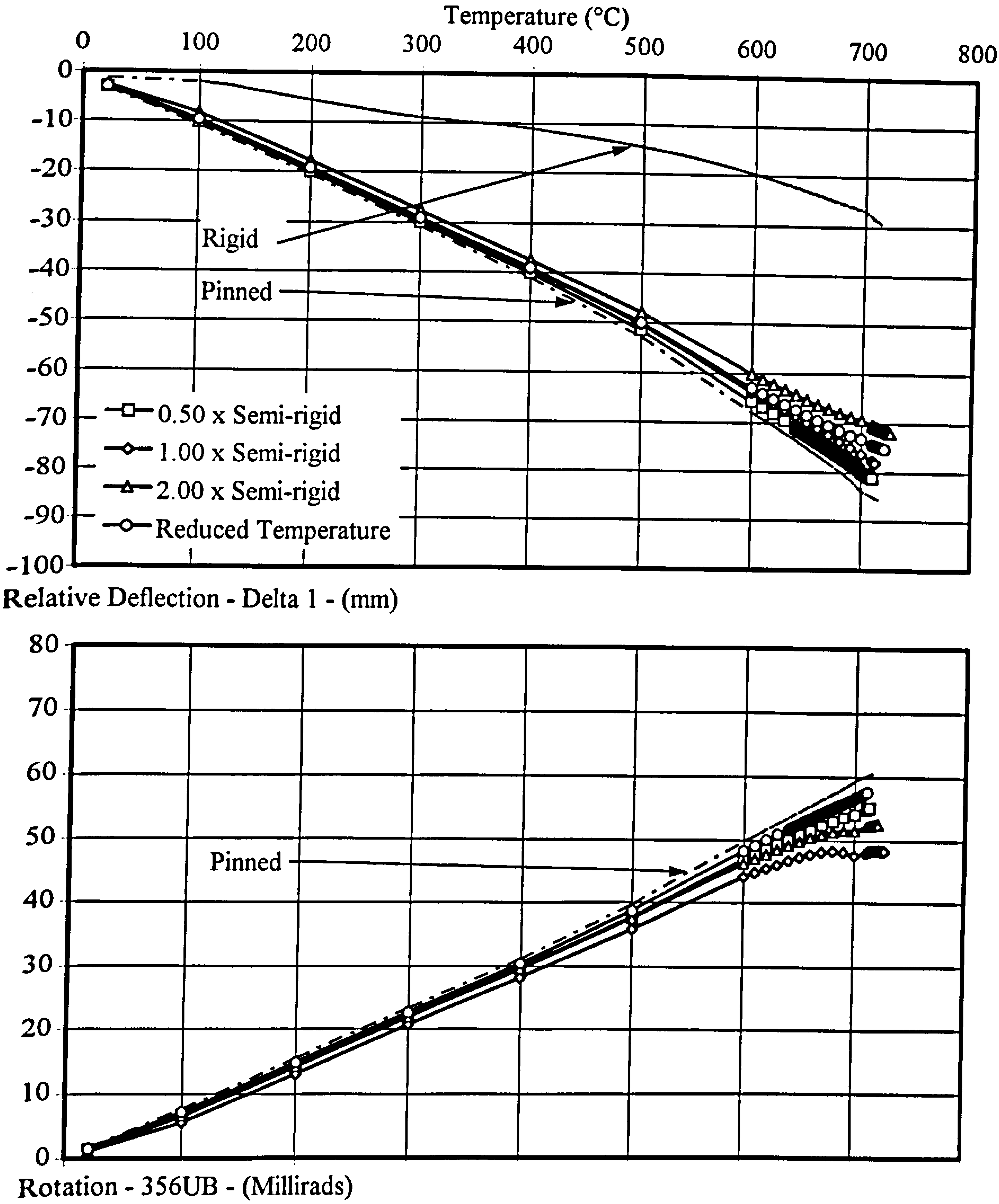


Figure 7.25. Relative Deflections and Corresponding Rotations for Delta 1 (356UB) - Analysis of Cardington Test 7 as 3D Composite -

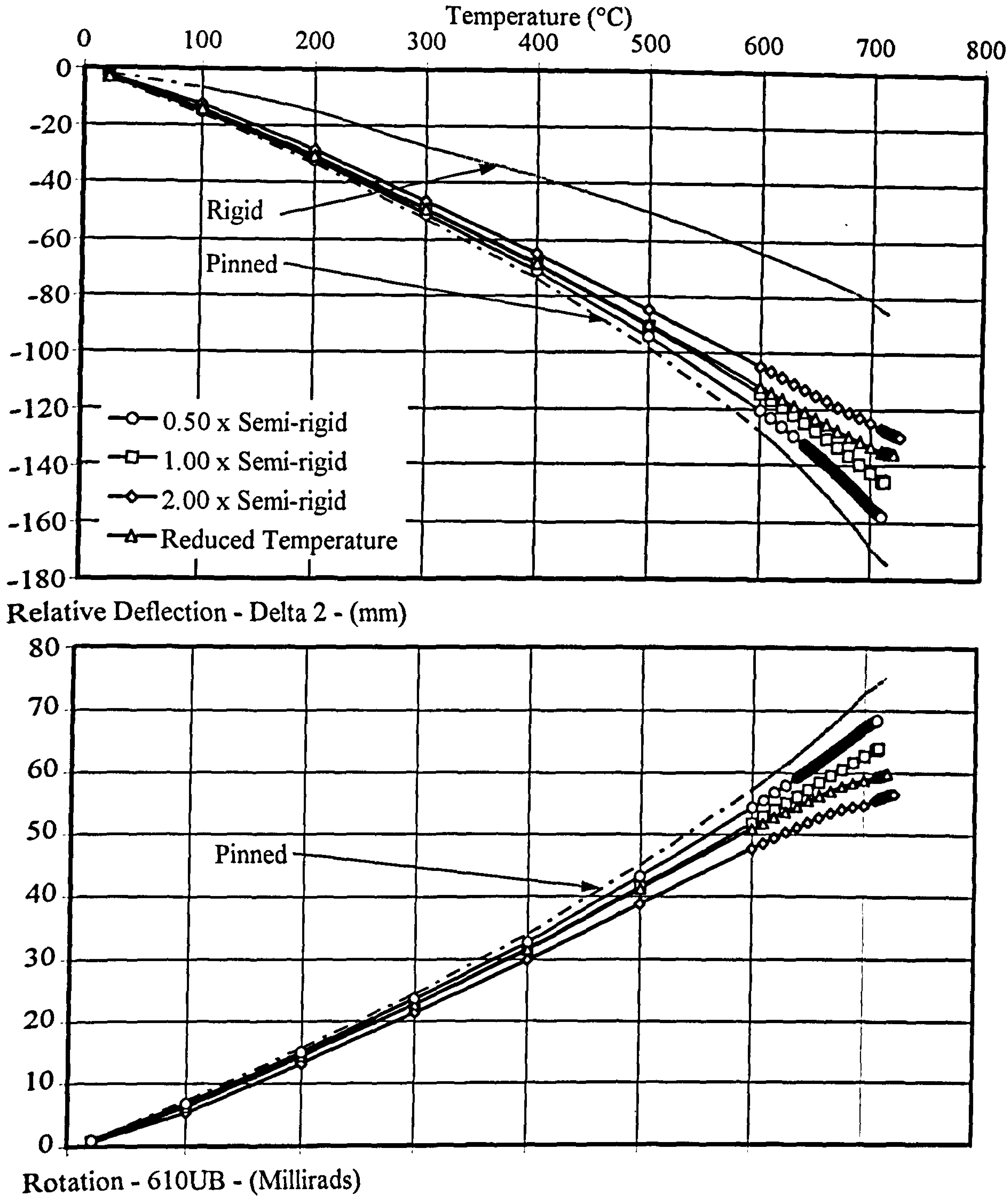


Figure 7.26. Relative Deflections and Corresponding Rotations for Delta 2 (610UB) - Analysis of Cardington Test 7 as 3D Composite -

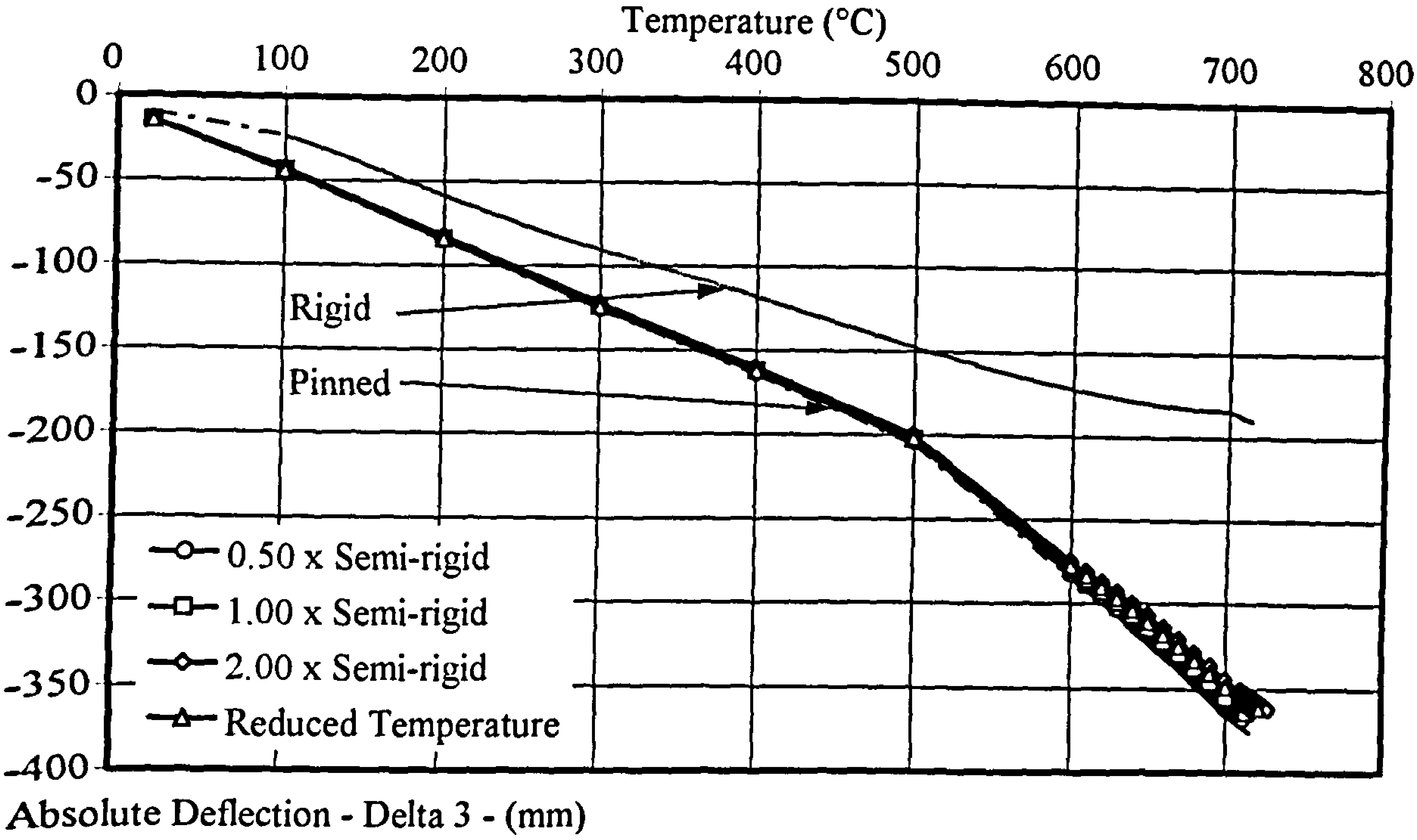


Figure 7.27. Absolute Deflections for Delta 3 (305UB)
- Analysis of Cardington Test 7 as 3D Composite -

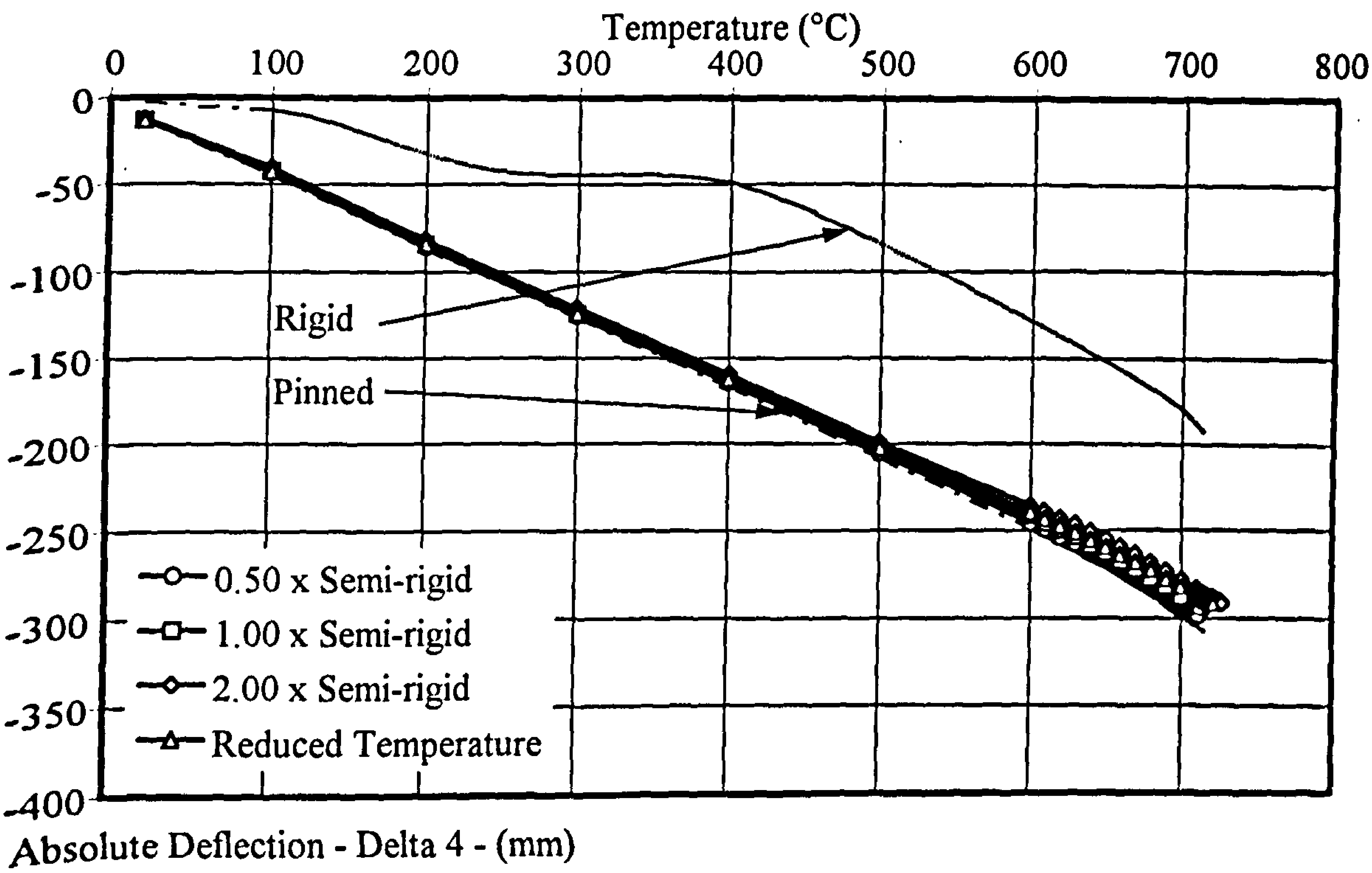


Figure 7.28. Absolute Deflections for Delta 4 (305UB)
- Analysis of Cardington Test 7 as 3D Composite -

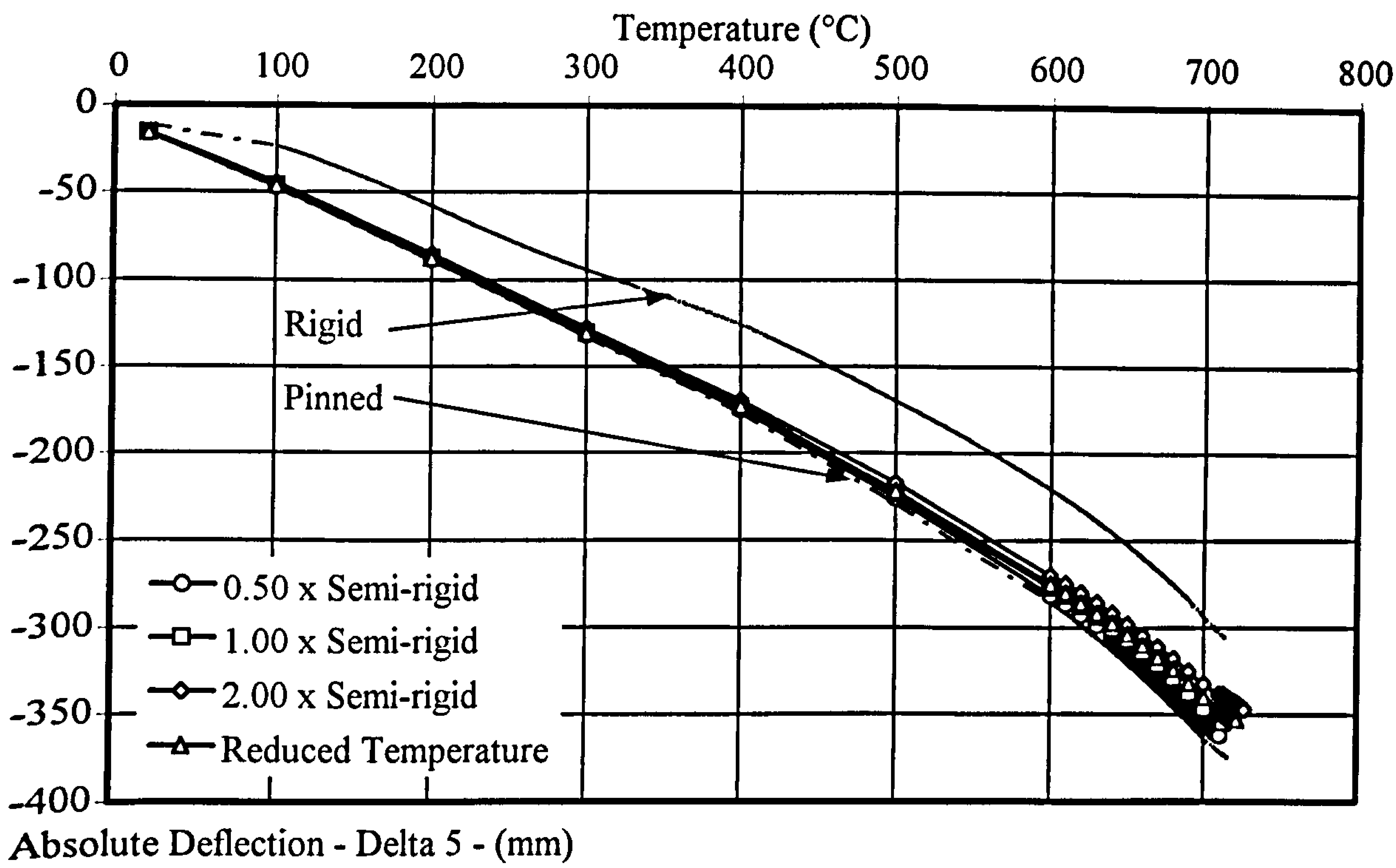


Figure 7.29. Absolute Deflections for Delta 5 (305UB)
- Analysis of Cardington Test 7 as 3D Composite -

Considering the response of the major axis framing 356UB and 610UB of Figs. 7.25 and 7.26 once more it may be seen that variation in deflection incorporating semi-rigid response is less than 10mm. As such, it may be concluded that even very flexible connections can have a significant effect when considering the connection to act compositely. It is interesting to note the enhanced response at Delta 4 arising from continuity, with the right hand end of the beam being connected continuously to an element of the structure remaining at ambient-temperature.

7.7. FAILURE MECHANISMS OBSERVED IN THE CARDINGTON TESTS

A significant observation from the Cardington frame tests was that in isolated cases failure of the weld connecting the partial-depth end-plate to the beam web fractured along its full length. It is expected that this failure occurred as a result of high tensile forces developing during cooling of the structure. As described in Chapter 2, the rate of thermal expansion of steel is in the region of 12x10-6/°C, representing a thermal expansion in the order of 9.6×10^{-3} strain for an increase in temperature to 900°C (86mm for a 9000mm span). Upon cooling a degree of thermal contraction is relieved by a reduction in the vertical deflection of the beams, but a considerable tensile force is still induced within the weld connecting the beam to the end-plate. A comparable mode of failure was observed upon inspection of the Broadgate structure after fire damage[11].

A tensile force approaching 400kN has been calculated by Bailey[22] for the Cardington restrained beam test (Test 2) upon cooling. The capacity of a single side of the weld connecting the beam for Test 2 is approximately 300kN at ambient-temperatures based on the recommendations of BS5950[161] and assuming the strength of the weld to be equal to that of the connected plate. This is clearly below the calculated applied force, and as such it would be anticipated that fracture of welds represents a realistic failure mechanism. It is interesting to note that this is a phenomenon which is exacerbated by compartmentation, with the degree of axial restraint provided being greater where remote parts of the structure remain at a significantly reduced temperature.

In all cases fracture of the weld was seen to occur along one side of the connection only. This may be expected for flexible end-plate connections as once one side of the weld has fractured, the horizontal flexibility of the connection increases significantly through deformation of the connecting plate. This results in the vertical shear forces being carried compositely by one half of the connection and the tension reinforcement within the slab.

Whilst in the case of composite connections it was observed that the slab provided a degree of additional capacity in resisting vertical shear forces, it may be advisable that in the design of connections for fire conditions precautions are adopted to ensure that the capacity of the bolts and weld are at least double that required to carry the resultant vertical ULS shear forces to prevent collapse.

7.8. CONCLUSIONS

The studies of Chapter 6 have been extended to consider the response of a realistic structure. It was decided to adopt the Cardington test frame as a case study as this was designed to be representative of current practice, and a series of fire tests conducted by the Building Research Establishment and British Steel will provide information of the true elevated-temperature response of the structure at a later date. Elevated-temperature tests have not been conducted to date for the connections contained within the Cardington test frame, and as such a series of ambient-temperature bare-steel tests conducted by Boreman[47] have been used as a basis for the postulation of both bare-steel and composite elevated-temperature connection characteristics. It should be remembered that whilst it is anticipated that postulated connection characteristics present a reasonable approximation of connection response, true behaviour may be different from that adopted in these studies. The analysis has been repeated for a range of connection response (50% and 200%) such that a realistic range of response may be defined.

Bare-steel connection characteristics have been degraded for increasing temperatures by varying the terms A and B within the Ramberg-Osgood expression, based on levels of strain contained within the proportional limit and of 0.5%, and the rates of degradation presented in EC3: Part 1.2[8], with these rates of degradation comparing closely with that observed experimentally in Chapter 3.

The structure was initially analysed as a two-dimensional bare-steel structure based on the plane-frame test (Test 3). True connection response follows two stages, with an increase of stiffness occurring when the beam lower flange comes into bearing with the column. This increase in capacity has been neglected, representing a conservative approximation of true behaviour. It was found that the incorporation of semi-rigid connection characteristics within frame analysis resulted in a slight enhancement in structural response considering central deflections of both the 356UB and 610UB. However, the resultant enhancement was less than that observed for the arrangement of Chapter 6, and was seen to diminish for increasing temperatures. The reduction in enhancement may have been anticipated as the flexible end-plate type connection typically has a lower relative capacity than flush end-plate connections, with connections CANT3 and CANT4 having relative capacities of $0.16M_p$ and $0.20M_p$ respectively, compared to $0.50M_p$ for the bare-steel flush end-plate connection tested. Considering Fig. 7.9 it may be seen that a constant deflection is predicted regardless of assumed connection characteristics for a temperature approaching 750°C. A similar form of response is predicted for the 610UB as shown in Fig. 7.10, although the temperature at which deflections converge is somewhat higher. This results in the predicted enhancement incorporating the characteristics of CANT3 being less than that for CANT4. It is suggested that the diminishing influence of semi-rigid characteristics may be attributable to the degree of axial restraint provided as discussed in Chapter 6.

Levels of rotation predicted were once more greater than 100 millirads, and as such connection response would be expected to enter stage 2, with this representing an increase in capacity to $0.27M_p$ for CANT3. As such the bare-steel sub-frame has been reanalysed incorporating the two-stage response of connection CANT3 (results only being available for stage 1 of CANT4), with the non-linear moment-rotation response being defined by a modified form of the Ramberg-Osgood expression. It was found that this resulted in an increase in capacity at higher temperatures, up to a level assuming approximately 200% of the characteristics of stage 1 alone. However, response was once more complicated by the convergence of displacements with increasing temperature. As such it would seem that a value of approximately 200% of the stage 1 connection characteristics may more accurately represent the true capacity of the connections, and it is therefore desirable that, when considering elevated-temperature response for flexible end-plate type connections, the full range of response is defined.

The prediction of composite response is complicated by its two-stage form, and relocation of the centre of rotation as the beam lower flange comes into bearing with the column. However, as results for stage 2 are only available for 2 of the 7 flexible end-plate connections tested, connection response has been based on stage 1 only. Rotation of the connection is assumed to occur about the beam lower flange. This represents an un-conservative approximation at low levels of rotation, but is more accurate for the range of response in which we are interested. The effects of shear-lag have been neglected, and an effective width of slab of 1000mm adopted. The incorporation of composite conditions resulted in a reduction in the relative capacity of connections CANT3 and CANT4 to approximately $0.14M_p$ and $0.16M_p$ respectively at ambient-temperature. Composite connection characteristics have been degraded for increasing temperatures based on the relative temperatures of the exposed connection and reinforcement at a reduced temperature.

Analysis of the two-dimensional plane-frame test incorporating the composite slab and semi-rigid connection characteristics once more demonstrated a slight enhancement in response compared to the assumption of pinned characteristics. However, as with the bare-steel arrangement, the resultant reduction in deflections at any given temperature was small due to the relatively low capacity of the flexible end-plate connection.

Analysis of the structure has been extended to consider full three-dimensional response, incorporating the area of the plane-frame analysis to allow consideration of the influence of slab action. Bare-steel and composite connection characteristics have once more been predicted for increasing temperatures based on ambient-temperature tests by Boreman.

It was observed that considering the full three-dimensional response of the structure the relative deflections of the 356UB and 610UB incorporated within the plane-frame analysis were significantly reduced, with deflections remaining below 100mm for temperatures in excess of 700°C. Deflections of secondary beams were predicted to be far greater, corresponding with the form of response observed from inspection of the structure after testing (Test 7). The increase in capacity from the inclusion of composite characteristics for the 356UB and 610UB were comparable with that observed for two-dimensional analysis, indicating that despite the significant enhancement observed considering three-dimensional response, semi-rigid action remains influential. However, as predicted displacements were small, the maximum reduction incorporating semi-rigid connection characteristics for the 356UB and 610UB was in the region of 5mm.

The influence of semi-rigid characteristics on the secondary beams considered was lower due to the reduced capacity of the fin-plate connections adopted for beam-to-beam connections. However, a slight increase in capacity was still observed, with mid-span deflections being reduced by approximately 10 to 25mm at 700°C. It should be remembered that these are plotted in absolute terms and as such will be influenced by the reduced deflection of the connected beam, and as such the relative influence is somewhat lower than that indicated.

In general it would seem from the studies of the Cardington test frame that when considering connections which possess a relative capacity significantly lower than that of the comparatively stiff flush end-plate connection tested, the influence of considering semi-rigid response diminishes accordingly. As such it is questionable as to whether the expense of developing and incorporating semi-rigid characteristics within analysis is validated for these types of connections, particularly when considering beam-to-beam connections in which a very flexible connection is commonly chosen such as the fin-plate connection.

Inspection of the Cardington test frame subsequent to testing demonstrated that in isolated cases the weld connecting the partial-depth end-plate to the beam web fractured along its entire length. It is suggested that this may have occurred as a result of the high tensile forces that are generated during the cooling phase, a phenomenon which becomes yet more pronounced where the extent of the fire is restricted to a small compartment. It was suggested that to avoid collapse through this potential failure mechanism, bolts and welds should be over designed such that a single half of the connection is capable of transmitting the vertical shear forces.

8. CONCLUSIONS AND FURTHER RECOMMENDATIONS

The provision of adequate fire resistance for steel and composite framed structures is generally provided by the use of some form of insulating material, with the aim of limiting the temperature of the steel such that sufficient strength is maintained. However, the fire protection of steel structures is costly due to both the direct application costs and the costs associated with the resultant delays in the construction process, and has remained a significant factor in the decision between the use of steel or concrete structures.

It has been known for many years that the performance of both bare-steel and composite steel-concrete frames is better in the case of a real fire than indicated considering the behaviour of isolated components, with beams, columns and floor slabs interacting with each other giving the frame a much higher fire resistance. This has generated much interest in the inherent fire resistance of steel structures over recent years, with the aim of reducing the cost of fire protection.

Observation of fire damaged structures[11] and recent fire tests at the Cardington LBTF[13] have suggested that even nominally 'simple' connections are capable of providing significant restraint at elevated-temperatures. As most frames are designed assuming pinned response at ambient-temperature, with no account being taken of the reduction in mid-span moments, this is an aspect of connectivity which may be utilised in the assessment of the fire resistance of steel framed buildings, without necessitating changes in the approach adopted in ambient-temperature design or construction. To date the assessment of the influence of connection response on frame behaviour has been limited by the quantity of available test data, although initial studies based on postulated moment-rotation-temperature characteristics concluded that the failure temperatures for beams are increased due to the rigidity of 'simple' connections[22].

8.1. EXPERIMENTAL STUDIES

Previous experimental studies into the elevated-temperature response of both bare-steel and composite connections have consisted of a single test for each arrangement, with the connection being tested under a constant load with increasing temperature. Clearly to define accurately the full moment-rotation-temperature response for a given arrangement it is necessary to conduct a series of tests, where specimens are subject to varying levels of constant temperature with increasing load, or varying constant load and similarly increasing temperatures.

As such a series of tests has been conducted for a single flush end-plate connection, both as bare-steel and composite with a concrete slab, for an arrangement of constant load and increasing temperatures. The scope of the programme was restricted by the resources available and the number of tests required to define accurately the connection characteristics at elevated-temperatures. The flush end-plate connection was selected as this represents the most common connection type currently used in non-composite building frames[46], and as the popularity of this connection type appears to be increasing with the trend towards the standardisation of connections[41,45].

For both the bare-steel and composite connections an initial moment-rotation test was conducted on a cruciform specimen at ambient-temperature.

The bare-steel specimen was tested up to rotations approaching 100 millirads. The maximum capacity of the connection was recorded as approximately 40kNm ($0.48M_p$), although the onset of plasticity occurred at a significantly lower moment of 17kNm. Failure of the connection was predominantly controlled by deformation of the relatively flexible column section. At the fire limit state the permissible deflections (and hence rotations) are far greater than those associated with ambient-temperature design, and as such it is desirable within experimentation that the range of rotations considered is increased accordingly. As seen for the bare-steel connection, the moments resisted by the connection increased significantly when including the plastic range of response.

Significant deformation of the column was also observed for the composite connection at ambient-temperature. However, failure of the composite arrangement was characterised by yielding of reinforcement in the tension zone at a rotation approaching 40 millirads. It had not been anticipated that reinforcement failure would occur at such low levels of rotation based on an assumed debonded length corresponding with either the location of the first shear stud or the first transverse reinforcing bar, and as such it is suggested that confinement of the concrete between the column flanges may have resulted in a reduction in debonded length. Due to the early yielding of reinforcement, the capacity of the composite connection was not increased significantly over that of the bare-steel arrangement.

Elevated-temperature tests were once more of cruciform arrangements, with specimens being located within a gas fired furnace. Instrumentation of elevated-temperature tests is complicated by the hostility of the environment. As such rotations were monitored indirectly using silica rods which passed through the wall of the furnace, with direct rotations being recorded using clinometer devices attached to the beams, where the accuracy of both approaches had been calibrated within ambient-temperature testing. The limiting temperature for the clinometers was approximately 80°C (compared to maximum furnace temperatures approaching 800°C), with working temperatures being limited by situating the devices within protective housings cooled by compressed air. Despite initial difficulties encountered due to the protected clinometers acting as a heat sink during cooling of the furnace, it was found that provided the furnace was cooled rapidly subsequent to testing, it was possible to limit the temperature of the clinometers within their working range, facilitating the direct measurement of rotations. A number of thermocouples were used to record the temperature distribution within the section during testing.

It was observed that for the bare-steel specimens tested at elevated-temperatures the mechanism of failure was qualitatively similar to that at ambient-temperature. Both stiffness and capacity of the connection were seen to decrease with increasing temperatures, and it was observed that there was a significant reduction in capacity for temperatures in the range of 500 to 600°C, corresponding with the critical temperature for steel.

With increasing temperatures it would be anticipated that the capacity of composite connections would degrade at a lower rate than their bare-steel counterpart, due to the reinforcement in the tension zone remaining at a reduced temperature as observed in the composite connection tests. In these the reinforcement temperature remained at approximately 20% of the beam lower flange. As with the ambient-temperature test, significant deformation was observed within the relatively flexible column. Due to the increased flexibility of the column web in the compression zone, at a significantly higher temperature than the reinforcement in the tension zone, it was observed that with increasing temperatures failure of the reinforcement within the tension zone was obviated. The degradation of composite connection stiffness was observed to be comparable to that of the bare-steel connection, where this was controlled by the stiffness of the column web in the compression zone.

Following the Broadgate Phase 8 fire[11] it was proposed that 'The current UK and European research work on connections requires further development to ensure the necessary balance of elasticity is maintained within the frame during the fire'. The maintenance of structural integrity, through ensuring sufficient ductility exists within connections at the fire limit state, should form a prerequisite in the consideration of connection behaviour. As discussed, for both the bare-steel and composite arrangements tested, significant levels of rotation were experienced with no evidence of the onset of failure (other than in an isolated case in which a bolt was seen to fracture), and in the case of the composite arrangement the ductility of the connection was seen to increase. It was observed subsequent to a series of large scale fire tests conducted at the Cardington LBTF that in general connection integrity was maintained. However, in isolated cases the weld connecting the partial-depth end-plate to the beam web fractured along its entire length. It is suggested that this may have occurred as a result of the high tensile forces that are generated during the cooling phase of a fire, a phenomenon which becomes yet more pronounced where the extent of the fire is restricted to a small compartment. It is suggested that to avoid collapse through this potential failure mechanism, bolts and welds may be over designed such that a single half of the connection is capable of transmitting the vertical shear force at the fire limit state.

The ductility of reinforcement within composite connections is controlled by the debonded length. Determination of the true debonded length is complicated by many factors, and as seen from the ambient-temperature test may be significantly reduced due to influences such as confinement of concrete between the column flanges. As such it seems that one acceptable approach to ensure the ductility of reinforcement at the fire limit state may be to artificially induce de-bonding of reinforcement over a length sufficient to ensure that yielding will not occur within the range of rotations anticipated. Whilst this would result in a reduction in the initial stiffness of the composite connection, at the large levels of rotation experienced at the fire limit state it has been observed that it is predominantly the plastic capacity of the connection which controls the resultant failure-temperature.

Consideration of the degradation of connection characteristics is desirable as this facilitates the approximation of elevated-temperature response based on the extensive fund of existing ambient-temperature test data.

As discussed, the stiffness of both bare-steel and composite arrangements degraded at a similar rate, where this was seen to be dominated by deformation of the column web in the compression zone. Adopting the temperature of the column web as the connection temperature it was observed that an acceptable prediction of connection stiffness was achieved for the arrangement tested based on the rates of degradation of material properties specified in EC3: Part 1.2[8], for a level of strain contained within the proportional limit.

Degradation of the capacity of the bare-steel connection was seen to be approximated with a sufficient degree of accuracy adopting the rates of material degradation specified in EC3: Part 1.2[8], and a level of strain of 0.5% (plastic-range), with the temperature of the connection once more being assumed to be that of the critical element.

Assessment of the degradation of composite connection capacity is complicated by the existence of reinforcing mesh in the tension zone, which remains at a significantly lower temperature than the exposed steel. Assessment of the proportion of overall connection capacity attributable to the bare-steel connection and reinforcing mesh, and degradation of connection capacity accordingly, resulted in a rate of degradation which deviated from that observed experimentally. It is suggested that this may be due to the relocation of the neutral axis as testing progressed, with the behaviour of the compression zone eventually controlling the capacity of the connection. A more accurate assessment of the degradation of composite connection response may be achieved for an arrangement in which the flexibility of the compression zone has a smaller influence, for example in situations where the column web is stiffened in the compression zone, or where a stiffer column section is adopted.

Moment-rotation responses for both the bare-steel and composite connections tested have been degraded for increasing temperatures based on predicted rates of degradation, and incorporated within the elevated-temperature analysis of two-dimensional sub-frames. It was observed that for both the bare-steel and composite arrangements an acceptable representation of overall frame response was achieved, despite the inaccuracies in predicting accurately the degradation of composite connection capacity. This supports the opinion that an acceptable representation of frame response may be achieved incorporating approximate connection characteristics.

8.2. REPRESENTATION OF CONNECTION CHARACTERISTICS

The representation of elevated-temperature in a form suitable for incorporation within numerical analysis is a primary concern in facilitating the assessment of the influence of semi-rigid response on frame behaviour.

At ambient-temperatures it is desirable that the equation should ideally represent the moment-rotation response in terms of key parameters such as initial-stiffness and moment capacity, should be capable of representing the full non-linear moment-rotation response passing through the origin, and should yield a positive slope corresponding with the rotational stiffness of the connection.

Nethercot *et. al.*[77] concluded from studies of both frames and individually restrained members that behaviour beyond 50 millirads has little practical significance in the case of ambient-temperature analysis. However, studies have shown that rotations in excess of 100 millirads are common with increasing-temperatures. Based on initial studies considering the influence of the form of curve-fit adopted on the response of a bare-steel sub-frame at elevated-temperatures, it has been demonstrated that:

1. A purely elastic representation of connection response results in an inaccurate prediction of elevated-temperature frame response, with the response tending towards that observed assuming rigid connections.
2. Due to the large levels of rotation experienced, it is required that the curve-fit is applied over the full range of moment-rotation response. Where experimental data is only available for a limited range of response, it is desirable that a plastic plateau should be assumed, restricting the capacity of the connection to that known.
3. Overall frame response is not highly sensitive to the form of curve-fit adopted at elevated-temperatures, and as such an acceptable representation of frame behaviour may be achieved representing fully non-linear moment-rotation response in a simplified bi-linear or multi-linear form, where care is paid to ensure that the plastic range of response is incorporated.
4. In the case of connections where the beam lower flange comes into contact with the column flange at high levels of rotation (such as the partial depth end-plate), the form of curve-fit adopted should be capable of following the subsequent increase in connection stiffness.

It was concluded that the Ramberg-Osgood[88] form of curve-fit is well suited to representing elevated-temperature moment-rotation response, being defined by a single expression, and always yielding a positive slope corresponding with the tangent-stiffness of the connection. Application of the Ramberg-Osgood expression to elevated-temperature connection data yields the advantage that the equation may be easily degraded for increasing temperatures by modification of the terms A and B, where these control the stiffness and capacity of the connection respectively. This assumes the general form of the moment-rotation response to remain consistent for increasing temperatures, an assumption which is supported by observation of the moment-rotation response for both the bare-steel and composite flush end-plate connections tested.

The Ramberg-Osgood expression describes a curve of decreasing stiffness with similarly increasing rotations, and as such is not capable of following the subsequent increase in stiffness observed for the flexible end-plate connection where the beam lower flange comes into bearing with the column flange. As such a modified form of the expression has been presented, where a second curve is superimposed at an artificially introduced origin (ϕ_l, M_l), corresponding with the location at which the beam comes into bearing with the supporting member. It has been demonstrated that neglecting the second phase of response for partial-depth end-plate connections may result in a significant underestimate of the influence of semi-rigid characteristics on frame response.

8.3. MODELLING CONNECTION RESPONSE

Whilst experimentation remains the most reliable form of generating connection characteristics, due to the large quantity of arrangements which may exist, and the expense of testing, it is desirable that the moment-rotation response of connections may be accurately predicted. The modelling of connection response becomes yet more significant at elevated-temperatures due to the increased number of tests required to define the response for each arrangement.

A spring-stiffness model has been presented for the prediction of elevated-temperature bare-steel and composite flush end-plate connection response. The use of a spring-stiffness model compares favourably with other forms of modelling due to the combination of efficient solution and the ability to follow accurately the full non-linear range of connection response, based on an understanding of the response of the component parts. A multi-linear representation of response has been adopted, where the stiffness of the connection is revised as elements entered the plastic range of response. As discussed above, overall frame response has been seen to be followed with a degree of sufficient accuracy based on a simplified representation of the true non-linear response, and the use of multi-linear modelling obviates the need to incorporate fully non-linear stress-strain properties within the analysis, thus allowing the determination of connection response from hand calculations. Formulation of both the bare-steel and composite model facilitates the introduction of any chosen temperature distribution across the depth of the connection.

Within the bare-steel spring stiffness model, flush end-plate response was assumed to be controlled by the deformation of bolts, end-plate and column flanges in the tension zone, and the column web in the compression zone. Simplified mechanical models have been presented for these component parts based on techniques associated with ambient-temperature modelling, with material properties being modified based on the component temperature. Comparison of the bare-steel model with existing test data demonstrated that connection response and failure mode may be accurately predicted. With increasing temperatures the degradation of connection stiffness and capacity was seen to compare closely with that observed for the bare-steel flush end-plate connection tested.

For the composite flush end-plate model the influence of reinforcement in the tension zone at a significantly reduced temperature has been incorporated, with allowance being made for slip at the beam-slab interface. The model presented was seen to follow closely the ambient-temperature moment-rotation response of the connection, and to accurately predict failure of the connection to be controlled by yielding of the column web in the compression zone, and failure of the reinforcement acting in tension. Modelling of the degradation of connection stiffness and capacity was once more effected by the propagation of the centre of rotation into the depth of the connection due to column web yielding. This resulted in inaccuracies in the calculated rates of degradation due to rotation of the connection being assumed to occur about the centre-line of the beam lower flange. As such it is recommended that further work is required to incorporate movement of the centre of rotation within the formulation. To facilitate accurate determination of the location of the centre of rotation it is felt that further experimental work is necessary, considering column web response in isolation. It is anticipated that in cases where the capacity of the column web is increased significantly, a closer representation of elevated-temperature response may be achieved from the described spring-stiffness model.

Predicted moment-rotation-temperature characteristics for the bare-steel and composite connections tested have once more incorporated within sub-frame analysis. It was observed for the bare-steel arrangement that the full temperature-deflection response was accurately predicted incorporating the predicted connection characteristics. For the composite arrangement the temperature-deflection response was predicted accurately at low temperatures, but with increasing temperatures deviated from the form of response observed incorporating experimental moment-rotation characteristics.

It is anticipated that within design, where interest in focused on failure-temperature as opposed to the full temperature-deflection response, it may be acceptable for typical arrangements of beam-to-column connections to adopt a rigid perfectly-plastic representation of connection behaviour, limiting the extent of modelling to the determination of the connection capacity at the level of rotation associated with the limiting deflection, and the degradation of capacity with increasing temperatures.

Finite element modelling of the bare-steel arrangement has been conducted by Liu[116] incorporating realistic material and geometrical properties, and temperature distributions, as obtained from experimentation. It was demonstrated that for the connection tested finite element modelling provides a powerful tool capable of accurately predicting elevated-temperature connection response. The composite flush end-plate tested is to be incorporated within the validation of a composite finite element connection model currently under development by Liu. Reliable finite-element models present an invaluable tool due to the expense of testing, particularly where the standardisation of connection types is considered, as this facilitates the development of accurate moment-rotation-temperature response for the range of connection types commonly used, and results in an improved understanding of connection response.

8.4. INFLUENCE OF CONNECTION RESPONSE ON FRAME BEHAVIOUR

Elevated-temperature moment-rotation characteristics for the bare-steel and composite flush end-plate connections tested have been incorporated within two-dimensional sub-frame analysis, using a finite-element program developed by Bailey[22].

It was observed for the bare-steel arrangement that the inclusion of experimentally generated connection characteristics resulted in a significant reduction in deflections compared to the common assumption of pinned response, with the resultant failure-temperature increasing by over 100°C. Corresponding rotations were predicted to be in excess of 100 millirads at a limiting deflection of span/20. Considering the high capacity of the connection at ambient-temperatures, approaching 50% of the plastic capacity of the beam, it may have been anticipated that the inclusion of connection characteristics within analysis would have resulted in a significant increase in the fire resistance of the sub-frame analysed. Within the SCI guide to simple connections a plate thickness of 8mm is specified for a connection such as that tested, compared to a 12mm plate thickness adopted in experimentation, and it would be anticipated that reducing the plate thickness accordingly would result in a significant reduction in the capacity of the connection.

Inclusion of composite connection characteristics within analysis was also observed to result in an increase in the failure temperature for the arrangement tested, though this was not as significant for the composite arrangement as for bare-steel arrangement considered. For a central deflection of 150mm (span/40) it was seen that there was an increase in the corresponding beam lower flange temperature of approximately 80°C incorporating semi-rigid characteristics, compared to the assumption of pinned connections. However, with increasing temperature deflections tended to converge towards a common deflection, corresponding with that for a simply supported span. It is suggested that this is in part attributable to the accelerated reduction in capacity for the composite connection tested due to the relative flexibility of the arrangement in the compression zone, but that axial restraint provided by the column is also influential, as discussed in Section 6.3. Levels of rotation for the composite arrangement compared closely with those for the bare-steel arrangement, highlighting the need to ensure ductility of reinforcement in the tension zone. It is important to remember that whilst the capacity of composite connections generally degrades at a lower rate than for bare-steel connections, similarly, the beam capacity also reduces at a lower rate due to the existence of the concrete slab acting compositely with the bare-steel section.

For the bare-steel and composite arrangements considered it was observed that the resultant failure-temperature is highly sensitive to the temperature of the connection. This presents the ability to increase the enhancement in capacity occurring from semi-rigid behaviour by extending the fire protection applied to columns to the underside of the floor slab, and providing fire protection along a short length of the beams, where this incorporates the connections.

Studies have been presented considering the influence of varying connection stiffness and capacity on failure-temperature. It was observed that whilst an almost linear relationship exists between connection moment capacity and associated failure-temperature, response remains insensitive to the stiffness of the connection once this is sufficiently high that the onset of plasticity occurs prior to failure.

Postulated elevated-temperature characteristics have been presented for the connections contained within the Cardington test frame, based on a series of ambient-temperature tests conducted by Boreman[47]. Whilst the moment-rotation-temperature characteristics presented may not predict with any certainty the true elevated-temperature response, the inclusion of approximate characteristics within analysis does facilitate an initial assessment of the enhancement in capacity that may occur from semi-rigid action. As discussed in Section 8.5, further testing is programmed considering arrangements of bare-steel and composite connections adopted within the Cardington test frame.

Inclusion of postulated connection characteristics within two-dimensional bare-steel analysis resulted in only a slight enhancement in the fire resistance of the structure, with response being dominated by the degree of axial restraint. Two dimensional analysis of the structure incorporating composite action resulted in a significant improvement in the inherent fire resistance of the structure due to the increased capacity of the composite section over its bare-steel counterpart, and due to the reduced rate of degradation of capacity for the composite beam. However, it was once more observed that the inclusion of semi-rigid connection characteristics within analysis resulted in only a slight enhancement in the fire resistance of the structure. For both the bare-steel and composite arrangements considered connection rotations were once more predicted to be in excess of 100 millirads. Due to the ambient-temperature test data presented being primarily concerned with low levels of rotation, the increase in capacity of flush end-plate connections due to the beam lower flange bearing against the column flange was not incorporated within the analysis. However, initial studies have indicated that inclusion of this form of behaviour can result in a significant increase in the contribution of semi-rigid characteristics to the inherent fire resistance of steel framed structures.

Further analysis has been presented considering the three-dimensional response of the Cardington test frame with increasing temperatures. It was seen that for a constant load ratio the incorporation of three-dimensional slab action resulted in a significant increase in the inherent fire resistance of the arrangement. The increase in capacity gained from the inclusion of semi-rigid beam-to-column connections was once more small, and this decreased yet further in the case of secondary beam-to-beam connections.

8.5. RECOMMENDATIONS FOR FURTHER WORK

The tests that have been carried out in the present project are the first in a systematic series aimed at quantifying the degradation of connection resistance as temperature increases. To gain a fuller understanding of elevated-temperature connection response further testing is necessary. As such a proposal has been presented in the form of a Partners in Technology project between the Building Research Establishment, University of Sheffield, Steel Construction Institute and British Steel, which is due to be completed in March 1998. The programme encompasses a total of 20 bare-steel and composite elevated-temperature tests of both flush and flexible end-plate connections (a total of 5 connection types), where the test procedure has been developed based on that adopted within experimental studies presented. The scope of the test programme includes consideration of:

1. The influence of end-plate thickness on the response of the flush end-plate connection tested (end-plate thickness being specified in accordance with the SCI guide for the design of simple connections)
2. The influence of varying beam and column sections for the flush end-plate connection.

3. The response of a flexible end-plate connection where beam and column sections are comparable with those for the flush end-plate connection (designed in accordance with the SCI guide for the design of simple connections).
4. The influence of varying beam and column sections for the flexible end-plate connection (where sections have been selected to correspond with those adopted within the Cardington test frame).
5. The influence of artificially de-bonding reinforcement in the tension zone on overall connection ductility and response.

Having defined the elevated-temperature response for further connections, including considered of the influence of varying parameters including plate thickness and beam depth, it will be possible to consider further the ability with which the presented spring-stiffness model is capable of accurately predicting elevated-temperature connection response. It is desirable that the described model also be extended to consider the response of partial depth end-plate connections, as this type of connection is increasing in popularity due to the associated reduction in fabrication costs, and has been adopted for all beam-to-column connections within the Cardington test frame.

Modelling of composite connection response requires further modification to consider the influence of relocation of the centre of rotation. However, as discussed the accuracy with which this can be modelled is limited by the extent of experimental data available describing the full elastic-plastic range of column web response in isolation. As such further experimentation may be valuable.

Having developed moment-rotation characteristics for further arrangements of beam-to-column connection it is essential to consider the influence of these on frame response, and in the case of predictions for the Cardington test frame, to compare these with the response observed from experimentation

8.6. CONCLUDING REMARK

It has been observed that whilst the inclusion of semi-rigid response within analysis can result in significant increases in the inherent fire resistance of both bare-steel and composite structures, for typical arrangements of beam-to-column connections, where the capacity of the connection is low compared to that of the connected beam, the resultant increase in the inherent fire resistance is small. However, this may prove to be influential in the categorisation of the fire resistance periods for a number of structures. The inclusion of elevated-temperature characteristics within design will be restricted by the inherent complexities associated with generating accurate moment-rotation-temperature response for the broad range of connection types currently adopted, and as such simple design guidance is necessary. Due to the insensitivity of frame response to the elastic range of response it seems that design may be simplified by considering elevated-temperature response in terms of the plastic capacity of the connection at a rotation corresponding with the limiting deflection.

Testing of isolated beam-to-column arrangements has shown that both bare-steel and composite arrangements are capable of withstanding significant levels of rotation at elevated-temperatures, and that in certain cases the ductility of connections increases with increasing temperatures. This ductility of connections is supported by observation of the Cardington test frame subsequent to a series of elevated-temperature tests, where overall structural integrity was maintained despite deflections existing far beyond those associated with 'failure' of the structure. This supports the opinion that since fire is an accidental occurrence, design methods for the fire safety of structures should concentrate primarily on the strength of the structure, and the prevention of disproportionate collapse.

REFERENCES

1. Read, R.E.H., and Morris, W.A., *Aspects of Fire Precautions in Buildings*, Building Research Establishment, 1983.
2. Latter, R., 'The European Market for Constructional Steelwork', *New Steel Construction*, **2 (5)**, October 1994.
3. *BS 5950, Structural Use of Steelwork in Buildings, Part 8: Code of Practice for Fire Resistant Design*, BSI, London, 1990.
4. *BS 4422: Glossary of Terms Associated with Fire, Part 5: Miscellaneous Terms*, BSI, London, 1976.
5. *Fire Resistance of Steel Structures, Modern Fire Protection Systems and Design Methods*, British Steel General Steels, January 1990.
6. *The Building Regulations: Approved Document B: Fire Safety*, Department of the Environment and the Welsh Office, HMSO, 1991.
7. *BS 449: The Use of Structural Steel in Building*, BSI, London, 1969.
8. *Eurocode 3: Design of Steel Structures, Part 1.2: Structural Fire Design (Draft)*, European Committee for Standardisation, 1993.
9. Dowling, J., 'Fire Protection Using Off-Site Applied Intumescent Coatings', *Proc. Instn Civ. Engrs Structs & Bldgs*, **112**, pp. 237-238, May 1997.
10. Robinson, J., *STIFF Meeting*, British Steel, Swindon Laboratories, 1996.
11. *Structural Fire Engineering - Investigation of Broadgate Phase 8 Fire*, The Steel Construction Institute, 1991.
12. Armer, G.S.T., and Moore, D.B., 'Full-Scale Testing on Complete Multi-Storey Structures', *The Structural Engineer*, Vol. **72**, No. 2, 1994.
13. *First Cardington Conference - First Results from the Large Building Test Facility*, Building research Establishment, November 1994.
14. *Loss Prevention Council, Code of Practice for the Construction of Buildings*, 1992.
15. *BS 476: Fire Tests on Building Materials and Structures, Part 20: Method of Determination of the Fire Resistance of Elements of Construction (General Principles)*, BSI, London, 1987.
16. *Fire Protection of Structural Steel in Buildings, 2nd Edition*, Association of Structural Fire Protection Contractors and Manufacturers Limited and the Steel Construction Institute, UK, 1989.
17. *International Fire Engineering Design for Steel Structures: State of the Art*, International Iron and Steel Institute, Brussels, 1993.

18. Dotreppe, J., Franssen, J., and Schleich, J., 'Numerical Simulation of Fire Resistance Tests on Steel and Composite Structural Elements or Frames', *Fire Safety Sci. - Proceedings of the First International Symposium*, October 1985.

19. Jeyarupalingam, N., and Virdi, K.S., 'Steel Beams and Columns Exposed to Fire Hazard', *Structural Design for Hazardous Loads*, Ed. Clarke, J.L., Garas, F.K., and Armer, G.S.T., E&FN Spon, 1992.

20. Wang, J.C., and Moore, D.B., 'Fire Resistance of Steel Beams', *International Seminar on Structural Design for Hazard Loads*, Brighton, UK, April 1991.

21. Najjar, S.R., *Three-Dimensional Analysis of Steel frames and Subframes in Fire*, Ph.D. Thesis, Department of Civil and Structural Engineering, University of Sheffield, 1994.

22. Bailey, C.G., *Simulation of the Structural Behaviour of Steel-Framed Buildings in Fire*, Ph.D. Thesis, Department of Civil and Structural Engineering, University of Sheffield, 1995.

23. Hilado, C.J., *Flammability Handbook for Plastics*, Stamford Conn. USA Technomic, 1969.

24. *ISO 834: Fire Resistance Tests - Elements of Building Construction*, 1985.

25. *BS 8110: The Structural Use of Concrete, Part 2: Code of practice for Special Circumstances*, BSI, London, 1990.

26. Wainman, D.E., and Kirby, B.R., *Compendium of UK Standard Fire Test Data on Unprotected Structural Steel*, British Steel Report (Swindon Labs), 1987.

27. Anderson, D., Bijlaard, F.S.K., and Nethercot, D.A., 'Analysis and Design of Steel Frames with Semi-Rigid Connections', *IABSE Surveys*, **S-39/87**, 1987.

28. Lawson, R.M., 'A Proposal for the Design of Steel Frames with Semi-Rigid Bolted Connections', *Steel Construction Today*, **2**, pp. 106-116, 1988.

29. Nethercot, D.A., 'Joint Action and the Design of Steel Frames', *The Structural Engineer*, Vol. **64**, No.12, Dec. 1985.

30. Lorenz, F.R., 'A New Alternative in Steel Construction - Partially Restrained Connections', *Connection Flexibility and Steel Frames*, Ed. Chen, W.F., 1985.

31. Moore, D.B., *Personal correspondence*, May 1996.

32. Wilson, W.M., and Moore, H.F., *Tests to Determine the Rigidity of Riveted Joints in Steel Structures*, University of Illinois, Engineering Experimentation Station, Bulletin No. 104, Urbana, USA, 1917.

33. *Joints in Structural Steelwork*, International Conference, Ed. Howlett, J.H., Jenkins, W.M., and Stainsby, R., Teeside Polytechnic, Pentech Press, April 1981.

34. Chen, W.F., and Kishi, N., 'Semi-Rigid Steel Beam-to-Column Connections: Data Base and Modelling', *J. Struct. Engrg.*, ASCE, **115(1)**, pp. 105-119.

35. Nethercot, D.A., *Steel Beam-to-Column Connections - A Review of Test Data*, CIRIA, London, 1985.

36. Kishi, N., and Chen, W.F., *Database of Steel Beam-to-Column Connections*, Structural Engineering Report No. CE-STR-86-26, School of Civ. Engrg., Purdue University, West Lafayette, Ind, 1986.

37. Goverdam, A.V., *A Collection of Experimental Moment-Rotation Curves - Evaluation of Predicting Equations for Semi-Rigid Connections*, Ph.D. Thesis, Vanderbilt University, Nashville, Tenesse, 1984.

38. Allen, P.H., Kirby, P.A., and Nethercot, D.A., *Semi-Rigid Action in Steel Framed Structures, 4th report to ECSC, September 1989.*

39. Aggarwal, A.K., and Cotes, R.C., 'Moment-Rotation Characteristics of Bolted Beam-to-Column Connections', *J. Construct. Steel Research*, **6**, pp. 303-318, 1986.

40. Nethercot, D.A., Jones, S.W., and Kirby, P.A., *The Analysis of Frames with Semi-Rigid Connections - A State of the Art Report*, Novemeber 1982.

41. Eurocode 3, *Design of Steel Structures. Part 1.1: Revised Annex J Joints and Building Frames (Draft)*, Document CEN/TC250/SC3 N419E, European Committee for Standardisation, 1993.

42. Kruppa, J., *Resistance on Feu des Assemblages par Boulons Haute Resistance*, Centre Technique Industriel de la Construction Metallique, St. Remy Chevreuse, France, 1976. (CTICM Report, Document No. 1013 - 1, English translation available entitled '*Fire Resistance of Joints with High Strength Bolts*').

43. *The Performance of Beam / Column / Beam Connections in the BS 5950: Part 8 Fire Test*, British Steel (Swindon labs.), Reports T/RS/1380/33/82D and T/RS/1380/34/82D.

44. Lawson, R.M., *Behaviour of Steel Beam-to-Column Connections in Fire*, The Steel Construction Institute, Document No. SCI-RT-007/1, June 1981.

45. Girardier, V., 'Construction Led - Chapter 4: The Role of Standardised Connections', *New Steel Construction*, pp. 16-18, Feb. 1993.

46. Moore, D.B., *Beam-to-Column Steelwork Connections - Trends in UK Practice*, Building Research Establishment, PD144/90, July 1990.

47. Boreman, J., *Personal correspondence*, 1996.

48. European Convention for Constructional Steelwork - Technical Committee 3 - Fire Safety of Structures, *European Recommendations for the Fire Safety of Steel Structures*, Elsevier, 1983.

49. Cooke, G.M.E., 'An Introduction to the Mechanical Properties of Steel at Elevated Temperatures', *Fire Safety Journal*, **13**, 1988.

50. Eurocode 4: *Design of Composite Steel and Concrete Structures, Part 1.2: Structural Fire Design (Draft)*, European Committee for Standardisation, 1992.

51. Kirby, B.R., and Preston, R.R., 'High Temperature Properties of Hot Rolled Structural Steels for Use in Fire Engineering Studies', *Fire Safety Journal*, **13**, 1988.

52. Jorgensen, J., and Sorensen, A., *Mechanical Properties of Structural Steel at Elevated Temperatures*, Institute of Building Technology and Structural Engineering, Report No. 8010, July 1980.

53. Lawson, R.M., and Newman, G.M., *Fire Resistant Design of Steel Structures - A Handbook to BS5950: Part 8*, The Steel Construction Institute, 1990.

54. Holmes, M., Anchor, R.D., Cooke, G.M.E., and Crook, R.N., 'The Effects of Elevated Temperatures on the Strength Properties of Reinforcing and Pre-stressing Steels', *The Structural Engineer*, Vol. **60B**, No. 1, March 1992.

55. *Design and Detailing of Concrete Structures for Fire Resistance*, IStructE and The Concrete Society, April 1978.

56. Kirby, B.R., 'The Behaviour of High Strength Grade 8.8 Bolts in Fire', *J. Construct. Steel Research*, **33**, pp. 3-38, 1995.

57. Jau, W.C., and Wu, G.G., 'Performance of Lightweight Concrete Panels Subject to Fire', *International Symposium on Structural Lightweight Aggregate Concrete*, Sandefjord, Norway, pp. 180-192, 20-24 June 1995.

58. Eurocode 4: *Design of Composite Steel and Concrete Structures, Part 1.1: General Rules and Rules for Building (Draft)*, European Committee for Standardisation, 1992.

59. An, L., and Cederwall, K., 'Push-out Tests on Studs in High Strength and Normal Strength Concrete', *J. Construct. Steel Research*, **36**, No. 1, pp 15-29, 1996.

60. Mottram, J.T., and Johnson, R.P., 'Push Tests on Studs Welded Through Profiled Steel Sheeting', *The Structural Engineer*, Vol. **68**, No. 10, 15th May 1990.

61. Twilt, L., and Kruppa, J., 'European Research into the Fire Behaviour of Composite Floors and Beams', *3rd International Conf. on Steel-Concrete Composite Structures*, Fukuoka, Japan, September 1991.

62. Twilt, L., and Kruppa, J., 'Current Research on Fire Resistance of Composite Floors and Beams', *International Conf. on Materials and Design Against Fire*, London, United Kingdom, October 1992.

63. Steel Construction Institute, *Joints in Simple Construction, Volume 1: Design Methods*, SCI Publication 105, 1991.

64. .Gibbons, C., *The Strength of Bi-axially Loaded Beam-Columns in Flexibly Connected Steel Frames*, PhD Thesis, Department of Civil and Structural Engineering, University of Sheffield, 1990.

65. Davison, J.B., *Strength of Beam-Columns in Flexibly Connected Steel Frames*, PhD Thesis, Department of Civil and Structural Engineering, University of Sheffield, 1987.

66. Horne, M.R. and Morris, L. J., *Plastic Design of Low Rise Frames*, Granada Publishing Ltd., 1981.

67. Moore, D.B., Sims, P.A.C., 'Tests on Full Scale Steel Frames with Semi-Rigid Connections', *Proc. Conference on Steel Structures - Recent Research Advances and their Application to Design.*, pp. 253-262, Budva, 1986.

68. Lennon, T., *Elevated-temperature Testing Facility: A Feasibility Study*, Building Research Establishment Internal Note N48/92, 1992.

69. Lennon, T. and Simm, C., *Elevated-temperature Column Tests: Results from Phase 1*, Building Research Establishment Internal Note N201/93, (1993).

70. Lennon, T. and Simm, C., *Elevated-temperature Column Tests: Results from Phase 2*, Building Research Establishment Internal Note N28/94, (1994).

71. Lennon, T., Jones, L.C., *Elevated-temperature Moment-Rotation Tests*, Building Research Establishment Internal Note N135/94, 1994.

72. Gibb, P., and Currie, D.M., 'Construction Loads for Composite Floor Slabs', *First Cardington Conference, First Results from The Large Building Test Facility*, Building Research Establishment, 16 to 17 November 1994.

73. BS 5950: *Structural Use of Steelwork in Buildings, Part 3: Design of Composite Construction, Section 3.1: Code of Practice for Design of Simple and Continuous Composite Beams*, 1990.

74. Lennon, T., Jones, L.C., *Elevated-Temperature Composite Connection Moment-Rotation Tests*, Building Research Establishment Internal Note N65/95, 1995.

75. Anderson, D., *Composite Construction in Buildings*, Lecture 3: Design of Main Beam, Construction Marketing, 1990.

76. El-Rimawi, J., *The Behaviour of Flexural Members Under Fire Conditions*, Ph.D. Thesis, Department of Civil Engineering, University of Sheffield, 1989.

77. Nethercot, D.A., Davison, J.B., and Kirby, P.A., *Connection Flexibility and Beam Design in Non-Sway Frames*, American Society of Civil Engineers, 1986

78. Baker, J.F., *Second Report*, Steel Structures Research Committee, Department of Scientific and Industrial Research. HMSO, London, 1934.

79. Rathburn, J., 'Elastic Properties of Riveted Connections', *Trans. Amer. Soc. Civil Engrs.*, **101**, pp. 524-63, 1936.

80. Lionberger, S.R., and Weever, W., 'Dynamic Response of Frames with Non-Rigid Connections', *J. Engng Mech. Div.*, ASCE, **95**(EM1), pp. 95-114, 1969.

81. Romstad, K.M., and Subramanian, C.V., 'Analysis of Frames with Partial Connection Rigidity', *J. Struct. Div.*, ASCE, **96**(ST11), pp. 2283-2300, 1970.

82. Moncartz, P.D., and Gerstle, K.H., 'Steel Frames with Non-Linear Connections', *J. Struct. Div.*, ASCE, **107**(ST8), pp. 1427-41, 1981.

83. Poggi, C., and Zandonini, R., 'Behaviour and Strength of Steel Frames with Semi-Rigid Connections', *Connection Flexibility and Steel Frame Behaviour*, Ed. W.F. Chen, American Society of Civil Engineers, 1985.

84. Kennedy, D.J.L., 'Moment-Rotation Characteristics of Shear Connections', *Engng. J., Amer. Inst. Steel Constr.*, pp. 105-15, October 1969.

85. Sommer, W.H., *Behaviour of Welded Header Plate Connections*, Master's Thesis, University of Toronto, Ontario, Canada, 1969.

86. Frye M.J., and Morris, G.A., 'Analysis of Flexibly Connected Steel Frames', *Canad. J. Civil Engng.*, **2**, pp. 280-91, 1975.

87. Jones, S.W., Kirby, P.A., and Nethercot, D.A., 'Modelling of Semi-Rigid Connection Behaviour and its Influence on Steel Column Behaviour', *Joints in Structural Steelwork*, Ed. J.H.Howlett *et. al.*, Pentech Press, London, pp 5.73-5.87, 1981.

88. Ramberg, W. and Osgood, W., *Description of Stress Strain Curves by Three Parameters*, National Advisory Committee for Aeronautics, Technical Note 902, 1942.

89. Ang K.M., and Morris, G.A., 'Analysis of 3-Dimensional Frames with Flexible Beam-Column Connections', *Canad. J. Civil Engng.*, **11**, pp. 245-54, 1984.

90. Lui, E.M., and Chen, W.F., 'Analysis and Behaviour of Flexibly Jointed Frames', *Engng. Struct.*, **8**(2), pp. 107-15, 1986.

91. Lothers, J.E., 'Elastic Restraint Equations for Semi-Rigid Connections', *Trans. ASCE*, **1**, pp. 480-502, 1951.

92. Lewitt, C.W., Chesson, E., and Munse, W., *Restraint Characteristics of Flexible Riveted and Bolted Beam to Column Connections*, Bulletin No. 500, Engineering Experiment Station, University of Illinois, Chicago, 1969.

93. Chen, W.F., and Kishi, N., *Moment-Rotation Relation of Top and Seat Angle Connections*, Department of Structural Engineering, Purdue University, Report CE-STR-87-4, 1987.

94. Kishi, N., Chen, W.F., Matsuoka, K.G., and Nomachi, S.G., 'Moment-Rotation Relationship of Top- and Seat-Angle with Double Web Angle Connections', *Connections in Steel Structures: Behaviour, Strength and Design*, Ed. R. Bjohovde *et. al.*, Elsevier Applied Science Publishers, London, pp. 121-34, 1988.

95. Kishi, N., Chen, W.F., Matsuoka, K.G., and Nomachi, S.G., 'Moment-Rotation Relation of Single/Double Web Angle Connections', *Connections in Steel Structures: Behaviour, Strength and Design*, Ed. R. Bjohovde *et. al.*, Elsevier Applied Science Publishers, London, pp. 135-49, 1988.

96. Johnson, R.P., and Law, C.L.C., 'Semi-Rigid Joints for Composite Frames', *Joints in Structural Steelwork*, Ed. J.H.Howlett, W.M.Jenkins and R.Stansby, Pentech Press, pp. 3.1-3.19, 1981.

97. Yee, Y.L., and Melchers, R.E., 'Moment-Rotation Curves for Bolted Connections', *Journal of Structural Engineering*, Vol. **112**, No. 3, pp. 615-635, March 1986.

98. Aribert, J.M., and Lachal, A., 'Experimental Investigation of Composite Connections and Global Interpretation', *Proc. COST C1 Workshop*, Strausbourg, Oct. 1992.

99. Laurie Kennedy, D.J., and Hafez, M.A., 'A Study of End-Plate Connections for Steel Beams', *Can. J. Civ. Eng.*, Vol. **11**, 1984.

100. Wales, W.M., and Roscow, E.C., 'Coupled Moment-Axial Force Behaviour in Bolted Joints', ASCE, *J. Struct. Engng.*, **109**(5), pp. 1250-66, 1983.

101. Chmielowiec, M. and Richard, R.M., *Moment Rotation Curves for Partially Restrained Steel Connections*, Report to AISC, University of Arizona, 1987.

102. Tschmmernegg, F., 'On the Non-Linear Behaviour of Joints in Steel frames', *Connections in Steel Structures: Behaviour, Strength and Design*, Ed. R.Bjorhovde *et. al.*, Elsevier Applied Science Publishers, London, pp. 158-65, 1988.

103. Madas, P.J., *Advanced Modelling of Composite Frames Subject to Earthquake Loading*, PhD Thesis, Imperial College, University of London, July 1993.

104. Tschmmernegg, F., 'A New Spring Model for Composite Joints', *Proc. COST C1 Workshop*, Strausbourg, pp. 356-368, Oct. 1992.

105. Bose, S.K., McNeice, G.M., and Sherbourne, A.N., 'Column Webs in Steel Beam to Column Connections, Part I, Formulation and Verification', *Computers and Structures*, **2**, pp. 253-72, February 1972.

106. Patel, K.V., and Chen, W.F., 'Non-Linear Analysis of Steel Moment Connections', ASCE, *J. Struct. Engng.*, **110**(8), pp. 1861-75, 1984.

107. Atmaz Sibai, W., and Frey, F., 'Numerical Simulation of the Behaviour up to Collapse of Two Welded Unstiffened One-Side Flange Connections', *Connections in Steel Structures: Behaviour, Strength and Design*, Ed. R.Bjorhovde *et. al.*, Elsevier Applied Science Publishers, London, pp. 85-92, 1988.

108. Lipson, S.L., and Hague, M.I., 'Elasto-Plastic Analysis of Single-Angle Bolted-Welded Connections Using the Finite Elements Method', *Computers and Structures*, 9(6), pp. 533-45, 1978.

109. Richard, R.M., Gillet, P.E., Kreigh, J.D., and Lewis, B.A., 'The Analysis and Design of Single Plate Framing Connections', *Engng. J.*, Amer. Inst. Steel Constr., **17(2)**, pp. 38-52, 1980.

110. Patel, W.V., and Chen, W.F., 'Analysis of a Fully Bolted Moment Connection using NONSAP', *Computers and Structures*, 21(3), pp. 505-11, 1985.

111. Beaulieu, D., and Picard, A., 'Finite Element Modelling of Connections', *Connections in Steel Structures: Behaviour, Strength and Design*, Ed. R.Bjorhovde *et. al.*, Elsevier Applied Science Publishers, London, pp. 96-103, 1988.

112. Richard, R.M., Rabern, D.A., Hornby, D.E., and Williams, G.C., 'Analytical Model for Steel Connections', *Behaviour of Metal Structures (Proc. W.H. Munse Symposium)*, Ed. W.J. Hall and M.P. Gaus, American Society of Civil Engineers, May 1983.

113. Krishmanurthy, N., 'Modelling and Prediction of Steel Bolted Connection Behaviour', *Computers and Structures*, **11**(2), pp. 75-82, 1980.

114. Liu, T.C.H., and Morris, L.J., 'The Development of a Shear Hinge and the Effect on Connection Flexibility', *Proc. of Asian Pacific Conf. Comp. Mech.*, Hong Kong, Vol. **1**, December 1991.

115. Liu, T.C.H., 'Theoretical Modelling of Steel Bolted Connections Under Fire Exposure', *Inter. Conf. on Computer Methods in Struct. and Geot. Eng. Mech.*, Hong Kong, Dec. 1994.

116. Liu, T.C.H., *Personal correspondence*, 1995.

117. Echeta, C.B., *Semi-Rigid Connections Between Concrete Filled Steel Columns and Composite Beams*, PhD Thesis, University of London, 1982.

118. Leon, R., and Lin, J., *Towards the Development of an Analytical Model for Composite Semi-Rigid Connections*, Report to AISC, Struct. Eng. Report No. 86-06, University of Minnesota, Minneapolis, 1986.

119. Davison, J.B., Lam, D., and Nethercot, D.A., 'Semi-Rigid Action of Composite Joints', *Structural Engineer*, Vol. **68**, 24, pp. 489-99, December 1990.

120. Puhali, R., Smotlak, I., and Zandonini, R., 'Semi-Rigid Action: Experimental Analysis and a Suitable Model', *Journal of Constructional Steel Research*, Vol. **15**, pp. 121-51, 1990.

121. Aribert, J.M., 'Critical Numerical Analysis of the methods Proposed by Eurocode 4 for Dimensioning of Steel-Concrete Composite beams with Partial Connection', *Construction Metallique*, **25**(1), pp. 32-36, 1988.

122. Nethercot, D.A., and Zandonini, R., 'Methods of Prediction of Joint Behaviour: Beam-to-Column Connections', Chapter 2, *Structural Connections - Stability and Strength*, Ed. R. Narayanan, Elsevier Applied Science, 1989.

123. Bravery, P.N.R., *Cardington Large Building Facility, Construction Details for the First Building*, Building Research Establishment, 1994.

124. Douty, R.T., and McGuire, W., 'High Strength Bolted Moment Connections', *J. Struct. Div.*, ASCE, 91, ST: 101 - 128, 1965.

125. Schutz, F.W., 'Strength of Moment Connections Using High Tensile Strength Bolts', American Institute of Steel Construction, *National Engineering Conference Proceedings*, April 1959.

126. Beedle, L.S., Le-Wu Lu, and Lee Chong Lin, 'Recent Developments in Plastic Design Practice', *J. Struct. Div.*, ASCE, **95**, ST9, 1911-1937, September 1969.

127. Nair, R.S., Birkemore, P.C., and Munse, W.H., 'High Strength Bolts Subject to Tension and Prying', *Jnl. Struct. Div. ASCE*, **100**, ST2: 351-372, 1974.

128. Struik, J.H.A., *Tests on High-Strength Bolted T-Stubs with Respect to a Bolted Beam to Column connection*, Stevin Laboratory Report 6-69-13, Delft University of Technology, Netherlands, 1969.

129. Agerskov, H., 'High Strength Bolted Connections Subject to Prying', *J. Struct. Div.*, ASCE, **102**, ST1: 161 - 175, 1976.

130. Packer, J.A., and Morris, L.J., 'A Limit State Design Method for the Tension Region of Bolted Beam-to-Column Connections', *The Structural Engineer*, Vol. **55**, 10: 446-458, 1977.

131. Surtees, J.O., and Mann, A.P., 'End-Plate Connections in Plastically Designed Structures', *Conference on Joints in Structures, University of Sheffield, and the Institution of Structural Engineers*, 1, Session A, Paper 5, 1970.

132. Eurocode 3, *Design of steel structures. Part 1: General Rules and Rules for Building*, Edited Draft, Issue 5, November 1990.

133. Jaramillo, T.J., 'Deflections and Moments Due to a Concentrated Load on a Cantilever Plate of Infinite Length', *Journal of Applied Mechanics*, pp. 67-72, March 1950.

134. Zoetemeijer, P., *A Design Method for the Tension Side of Statically Loaded, Bolted Beam-to-Column Connections*, Heron, 20, No. 1, 1974.

135. Yee, Y.L., and Melchers, R.E., 'Moment-Rotation Curves for Bolted Connections', *Journal of Structural Engineering*, Vol. **112**, No. 3, pp. 615-635, March 1986.

136. Eurocode 3, *Design of steel structures. Part 1.1: Annex J {normative}: Beam-to-Column Connections (Draft)*, Document ENV 1993-1-1 : 1992.

137. Chen, W.F., and Newlin, D.E., 'Column Web Strength in Beam-to-Column Connections', *Journal of the Structural Division*, ASCE, Vol. 99, No. ST9, Technical Note, Sept. 1973, pp. 1978.

138. *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings*, American Institute for Steel Construction, Feb. 1969.

139. Walker, A.C., 'The Post-Buckling Behaviour of Simply-Supported Square Plates', *The Aeronautical Quarterly*, Vol. **XX**, pp. 203-222, August 1969.

140. Schmidt, H., 'Verification of Quality Assurance of European 4.6 and 8.8 Bolts', *Connections in Steel Structures: Behaviour, Strength and Design*, Ed. R.Bjorhovde, Elsevier Applied Science, pp. 11 - 18, 1988.

141. Jaspart, J.P., *Etude de la Semi-Rigidité des Noeuds Poutre-Collone et son Influence sur la Résistance et la Stabilité des Ossatures en Acier*, Ph.D Thesis, University of Liège, Belgium, 1990.

142. Gerady, J.C., and Schleich, J.B., 'Semi-Rigid Action in Steel Frame Structures', *Contributions, Nordic Steel Colloquium*, Odense, Denmark, 389-399, 1991.

143. Anderson, D., and Najafi, A.A., 'Performance of Composite Connections: Major Axis End Plate Joints', *J. Construct. Steel Research*, **31**, pp. 31 - 57, 1994.

144. Menzies, J.B., 'CP117 and Shear Connectors in Steel-Concrete Composite Beams Made with Normal Density or Lightweight Concrete', *Struct. Eng.*, **49**, 3: 137-154, 1971.

145. Dowling, P.J., and Burgan, B.A., 'Shear Lag in Steel and Composite Structures: A State of the Art Review', *Composite Steel Structures: Advances, Design and Construction*, Ed. R.Narayanan, Elsevier Applied Science, 1987.

146. Evans, H.R., and Wright, H.D., 'Steel-Concrete Composite Flooring Deck Structures', Chapter 2, *Steel-Concrete Composite Structures: Stability and Strength*, Ed. R.Narayanan, Elsevier Applied Science, 1988.

147. Bernussi, F., Puhali, R., and Zandonini, R., 'Experimental Analysis of Semi-Rigid Connections in Composite Frames', *Proc. Int. Conf on Steel Structures: Recent Research Advances and their Applications to Design*, Budva, Yugoslavia, September 1986.

148. Mander, J.P., Priestly, J.N., and Park, P., 'Theoretical Stress-Strain Model for Confined Concrete', *Journal of Structural Engineering*, ASCE, Vol. **114**, No. 8, August 1988.

149. Krawinkler, H., 'Shear in Beam-Column Joints in Seismic Design of Steel Frames', *Engineering Journal*, AISC, **15**, 3: 82-91, 1978.

150. Nakao, M., *Research on the Behaviour of Steel Beam-To-Column Rigid Connections*, Doctoral Dissertation, University of Tokyo, Japan, 1995.

151. Kato, B., Chen, W.F., and Nakao, M., 'Effects of Joint-Panel Shear Deformation on Frames', *Journal of Constructional Steel Research*, **10**: 269-320, 1988.

152. Lui, E.M., and Chen, W.F., 'Frame Analysis with Panel Deformation', *International Journal of Solids and Structures*, **22**, 12: 1599-1627, 1986.

153. Fielding, D.J., and Huang, J.S., 'Shear on Beam-to-Column Connections', *Welding Journal*, 50(7), Research Supplement, 313s-326s, July 1971.

154. Bertero, V.V., Popov, E.P., and Krawinkler, H., 'Beam-Column Subassemblages Under Repeated Loading', *J. Struct. Div.*, Proc. ASCE, **98**(ST5), 1137-59, 1972.

155. Becker, R., 'Panel Zone Effect on the Strength and Stiffness of Steel Rigid Frames', *Engng. J.*, AISC, 12(1), 19-28, 1975.

156. Stutzki, C., *Traglastberechnung Raeumlicker Stabwerke unter Berueecksichtigung Verformbaren Anschluesse*, Ph.D Thesis, University of Aachen, Germany, 1982.

157. Galea, Y., Colson, A., and Pilvin, P., 'Programme D'analyse de Structures Planes à Barre avec Liasions Semi-Rigides à Comportement Non-linéaire', *Construction Métallique*, No. **2**, 3-16, 1986.

158. Anderson, D., and Kavinapour, K., 'Analysis of Steel Frames with Semi-Rigid Connections', *Structural Engineering Review*, Vol. **3**, No. 2, 79-87, June 1991.

159. El Zantay, M.H., and Murray, D.W., 'Non-Linear Finite Element Analysis of Steel Frames', ASCE, *J. Struct. Div.*, **109**(ST2), pp. 353-368, 1983.

160. Saab, H.A., *Nonlinear Finite Element Analysis of Steel Frames in Fire*, Ph.D. Thesis, University of Sheffield, 1990.

161. BS5950: *Structural Use of Steelwork in Building: Part 1: Code of Practice for Design in Simple and Continuous Construction: Hot Rolled Sections*, BSI, London, 1990.

162. El-Rimawi, J.A., Burgess, I.W., Plank, R.J., 'Model Studies of Composite Building Frame Behaviour in Fire', *in press*.

163. El-Rimawi, J.A., Burgess, I.W., and Plank, R.J., *Modelling the Behaviour of Steel Frames and Subframes with Semi-Rigid Connections in Fire*, University of Sheffield, Dept. of Civil and Structural Engineering, Research Report DCSE/93/S/02, 1993.

164. Bjorhovde, R., Brozzetti, J., and Colson, A., 'A Classification System for Beam to Column Connections', *J. Struct. Engng*, ASCE, **116**(11), pp. 3059-76, 1990.

165. Eurocode 3, *Design of Steel Structures. Part 1: General Rules and Rules for Building*, Edited Draft, Issue 5, November 1990.

166. Liew, R.J.Y., White, D.W., and Chen, W.F., 'Limit State Design of Semi-Rigid Frames Using Advanced Analysis: Part 1: Connection Modelling and Classification', *J. Construct. Steel Research*, **26**, pp. 1-27, 1993.

167. Bijlaard, F.S.K., and Steenhuis, C.M., 'Prediction of the Influence of Connection Behaviour on the Strength, Deformations and Stability of Frames, By Classification of Connections', *Proceedings of the Second International Workshop*, Pittsburgh, AISC, pp. 307-318, 1991.

168. Steel Construction Institute, *Joints in Simple Construction, Volume 2: Practical Applications*, SCI Publication 206, 1992.

169. *BS EN 10002: Tensile Testing of Metallic Materials , Part 1: Method of Test at Ambient Temperature*, 1990.

170. *BS 8110: Structural Use of Concrete, Part 1: Code of Practice for Design and Construction*, 1985

171. *BS 1881: Testing Concrete, Part 116: Method of Determination of Compressive Strength of Concrete Cubes*, 1983.

172. *BS 1881: Testing Concrete, Part 117: Method of Determination of Tensile Splitting Strength*, 1983.

173. *BS 4: Structural Steel Sections, Part 1: Specification for Hot Rolled Sections*, 1993.

174. *BS EN 10034: Structural Steel I and H Sections, Tolerances on Shape and Dimensions*, 1993.

175. Jaeger, L.G., *Elementary Theory of Elastic Plates*, Pergamon Press, 1964.

176. Timoshenko, S., and Woinowski-Krieger, S., *Theory of Plates and Shells*, Mc Graw-Hill, 1959.

APPENDIX A. MATERIAL AND GEOMETRICAL PROPERTIES

A.1. INTRODUCTION

A series of tests has been conducted to establish ambient-temperature material and dimensional properties for the structural members, reinforcing mesh and concrete used in both the bare steel and composite connection tests. This allows a comparison to be made between the specified and recorded material properties, and definition of material properties applicable to the connection models and the other analyses described. Results from material tests conducted for the sections contained within the Cardington test frame are summarised, providing some indication of the variation of material properties, and establishing those suitable for incorporation within the Cardington test frame analysis. Unfortunately it was not possible to obtain specific elevated-temperature material properties due to the cost of testing, but these may be estimated based on existing elevated-temperature steel tests, as described in Chapter 2.

A.2. MATERIAL PROPERTIES

A.2.1. Tensile Coupon Tests

All members used for both bare steel and composite connection tests were taken from the same batch, provided by British Steel. Only representative tensile coupons were tested for both beam and column sections. The anticipated variation in steel properties from the same batch is small, allowing the properties for all sections to be inferred from the coupon tests conducted.

Location:	**Area (mm^2):**	**Yield Stress (kN/mm^2):**	**Max. Stress (kN/mm^2):**	**Gauge Length (mm):**	**Elongation (%):**
F.A.B.	12.59 x 6.28	322	462	50	40.7
F.B.B.	12.51 x 6.20	319	462	50	38.1
W.B.	12.57 x 6.08	312	463	49	37.8
Average	77.68	318	462	50	38.9

Table A.1: Summary of Recorded Beam Material Properties

Location:	**Area (mm^2):**	**Yield Stress (kN/mm^2):**	**Max. Stress (kN/mm^2):**	**Gauge Length (mm):**	**Elongation (%):**
F.A.C.	12.54 x 6.44	310	472	50	35.3
F.B.C.	12.54 x 6.66	315	462	52	35.6
W.C.	12.48 x 6.08	336	466	49	37.4
Average	80.05	320	467	50	36.1

Table A.2: Summary of Recorded Column Material Properties

The shapes and locations of tensile coupon specimens cut from beam and column sections are detailed in Fig. A1, being in accordance with the recommendations presented in BS EN 10002-1:1990[169]. Testing was conducted by TBV Stanger. Results from beam and column sections are summarised in Tables A.1 and A.2.

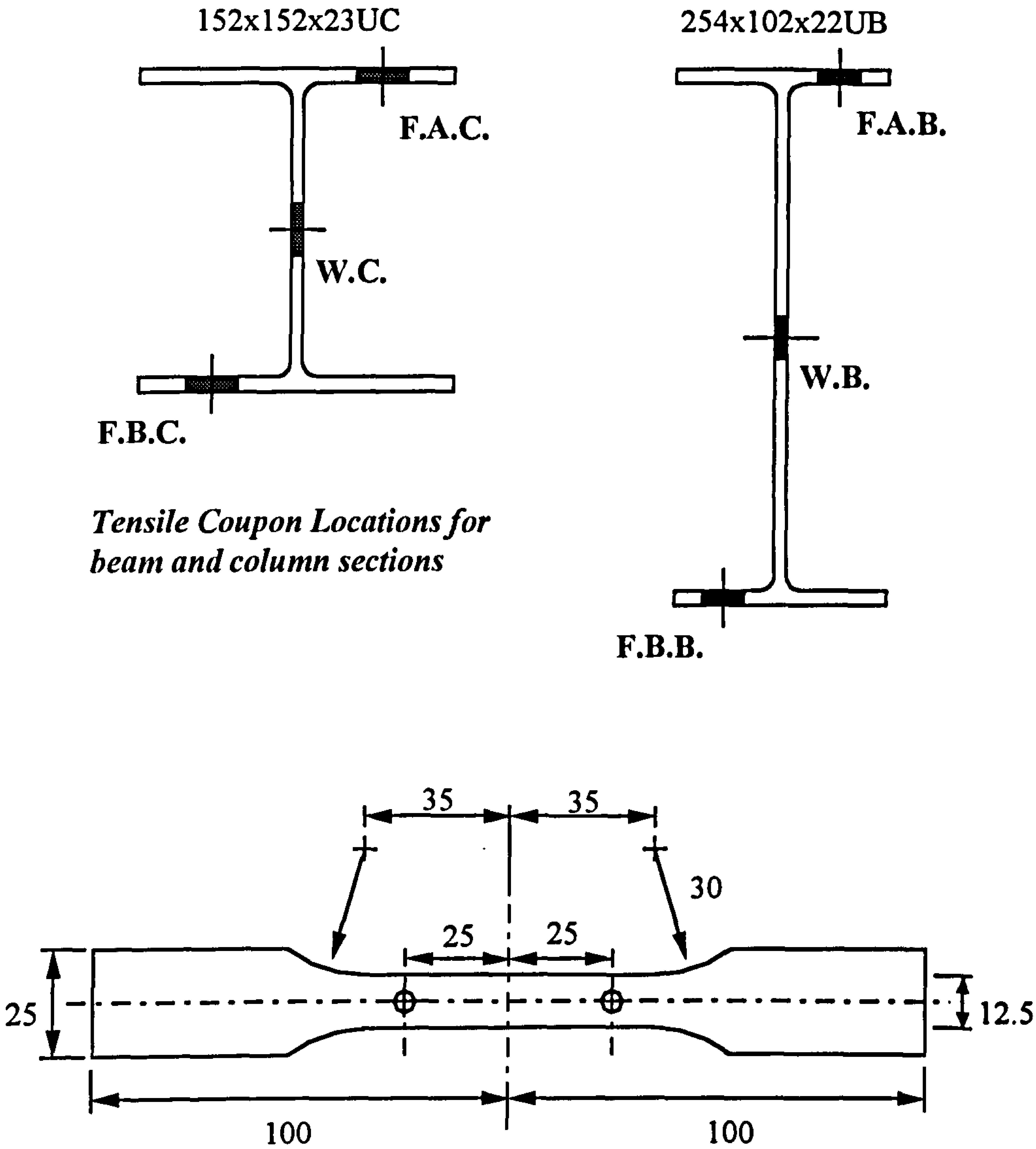


Figure A.1: Tensile Coupon Tests

It may be seen that a close correlation exists between results from beam and column sections, and between test points from each specimen. Actual recorded material properties are significantly higher than those nominally specified for Grade 43 steel. Nominal yield stress for Grade 43 steel is specified in BS5950[161] as 275N/mm^2, assuming a flange thickness less than 16mm. Actual yield stress was approximately 16% higher than that specified, demonstrating a significant enhancement in strength. Ultimate stress was in the region of 465N/mm^2, approximately 8% greater than the nominal value of 430N/mm^2. Both beam and column sections demonstrated significant ductility, with an average elongation at failure of 37.5%. Although modulus of elasticity was not explicitly presented for the steel coupons tested, assessment of the load-deformation behaviour suggests a value of approximately 220kN/mm^2, indicating a slightly stiffer behaviour than that expected based on the BS 5950 value of 205kN/mm^2 or the EC3[132] value of 210kN/mm^2.

A.2.2. Reinforcing Mesh

Tensile tests were again conducted by TBV Stanger in accordance with BS EN 10002-1:1990, to assess the actual material properties for the A142 reinforcement mesh used in the composite connection tests. Test results are summarised in Table A.3.

Specimen:	**Area (mm^2):**	**Yield Stress (kN/mm^2):**	**Max. Stress (kN/mm^2):**	**Gauge Length (mm):**	**Elongation (%):**
No. 1	25.94	628	650	30	14.7
No. 2	25.94	636	685	30	*
No. 3	25.94	622	672	30	13.7
Average	25.94	629	669	30	14.2

Note: * denotes that fracture occurred outside gauge length.

Table A.3: Summary of Recorded Reinforcing Mesh Properties

In all cases a cross-sectional area of 25.94mm^2 was recorded, being slightly lower than the nominal value of 28.27mm^2 for A142 reinforcing mesh[170]. This gives a cross-section area of 130mm^2/m length, some 9% less than the nominal value. However, the yield strength for high strength steel is specified as 460N/mm^2, compared to the test value of approximately 629N/mm^2. The cumulative effect of variation in cross sectional area and yield strength results in an actual yield strength typically 25% greater than that obtained assuming nominal material and sectional properties. The ultimate stress recorded for the reinforcement was typically 669N/mm^2. The average elongation of the reinforcement was approximately 14.2%.

A.2.3. Concrete Properties

Concrete was supplied by Ready Mixed Concrete (Transite) Limited based on a Grade 35 mix with 12mm Lytag lightweight aggregate. Exact details of the mix are not known as these were detailed by the concrete supplier, based on a specified compressive strength.

Compressive 100mm cube tests were conducted to assess the strength of the lightweight ready mixed concrete used in composite connection tests at 7 days and 28 days after casting, and at all subsequent connection test dates. Three tests were conducted at each date due to the natural variability of concrete. Three of the concrete specimens were stored in a saturated state, at a water temperature of 20°C, for testing at 28 days, whilst all other specimens were covered in damp hessian and polythene sheeting and stored at the same location as the cruciform test arrangements until the day of testing. Tests were conducted by the concrete laboratories at the Building Research Establishment in accordance with the recommendation presented in BS 1881: Part 116: 1983[171]. Results for the compressive tests are summarised in table A.4.

Age at Test:	*Saturated Mass (g):*	*Density (kg/m³):*	*Max. load at Failure (kN):*	*Compressive Strength (N/mm²):*
7 days (moist)	1975	1980	320.4	32
	1986	1990	319.5	32
	1984	1980	338.2	34
Average	1982	1980	326.0	33
28 days (sat) CFEP AMB	1997	1990	509.3	51
	2013	1990	493.6	49
	2007	1990	494.1	49
Average	2006	1990	499.0	50
28 days (moist) CFEP AMB	1969	1970	427.2	43
	1979	1980	450.2	45
	1977	1980	412.5	41
Average	1975	1980	430.0	43
39 days (moist) CFEP 15	2000	1980	463.3	46
	1989	1990	473.4	47
	1980	1960	457.8	46
Average	1990	1980	464.8	46
43 days (moist) CFEP 25	1987	1990	462.8	46
	1967	1970	444.4	44
	1989	1990	458.8	46
Average	1981	1980	455.3	46
59 days (moist) CFEP 32	1972	1970	483.6	48
	1976	1980	475.5	48
	1975	1980	462.8	46
Average	1974	1980	474.0	47

Table A.4. Summary of Recorded Concrete Compressive Material Properties

Concrete strength increases with age, due to the process of hydration. This process is more rapid in the early stages, with concrete typically being assumed to have attained full strength after a period of 28 days although in reality it continues to increase in strength at a slower rate after this. It may be seen from the results presented in Table A.4 that the 7-day strength is significantly lower than at later tests. Having shown an average strength of 33N/mm^2. At 28 days, the strength had increased to a value of 50N/mm^2 for the saturated tests and 43N/mm^2 for the moist tests. This variation in values is expected, due to a reduction in the rate of curing for the specimen contained in water, ensuring full hydration, and resulting in a stronger, more durable specimen.

Subsequent to the 28-day test, further specimens were tested to coincide with the cruciform connection tests. It may be seen that these tests produced consistent compressive strengths of approximately 46N/mm^2, slightly higher than at 28 days. Recorded concrete strengths suggest a significant enhancement over the specified strength of 35N/mm^2, as is typical due to manufacturers generally producing higher-strength mixes to account for the natural variability of concrete.

It should be noted that compressive cube tests generally produce higher strengths than corresponding cylinder tests due to shape effects. It is typically assumed that cylinder and cube strengths may be related by the following equation:

$$f_c = 0.85 f_{cu} \qquad \text{Eq. A.1.}$$

Where f_c and f_{cu} denote cylinder and cube strengths respectively. Allowing for the influence of shape effects, a characteristic compressive strength of 39N/mm^2 is obtained for the concrete.

Additional tests were conducted at 28 days to establish the concrete's tensile strength. This is considerably lower than the compressive strength, and depends on the method of testing adopted. The direct tensile strength of concrete, f_{ct}, is obtained from simple pull tests, and may be assumed to be related to the compressive strength of normal-weight concrete, by the commonly used empirical formula:

$$f_{ct} = 0.4\sqrt{f_c} \qquad \text{Eq. A.2.}$$

Where f_c and f_{ct} are in N/mm^2.

Age at Test:	*Saturated Mass (g):*	*Density (kg/m^3):*	*Max. load at Failure (kN):*	*Tensile Splitting Strength (N/mm^2):*
28 days (moist)	3104.7	1980	107.5	3.40
	3104.2	1980	107.6	3.45
	3097.1	1980	119.2	3.80
Average	3102.0	1980	114.4	3.55

Table A.5. Summary of Recorded Concrete Tensile Splitting Properties

The resistance of the slab to splitting stresses, f_{cb}, may be obtained from tensile splitting tests, also known as Brazil tests. Tensile splitting tests were conducted according to BS 1881: Part 117: 1983[172], using 200mm by 100mm diameter cylindrical specimens. Once more, the tensile splitting specimens had been stored in a moist state at the location of the test arrangements until the day of testing. Results from the tensile splitting tests are presented in Table A.5.

It may be seen that the average tensile splitting strength was recorded as 3.55N/mm^2, approximately 10% of the compressive strength. The tensile splitting strength may be related to the compressive strength by the equation:

$$f_{ct} = 0.5\sqrt{f_c} \qquad \text{Eq. A.3.}$$

As a guideline to the tensile strength for lightweight concrete, it is suggested that the strength be reduced by a modification factor η_{lt} as defined in Eurocode 4 as:

$$\eta_{lt} = 0.3 + 0.7\frac{\rho_c}{24} \qquad \text{Eq. A.4.}$$

Where the unit weight of concrete ρ_c is measured in kN/m^3.

The use of the empirical relationship given in Eq. A.3 suggests a tensile splitting strength of 3N/mm^2 based on recorded material properties, providing a reasonably conservative approximation.

A.3. GEOMETRICAL PROPERTIES

An accurate assessment was conducted of beam and column sections to assess their actual dimensions as compared to those specified, as there can be a significant difference between the two. For both the beam and column sections, measurements were recorded at three points along the length of each section. Tables A.6 and A.7 compare the average recorded dimensions with those specified in BS 4[173]. The coefficient of variation (Standard deviation / Average) is presented as a non-dimensionalized measure of the degree of scatter of the raw data.

It may be seen from Table A.6 that generally the measured dimensions were greater than those specified in BS 4, with the exception of the flange thickness. Average measured flange thickness was over 8% less than the nominal value, far in excess of the 2% tolerance specified in BS EN 10034: 1993[174]. The variation in flange thickness results in un-conservative values being specified for second moment of area and elastic modulus. Cross sectional area was greater than the nominal value. As previously described, the actual steel strength was approximately 16% greater than the nominal value, the cumulative effect of which will more than account for the observed geometrical deviation. The coefficient of variation suggests a low dispersion of recorded dimensions. Assessment of the geometrical properties of nominally identical specimens tested by Davison in 1987[65] suggested that average geometrical properties were greater than the nominal values, although a number of values did fall slightly below the nominal values.

Geometrical Properties:	Average:	Nominal:	Percentage Difference:	Standard Deviation:	Coefficient of Variation:
Breadth (mm)	104.37	101.60	+2.73	0.41	0.0039
Depth (mm)	255.54	254.00	+0.60	0.22	0.0009
Flange thi. (mm)	6.24	6.80	-8.29	0.12	0.0192
Web thi. (mm)	6.03	5.80	+3.90	0.12	0.0197
Area (cm^2)	28.91	28.40	+1.81	0.57	0.0198
Ixx (cm^4)	2831.13	2870.00	-1.35	57.66	0.0204
Iyy (cm^4)	118.64	120.00	-1.13	3.51	0.0296
Zxx (cm^3)	221.92	226.00	-1.81	4.40	0.0198
Zyy (cm^3)	22.89	23.60	-3.03	0.61	0.0268

Table A.6. Geometrical Beam Properties

Similar properties were recorded for column sections, with the average flange thickness once more falling considerably below the nominal value. For the column section the average divergence was increased to 11.4%, whilst there was still a limited scatter of data. It would be expected once more that the enhanced steel strength would more than compensate for the reduced sectional properties. Results were once more compared with those obtained by Davison. It was observed that these came out close to the nominal values, with the actual values typically being greater than the nominal. However, average flange thickness was observed to be 3.6% below the nominal value.

Geometrical Properties:	Average:	Nominal:	Percentage Difference:	Standard Deviation:	Coefficient of Variation:
Breadth (mm)	153.91	152.40	+0.99	0.88	0.0057
Depth (mm)	156.88	152.40	+2.94	0.60	0.0038
Flange thi. (mm)	6.03	6.80	-11.40	0.10	0.0172
Web thi. (mm)	6.11	6.10	+0.15	0.12	0.0196
Area (cm^2)	28.62	29.80	-3.97	0.45	0.0158
Ixx (cm^4)	1234.80	1260.00	-2.00	22.12	0.0179
Iyy (cm^4)	367.36	403.00	-8.84	8.28	0.0225
Zxx (cm^3)	158.57	166.00	-4.47	2.60	0.0164
Zyy (cm^3)	47.84	52.90	-9.56	0.95	0.0198

Table A.7. Geometrical Column Properties

A.4. CARDINGTON MATERIAL PROPERTIES

Testing was commissioned by the Building Research Establishment to assess material properties for the structural steelwork, reinforcement and concrete contained within the Cardington test frame. It was originally intended that the steelwork would be rolled at British Steel's Scunthorpe mill, but due to a misunderstanding the work was split between three mills, Lackenby, Shelton and Scunthorpe. This provides an indication of the variability of steel from different mills, and provides valuable data for the consideration of the response of the Cardington test frame.

Material properties for the steel sections are summarised in Table 123, with more comprehensive data being presented in Ref. A-10. Average results presented are based on the number of specimens tested from each rolling mill, and as such may appear misleading.

In addition to the assessment of steel properties, reinforcement, bolt and concrete properties were also recorded. As in the case of the composite tests presented in Chapter 2, a nominal A142 mesh reinforcement was adopted. Average 0.2% proof stress was 629N/mm^2, with the ultimate stress being 732N/mm^2, at an elongation of 14.2%.

Both M20 and M24 bolts were incorporated within the Cardington test frame. This is the only source of information on bolt characteristics, as no tests were conducted on the bolts contained within the connection tests. Unfortunately bolt dimensions were not identical, with M16 bolts being used in the connection tests. For the M20 Grade 8.8 bolts, a tensile strength of 850N/mm^2 was observed, with an ultimate elongation of 17.6%. For the M20 bolts, there was a slight enhancement in capacity to 882N/mm^2, but a reduction in ductility to 15.6%.

Cube strength was assessed for the concrete used for the composite slab at both 7 and 28 days. The 7-day strength was recorded as 26.1N/mm^2, increasing to 47N/mm^2 by 28 days.

Steelwork:	Yield Stress (kN/mm^2):		Max. Stress (kN/mm^2):		Elongation (%):	
Lackenby	314 (43)	391 (50)	483 (43)	530 (50)	26 (43)	26 (50)
Shelton	-	389 (50)	-	541 (50)	-	27 (50)
Scunthorpe	308 (43)	-	472 (43)	-	27 (43)	-
Average	308 (43)	389 (50)	472 (43)	540 (50)	27 (43)	27 (50)

Table A.8. Cardington Steel Properties

A.5. CONCLUSIONS

A number of mechanical and geometrical tests have been conducted for the sections used in the bare steel and composite connection tests, to provide data for connection modelling, and as an indication of the variability of nominally identical sections.

It is observed that the strength of the steel was significantly greater than the nominal value for both beam and column sections, and that there was a close correlation between recorded values. Geometrical properties were generally close to the nominal values, although there was a significant reduction in flange thickness for beams and columns. The influence of this is compensated for by the enhancement in strength. Reinforcing mesh also demonstrated a significant increase in strength over the nominal value, but a reduction in cross-sectional area.

Compressive tests conducted to assess the strength of the concrete mix indicated a strength of approximately 46N/mm^2, considerably greater than the specified C35 mix. This is expected, as concrete mixes are generally over-conservative to account for natural variability. The tensile strength of the concrete was recorded as 3.55N/mm^2.

There is generally a close correlation between the material properties recorded for the Cardington test frame and those obtained from the connection tests, with yield stresses of 319N/mm^2 and 308N/mm^2 and ultimate stresses of 465N/mm^2 and 472N/mm^2 for the Grade 43 steel from the connection tests and Cardington test frame respectively. Ductility of the steel for the connection tests was seen to be greater than that for the Cardington test frame, with an average elongation of 37.5% compared to 27%. Properties of steel produced for the Cardington test frame compare closely, despite the steel having been rolled at three different mills. The yield stress of the A142 reinforcing mesh used in the connection tests was identical to that from the Cardington test frame, although the maximum stress was less for the connection tests. Concrete compressive strength was also close.

APPENDIX B. DEVELOPMENT OF PLATE BENDING THEORY FOR FLUSH END-PLATES

B.1. INTRODUCTION

As described in Chapter 5, the stiffness of end-plates welded all-round appears to have been insufficiently considered within existent spring stiffness models. It is suggested that a more acceptable representation of response may be obtained through the application of plate bending theory. Exact solution of the problem in hand would become laborious due to the complex arrangement of boundary conditions and loading arrangements required to model a welded end-plate, and it is therefore suggested that the plate is modelled assuming simplified 'potential energy methods'.

B.2. POTENTIAL ENERGY METHODS

The potential energy method is an approximate technique used for solving the equilibrium of elastic structures. In applying this principle one must consider all possible compatible deformation patterns, and derive an expression for the strain energy stored within the plate in terms of the deflection, w. It may be shown that the total potential energy (T) of an arrangement consists of the strain energy of the plate (U) and the potential energy of the load (V), with the total potential energy of the plate being at a minimum when the loaded plate is in stable equilibrium. As such, the total potential energy may be expressed as[175]:

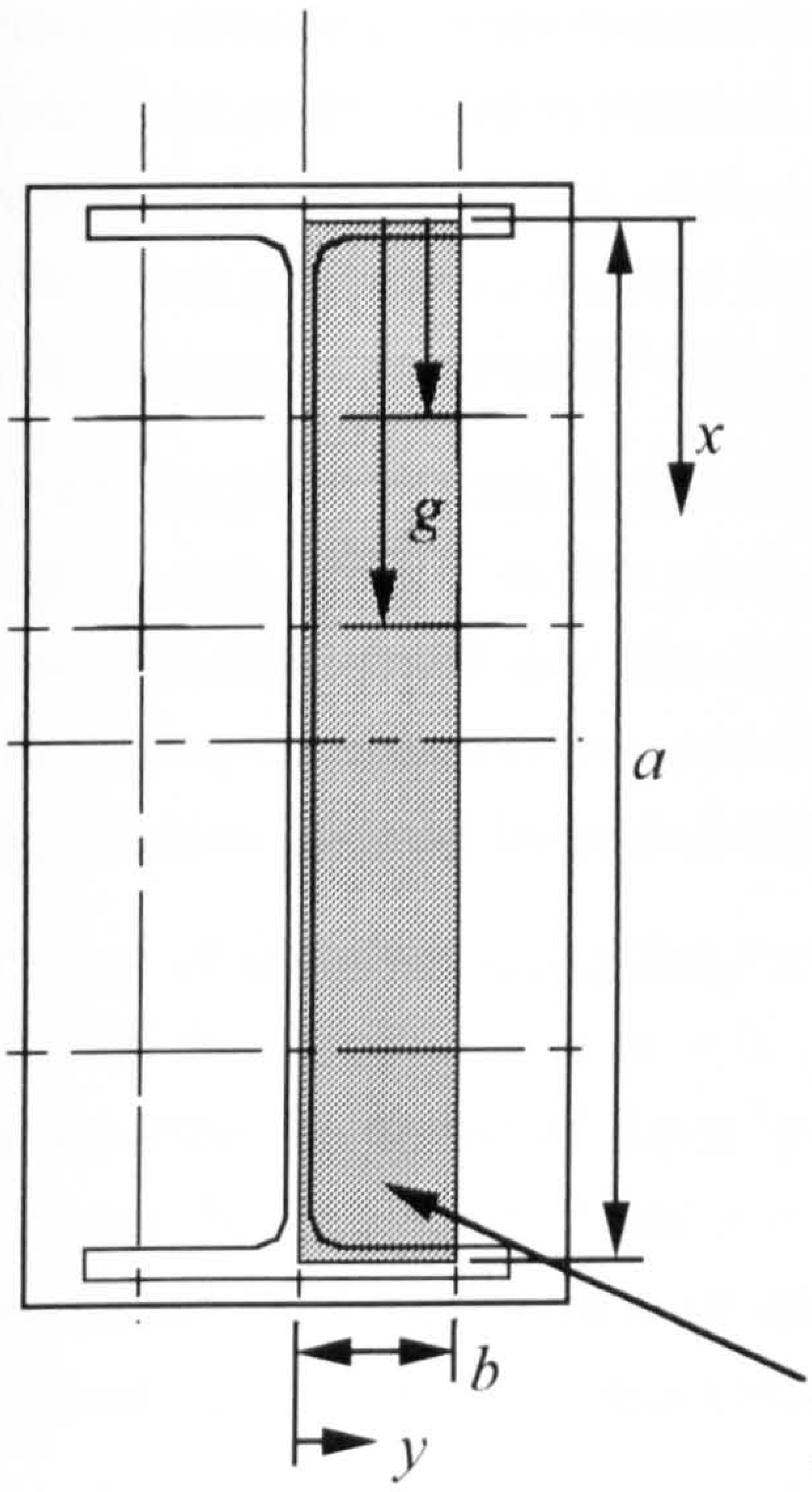
$$T = \int_0^a \int_0^b \left[\frac{D}{2} \left\{ \left(\frac{\partial^2 w}{\partial^2 x} + \frac{\partial^2 w}{\partial^2 y} \right)^2 - 2(1-\upsilon) \left[\frac{\partial^2 w}{\partial^2 x} \frac{\partial^2 w}{\partial^2 y} - \left(\frac{\partial^2 w}{\partial x \partial y} \right)^2 \right] \right\} - V \right] dx dy \qquad \text{Eq. B.1.}$$

Exact solution of the problem in hand is possible by satisfying all external boundary conditions, and minimising the total potential energy (T) in Eq. B.1. To achieve this one seeks a representation of w (typically in the form of a finite series) which is capable of representing adequately the deflection pattern. Clearly the exact solution of Eq. B.1 is a complex procedure, and the more significant application of the potential energy method is in the realms of approximate solutions. Approximate solution of the potential energy equation is due to Ritz, in which one approximates the deflected shape of the structure by a set of known shapes with amplitudes to be found. Functions are selected so as to satisfy the boundary conditions and generate the form of deflection pattern expected, the accuracy of the solution depending on the suitability and number of the assumed functions.

B.3. MODELLING OF END-PLATE RESPONSE

B.3.1. Definition of End-plate Model

Application of plate bending theory in the spring stiffness model presented in Chapter 5 is primarily concerned with full-depth end-plates in which the beam is assumed to be 'welded all-round'. An idealised representation of a typical connection is illustrated in Fig. B.1(a). Use of symmetry may be made along the y-axis of the beam, simplifying the problem in hand to one of a rectangular plate supported along three sides, with the fourth side remaining free to displace.



(a) Geometrical Conditions:

$a = D_b - t_{bf}$

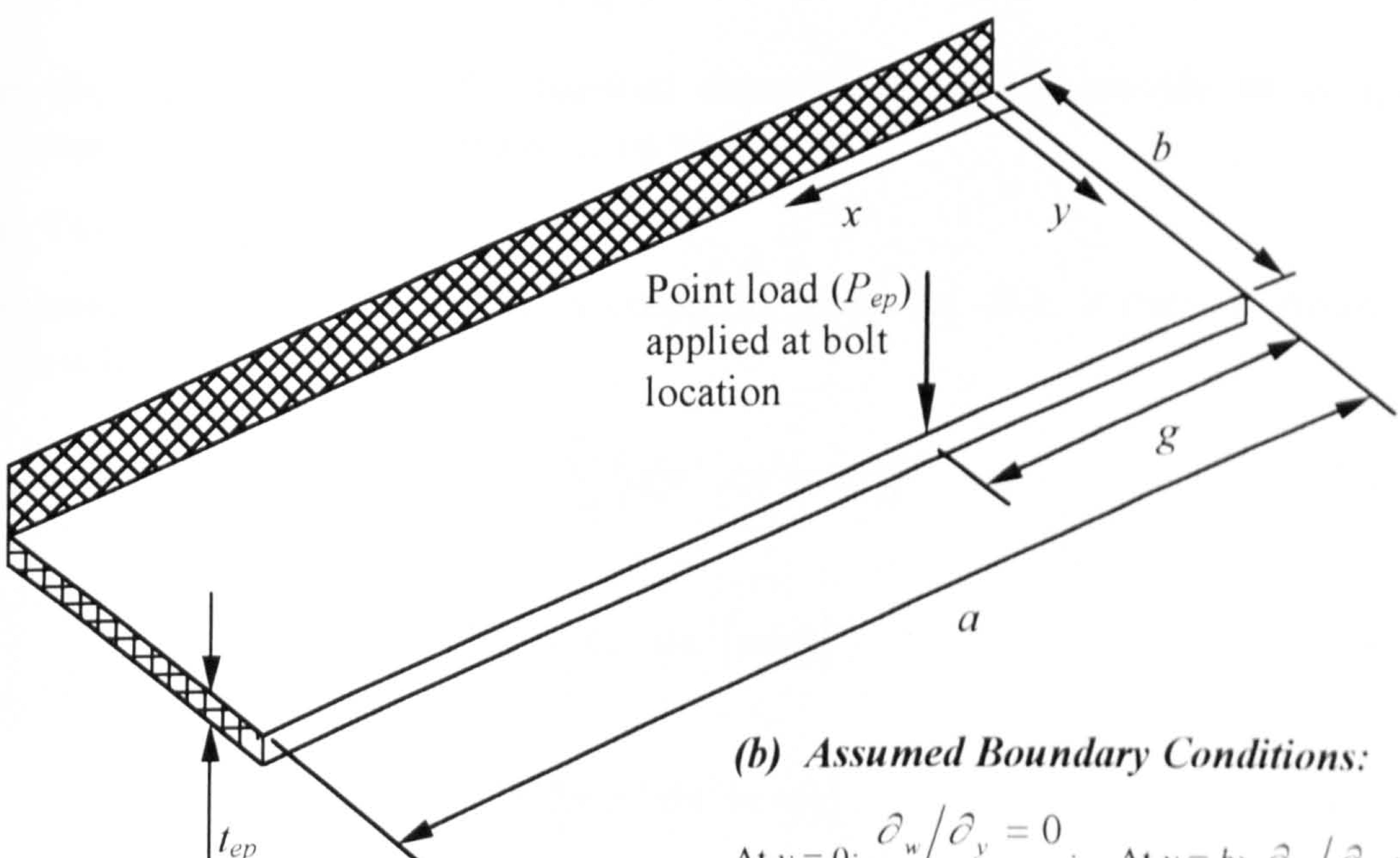
$b = gauge / 2$

Where

D_b is the depth of beam section;

t_{bf} is the thickness of beam flanges;

g is the distance from the centre of the top beam flange to the centre of the bolt row under consideration.



(b) Assumed Boundary Conditions:

At $y = 0$: $\partial_w / \partial_y = 0$; $w = 0$; At $y = b$: $\partial_w / \partial_y = 0$

At $x = 0, a$: $w = 0$

Figure B.1. Idealised Representation of End-Plate

Along the line of symmetry ($y = 0$), it is assumed that the plate is 'built in' due to continuity, and as such both rotation and vertical displacement are restrained. Along the edges welded to the beam flanges ($x = 0$ and a) the plate element is assumed to be restrained in position; it is expected that some degree of rotational restraint would occur but the extent of this is difficult to quantify, as such this is neglected, resulting in a conservative solution. Representation of the free edge of the plate has been simplified by considering the plate to be restrained against rotation along the line of the bolts, where the end-plate effectively remains clamped to the column flanges. Based on the above assumption it is possible to assume the free edge to correspond with the bolt centreline, and the resultant area of plate under consideration to be as shaded.

Loading of the plate occurs as the end-plate is pulled from the column flanges, resulting in point loads being applied to the plate at bolt locations. It is assumed in the formulation of the spring-stiffness model that the interaction between joint elements has a negligible effect on the response of components considered in isolation, as such the load applied at each of the bolt locations is considered individually.

Deformation of the plate along the y axis is controlled by the boundary conditions $\partial w/\partial y = 0$ at $y = 0$ and b, and $w = 0$ at $y = 0$. As such the function $(1 - \cos \pi y/b)$ would seem to suitably describe the deflected form 'y-wise'. Representation of a point load along the edge $y = b$ (where the edges $x = 0$ and $x = a$ are simply supported) causes little difficulty as the deflected shape of the plate may be analysed in the form of a series of sinusoidally varying displacement functions. It is thus assumed that w may be specified as:

$$w = \sum_{n=1}^{\infty} q_n \left\{ 1 - \cos\left(\frac{\pi y}{b}\right) \right\} \sin(n\pi\xi) \sin\left(\frac{n\pi x}{a}\right) \qquad \text{Eq. B.2.}$$

Where the number of terms (n) required along the y axis to provide an acceptable representation of a point load remains to be found.

B.3.2. Formulation

Substituting w into each of the terms contained within Eq. B.1, it may be shown after considerable algebra that:

$$\frac{D}{2}\int_0^a\int_0^b \left(\frac{\partial^2 w}{\partial x^2}\right)^2 dxdy = \frac{3Db\pi^4}{8a^3}\sum_{n=0}^{\infty}\left\{q_n^2 n^4 \sin^2(n\pi\xi)\right\} \qquad \text{Eq. B.3.}$$

$$\frac{D}{2}\int_0^a\int_0^b \left(\frac{\partial^2 w}{\partial y^2}\right)^2 dxdy = \frac{D\pi^4 a}{8b^3}\sum_{n=1}^{\infty}\left\{q_n^2 \sin^2(n\pi\xi)\right\} \qquad \text{Eq. B.4.}$$

$$\frac{D}{2}\int_0^a\int_0^b \left(\frac{\partial^2 w}{\partial x \partial y}\right) dxdy = \frac{D\pi^4}{8ba}\sum_{n=1}^{\infty}\left\{q_n^2 n^2 \sin^2(n\pi\xi)\right\} \qquad \text{Eq. B.5.}$$

$$\frac{D}{2}\int_0^a\int_0^b \left(\frac{\partial^2 w}{\partial x}\frac{\partial^2 w}{\partial y}\right) dxdy = \frac{D\pi^4}{8ba}\sum_{n=1}^{\infty}\left\{q_n^2 n^2 \sin^2(n\pi\xi)\right\} \qquad \text{Eq. B.6.}$$

Hence, the strain energy of the plate for the assumed boundary conditions is:

$$U = \frac{D\pi^4}{8}\sum_{n=1}^{\infty}\left[\frac{3b}{a^3}\left\{q_n^2 n^4 \sin^2(n\pi\xi)\right\} + \frac{2}{ba}\left\{q_n^2 n^2 \sin^2(n\pi\xi)\right\} + \frac{a}{b^3}\left\{q_n^2 n^4 \sin^2(n\pi\xi)\right\}\right] \qquad \text{Eq. B.7.}$$

Considering the plate to be subject to a single point load along the edge $y = b$, corresponding with the selected bolt location, it can be demonstrated that the term describing the 'applied load potential energy' may be expressed:

$$V = 2P\sum_{n=1}^{\infty}\sin^2(n\pi\xi) \qquad \text{Eq. B.8.}$$

Making the total potential energy (T) as small as possible by setting all $\partial T/\partial q_n = 0$, the magnitudes of the various functions describing the deformation of the plate is defined as:

$$q_n = \frac{8P}{D\pi^4\sum_{n=1}^{\infty}\left\{\frac{3bn^4}{a^3}+\frac{2n^2}{ba}+\frac{a}{b^3}\right\}} \qquad \text{Eq. B.9.}$$

Having solved for the terms q_n described above, it is thus possible to define the shape of the plate at any given location based on the deflected form described in Eq. B.2. As the primary concern is the level of deformation occurring at bolt locations the expression may be simplified, expressing the term defining the deflection w of the plate specific to the deflection at the bolt location, Δ_{ep} as:

$$\Delta_{ep} = 2\sum_{n=1}^{\infty} q_n \sin^2(n\pi\xi) \qquad \text{Eq. B.10.}$$

Substituting the expression for q_n from Eq. B.9 into Eq. B.10:

$$\Delta_{ep} = \sum_{n=1}^{\infty}\frac{16P\sin^2(n\pi\xi)}{D\pi^4\left\{\frac{3bn^4}{a^3}+\frac{2n^2}{ba}+\frac{a}{b^3}\right\}} \qquad \text{Eq. B.11.}$$

Hence, the stiffness of a rectangular end-plate restrained along three edges, subject to a single point load may be obtained:

$$K_{ep} = P/\Delta_{ep} \qquad \text{Eq. B.12.}$$

Analysis of the end-plate tested at elevated temperatures, as described in Chapter 3, has been conducted assuming $\xi = 0.2$, with the aspect ratio of the plate (a/b) being approximately 6.5. The resultant deflected shape of the plate is illustrated in Fig. B.2, having expanded the series 'x-wise' to include ten terms.

B.4. DISCUSSION

It may be seen from Fig. B.2 that the resultant deflected shape of the plate appears reasonable, with maximum deflection occurring at the location of the point load, and most non-relevant sine waves having been removed. A convergence study was conducted based on the plate described with a point load situated at $\xi = 0.2$, to assess the influence of the number of terms contained 'x-wise' on the stiffness of the plate at the bolt location, as illustrated in Fig. B.3. It may be seen that the stiffness of the plate is greatly overestimated based on a single term, as would be anticipated; however as the number of terms increases to approximately ten, the predicted stiffness quickly converges towards the exact solution.

Discontinuities observed in the convergence study are attributable to functions of sine waves where the resultant is zero at the location of the point load. Assessment based on differing ratios of ξ demonstrated a similar rate of convergence.

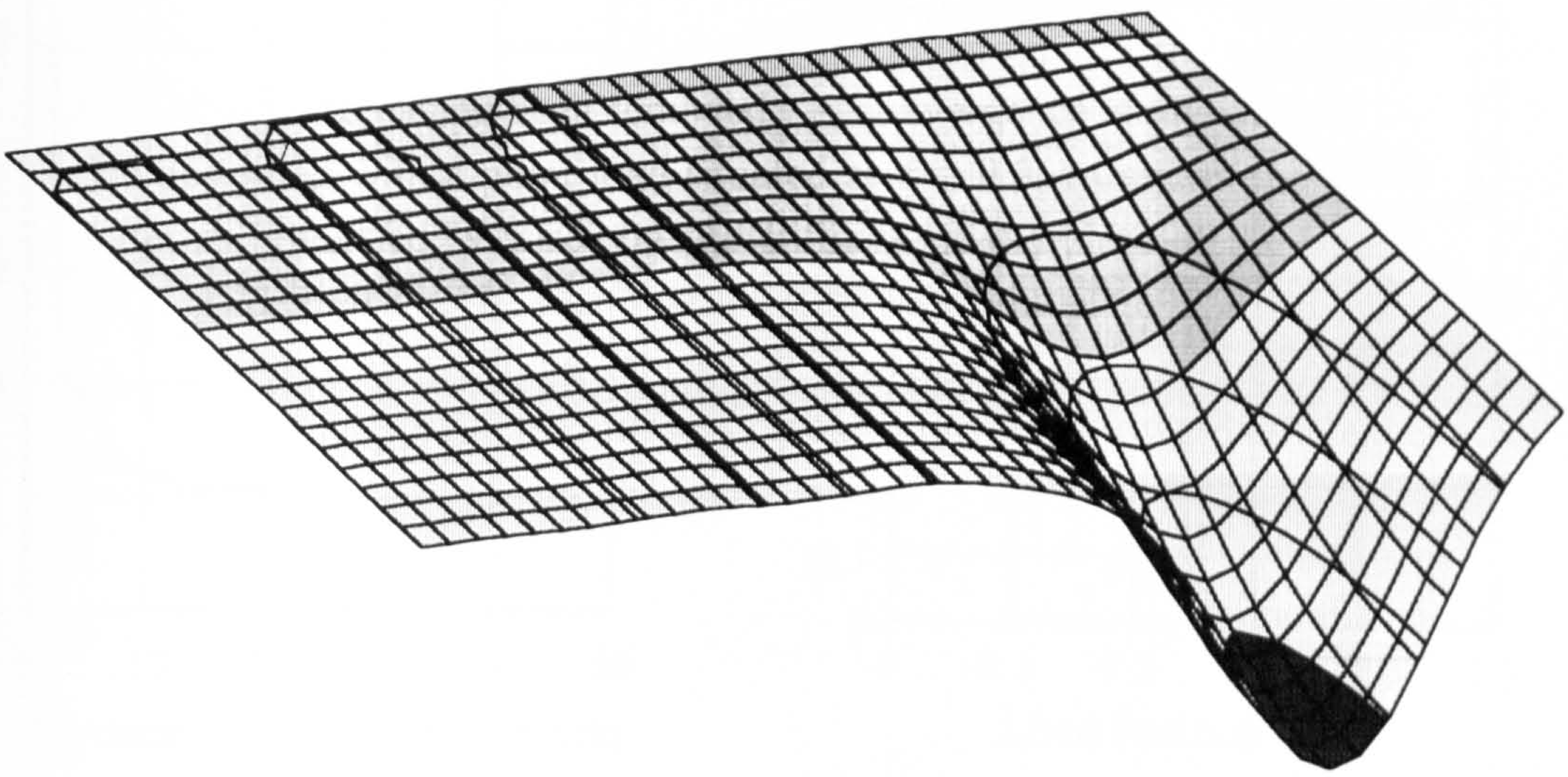


Figure B.2. Resultant Deflected Form

Considering the deflected form illustrated in Fig. B.2 it may be seen that the deflection of the plate soon becomes insignificant as one moves away from the point of loading. This seems to suggest that for the load position considered the restraint provided by the weld to the beam flanges has little influence on the stiffness of the plate, with the end-plate effectively acting as a cantilever of infinite length as described by Jarimillo[133]. The analysis was repeated for the rectangular plate with values of ξ in the range 0.1 to 0.5, results from which are presented in Fig. B.4. For a value of ξ approaching zero, the stiffness of the plate approaches infinity. As the location of the point load moves away from the supporting flange there is a rapid reduction in the stiffness of the end-plate, and for a value of ξ of 0.2 it may be seen that the restraining edges become insignificant, resulting in the plate acting as a cantilever of infinite length. A similar response has been observed by Timoshenko and Woinowski-Krieger[176], who commented that '*the maximum deflection rapidly approaches that of an infinitely long plate as the length of the plate increases*' when considering the case of a simply supported rectangular plate subject to a single point load. It was felt that this phenomenon is related to the aspect ratio of the plate, and the analysis was therefore repeated for a square plate of sides 200mm subject to the same restraint conditions as previously, with a single point load acting at the free edge. Once more it may be seen that the influence of edge restraint on the stiffness of the plate soon becomes insignificant as ξ increases. The 254x102UB(43) end-plate tested represents the lower range of aspect ratios for typical connection arrangements, and as such it would seem reasonable to assume that unless a bolt is situated within the top 10% of a beam depth, the influence of edge restraint may be neglected, and the problem analysed as a cantilever of infinite length.

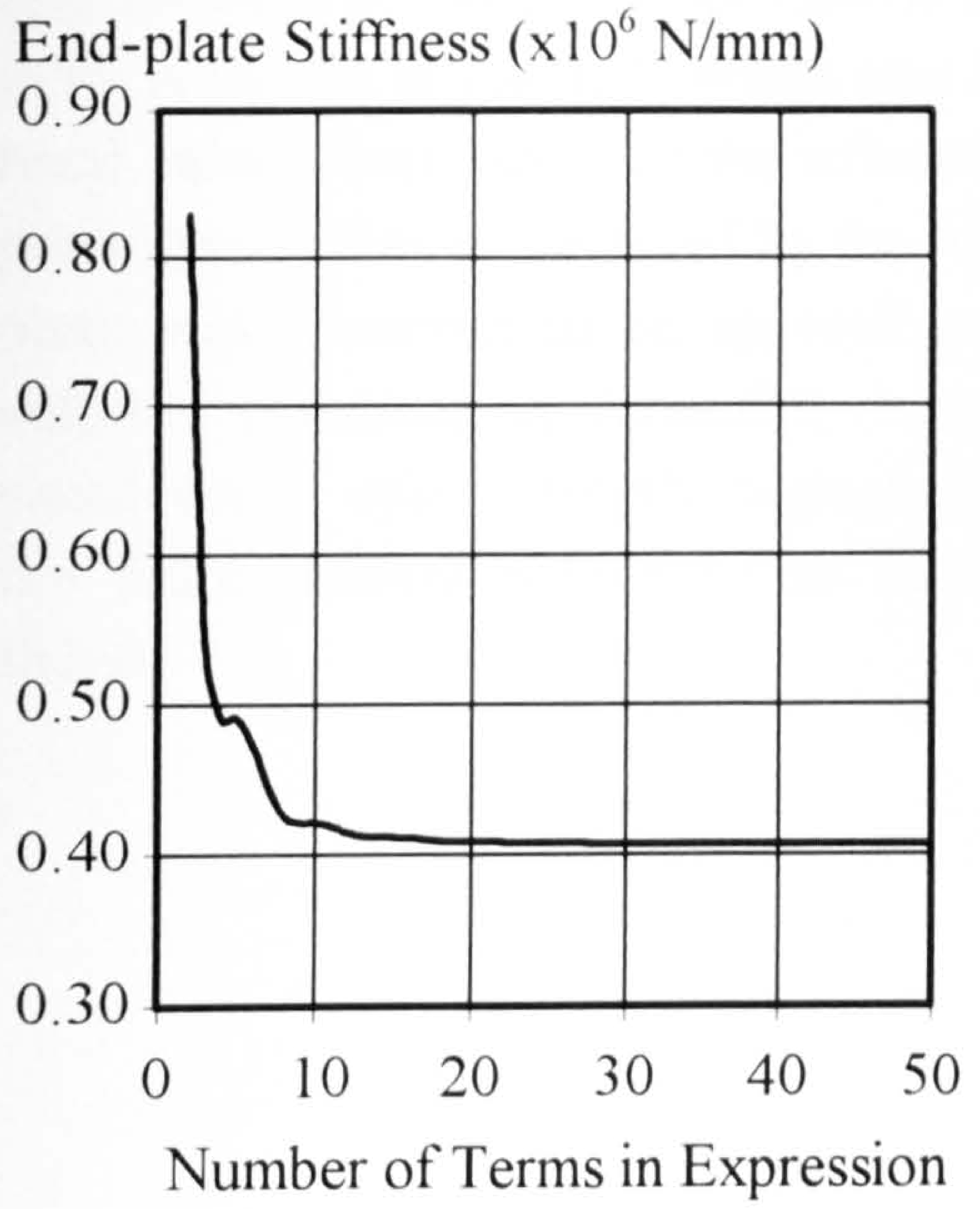


Figure B.3. Convergence Study of Number of Terms 'x-wise'

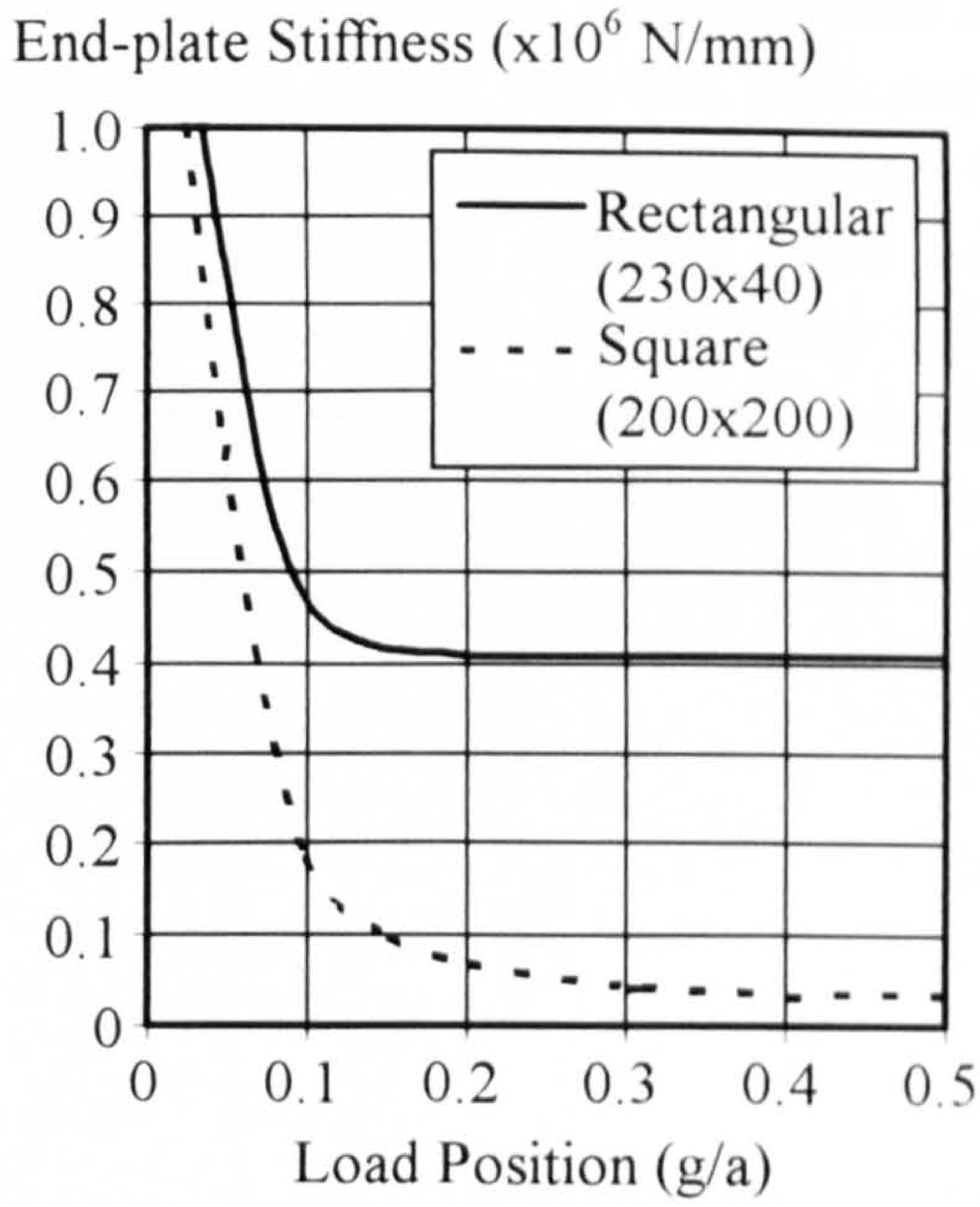


Figure B.4. Influence of Load Position on Plate Stiffness

The stiffness of the rectangular end-plate described above was predicted to be approximately 0.407×10^6 N/mm based on plate bending theory (for a single side of the end-plate). This compares with a value of 0.221×10^6 N/mm based on the exact solution for a cantilever of infinite length developed by Jaramillo[133], and more recently adopted by both Johnson and Law[96] and Madas[103] to represent the response of column flanges subject to bolt loads. Jaramillo did not restrain the plate against rotation at the bolt location, and as such a lower predicted stiffness would be expected. However, Johnson and Law validated results based on Jaramillo's theory through the consideration of appropriate tests on unstiffened column flanges conducted by Zoetemeijer[134] and Packer and Morris[130], with close agreement.

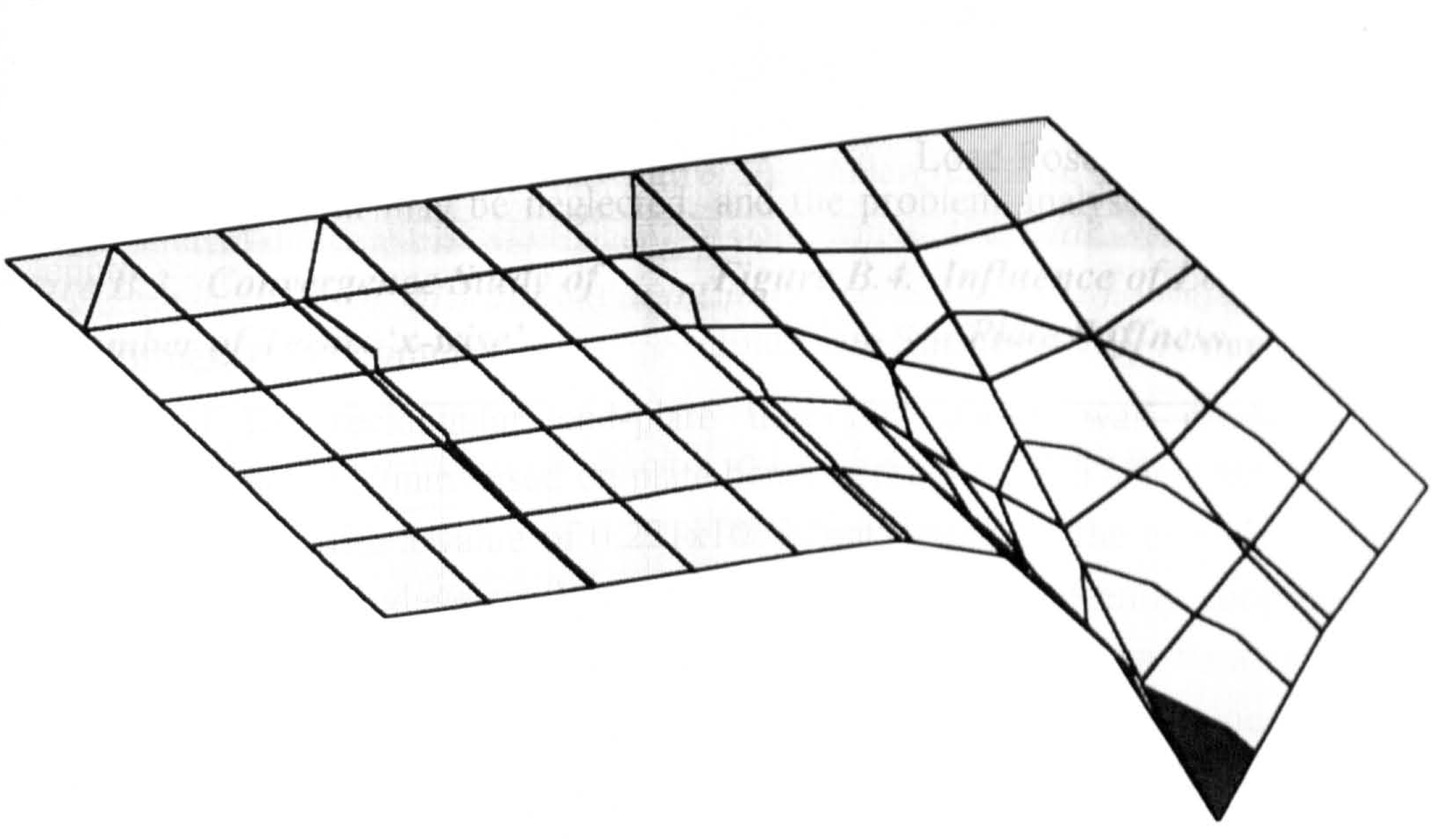


Figure B.5. Response Predicted by Finite Element Analysis

Analysis of the plate was repeated using finite element analysis based on an 'exact' solution of thin plate bending theory[176]. Restraint conditions and loading were as for the approximate potential energy method detailed above. The resultant deflected form of the plate is shown in Fig. B.5, which may be seen to compare closely with that predicted from hand calculations, although the influence of restraint against rotation along the edges is less pronounced than represented by the function $(1 - \cos \pi y/b)$. The resultant stiffness of the plate was observed to be approximately 0.263×10^6 N/mm, comparing closely with the solution presented by Jaramillo, once more supporting the applicability of analysis as a cantilever of infinite length, neglecting restraint against rotation at bolt locations. Use of the finite element software was validated using standard solutions from plate bending theory[176].

APPENDIX C. DERIVATION OF α FOR DETERMINATION OF YIELD LINE LENGTHS

Mathematical derivation is presented here for the term α used in the derivation of effective yield lengths when considering end-plate and column flange failure, as presented in Chapter 5. This is found by satisfying the conditional statements below, and solving for F as appropriate.

Conditional Statements

1. If $\lambda_1 \leq$ F1 then, $\alpha = 2\pi$
2. If $\lambda_1 \geq$ F2 then, $\alpha = 4.45$
3. If F1 $< \lambda_1 <$ F2 then,
   (a) If $\lambda_2 \geq 0.45$ then, $\alpha =$ F3
   (b) If $(0.2768\,\lambda_1 + 0.14) \leq \lambda_2 < 0.45$ then, $\alpha =$ F4
   (c) If $(1.2971\,\lambda_1 - 0.7782) \leq \lambda_2 < 0.2768\,\lambda_1$ then, $\alpha =$ F5
   (d) If $\lambda_2 < (1.2971\,\lambda_1 - 0.7782)$ then, $\alpha =$ F6

Formulae

$$F1 = 0.99477448 - 2.45848503\lambda_1 + 3.15497168\lambda_1^2 - 2.230174344\lambda_1^3 + 0.52850212\lambda_1^4$$

$$F2 = 1.04213142 - 0.857591820\lambda_2 + 1.15828063\lambda_2^2 - 0.79910192\lambda_2^3 + 0.21398139\lambda_2^4$$

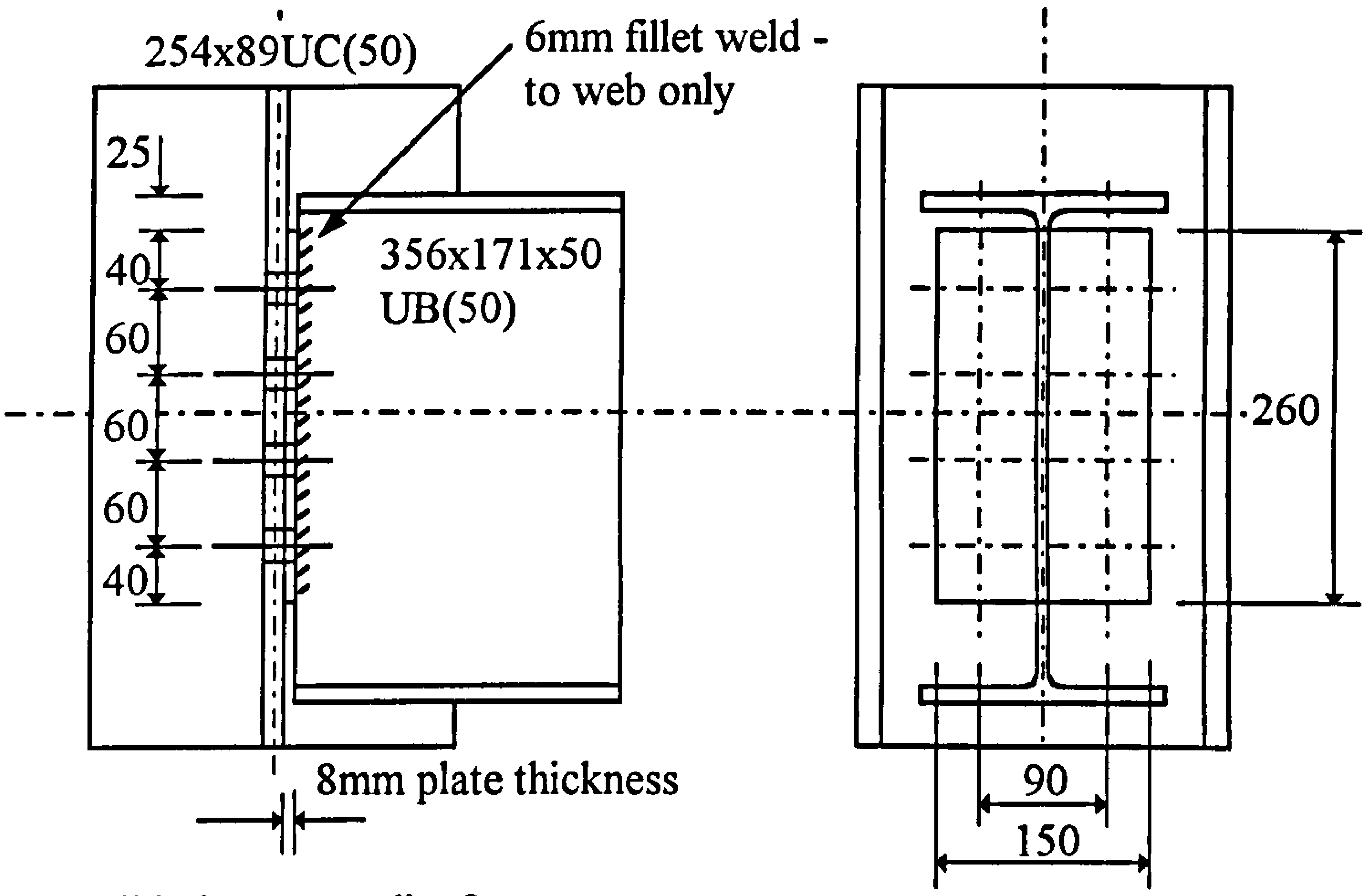
$$F3 = 8.130283 + 4.488295\lambda_1 - 3.441231\lambda_2 - 16.699661\lambda_1^2 + 4.657641\lambda_2^2 - 6.805232\lambda_1\lambda_2 + 8.747474\lambda_1^3 - 1.197675\lambda_2^3 - 1.227359\lambda_1\lambda_2^2 + 8.318217\lambda_1^2\lambda_2$$

$$F4 = 1.245666 + 39.333003\lambda_1 + 3.580332\lambda_2 - 55.940605\lambda_1^2 + 40.544586\lambda_2^2 - 55.34357\lambda_1\lambda_2 + 21.049463\lambda_1^3 - 33.001768\lambda_2^3 + 2.792410\lambda_1\lambda_2^2 + 44.062493\lambda_1^2\lambda_2$$

$$F5 = -86.5052 + 478.58887\lambda_1 + 79.4300092\lambda_2 - 935.102794\lambda_1^2 - 329.854733\lambda_2^2 - 68.228567\lambda_1\lambda_2 + 809.056164\lambda_1^3 + 531.672952\lambda_2^3 + 252.193252\lambda_1\lambda_2^2 - 44.242644\lambda_1^2\lambda_2 - 254.659837\lambda_1^4 - 605.622885\lambda_2^4$$

$$F6 = -226.979097 + 1095.760732\lambda_1 - 12.1186777\lambda_2 - 1848.467314\lambda_1^2 + 717.104423\lambda_2^2 - 264.307024\lambda_1\lambda_2 + 1369.007748\lambda_1^3 - 2120.516058\lambda_2^3 - 69.105002\lambda_1\lambda_2^2 + 195.697905\lambda_1^2\lambda_2 - 381.685783\lambda_1^4 + 2562.146768\lambda_2^4$$

APPENDIX D. AMBIENT-TEMPERATURE CARDINGTON CONNECTION TESTS



All holes 22mm dia. for - M20 Grade 8.8 bolts

Minor-Axis Flexible End-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

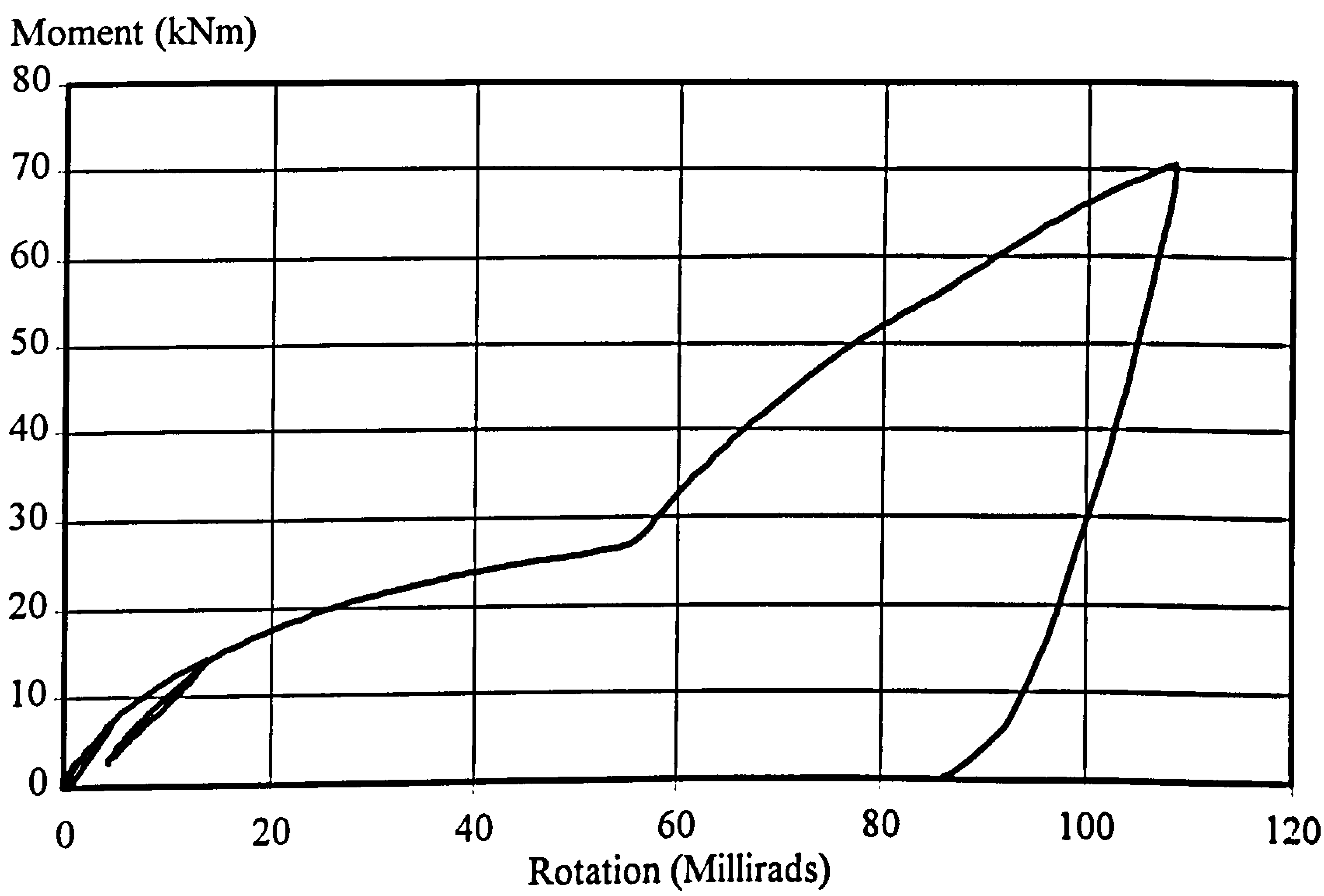
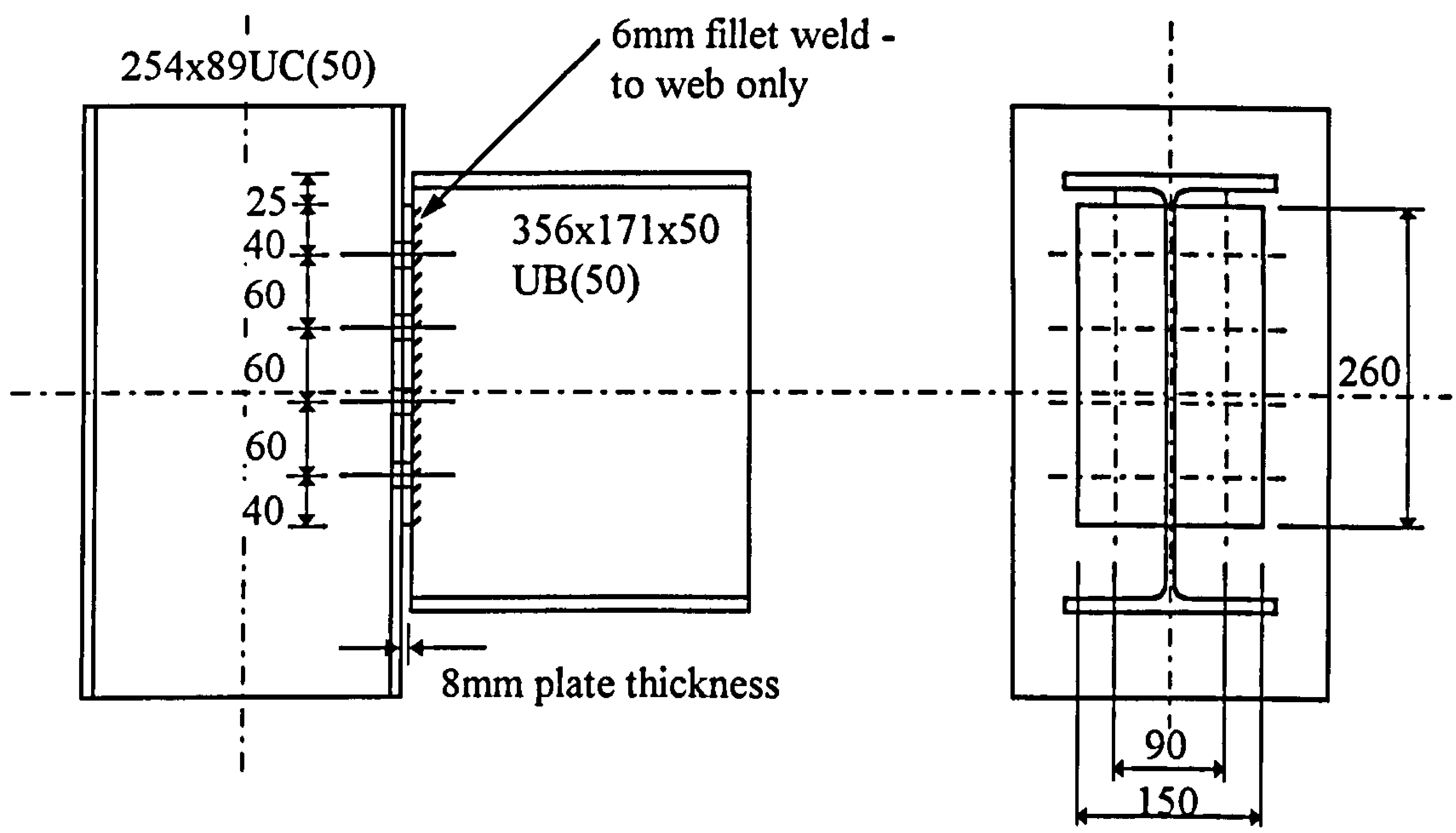


Figure D.1. Ambient-Temperature Moment-Rotation Results for CANT1



All holes 22mm dia. for - M20 Grade 8.8 bolts

Major-Axis Flexible End-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

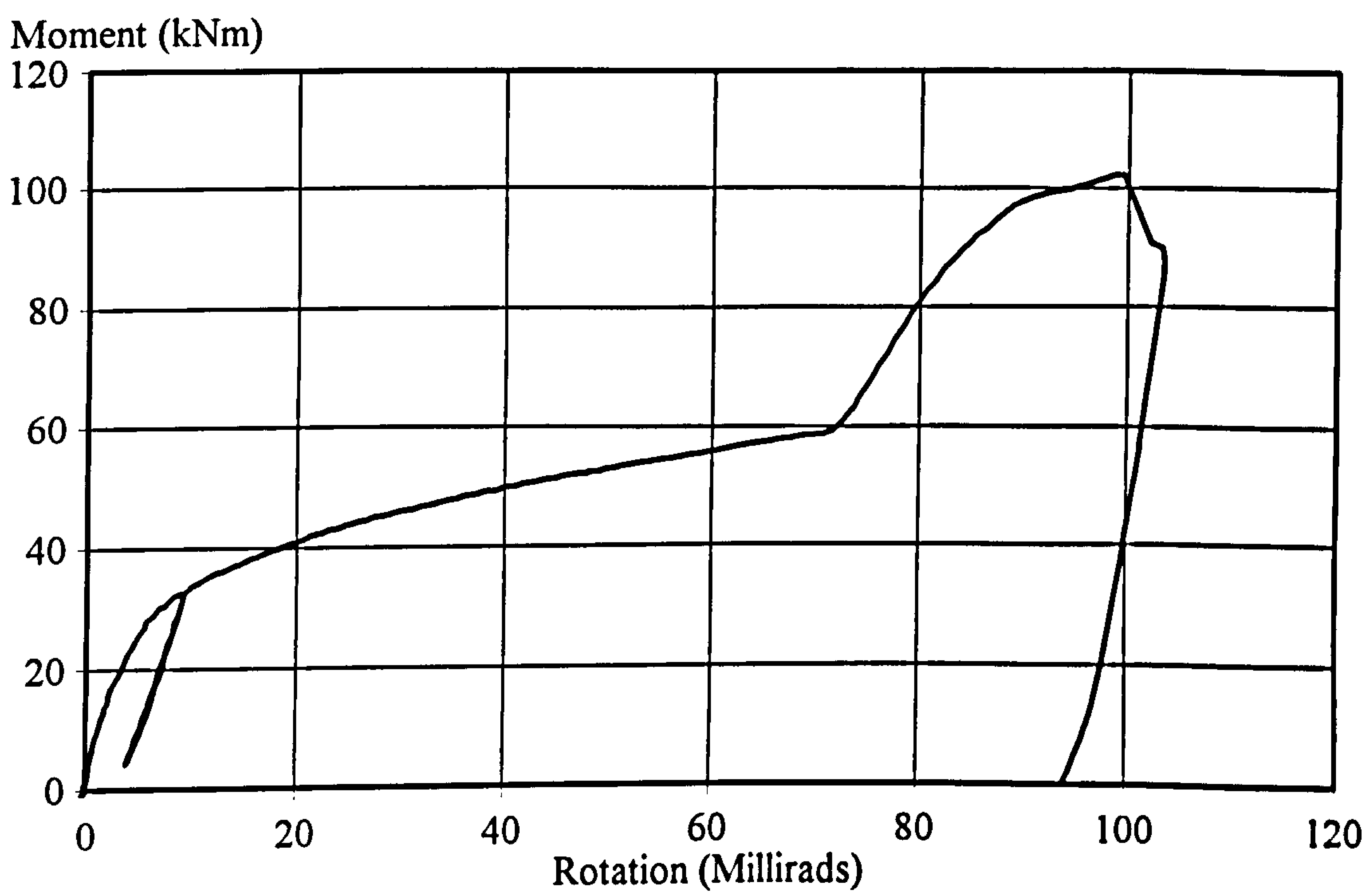
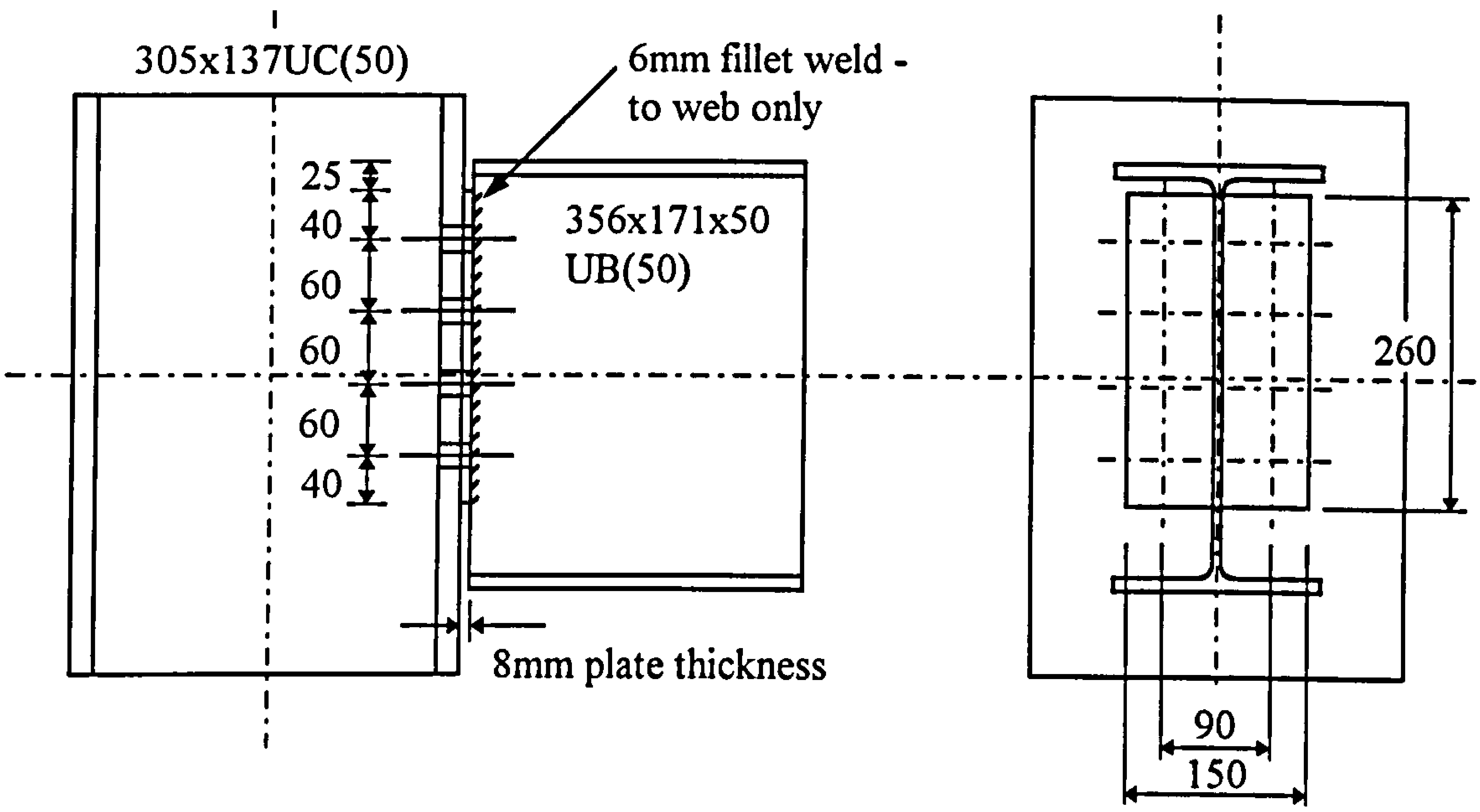


Figure D.2. Ambient-Temperature Moment-Rotation Results for CANT2



All holes 22mm dia. for -
M20 Grade 8.8 bolts

Major-Axis Flexible End-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

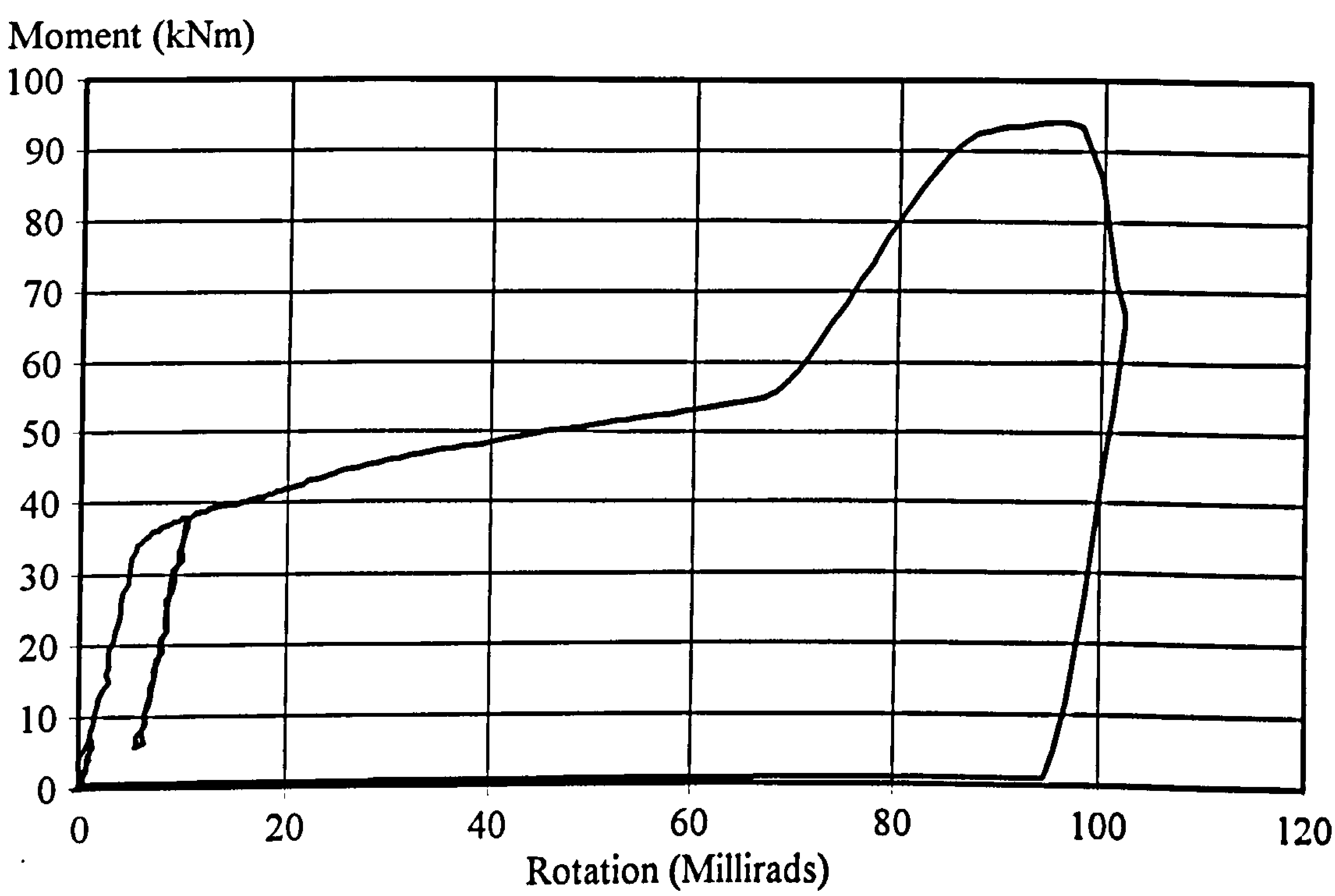
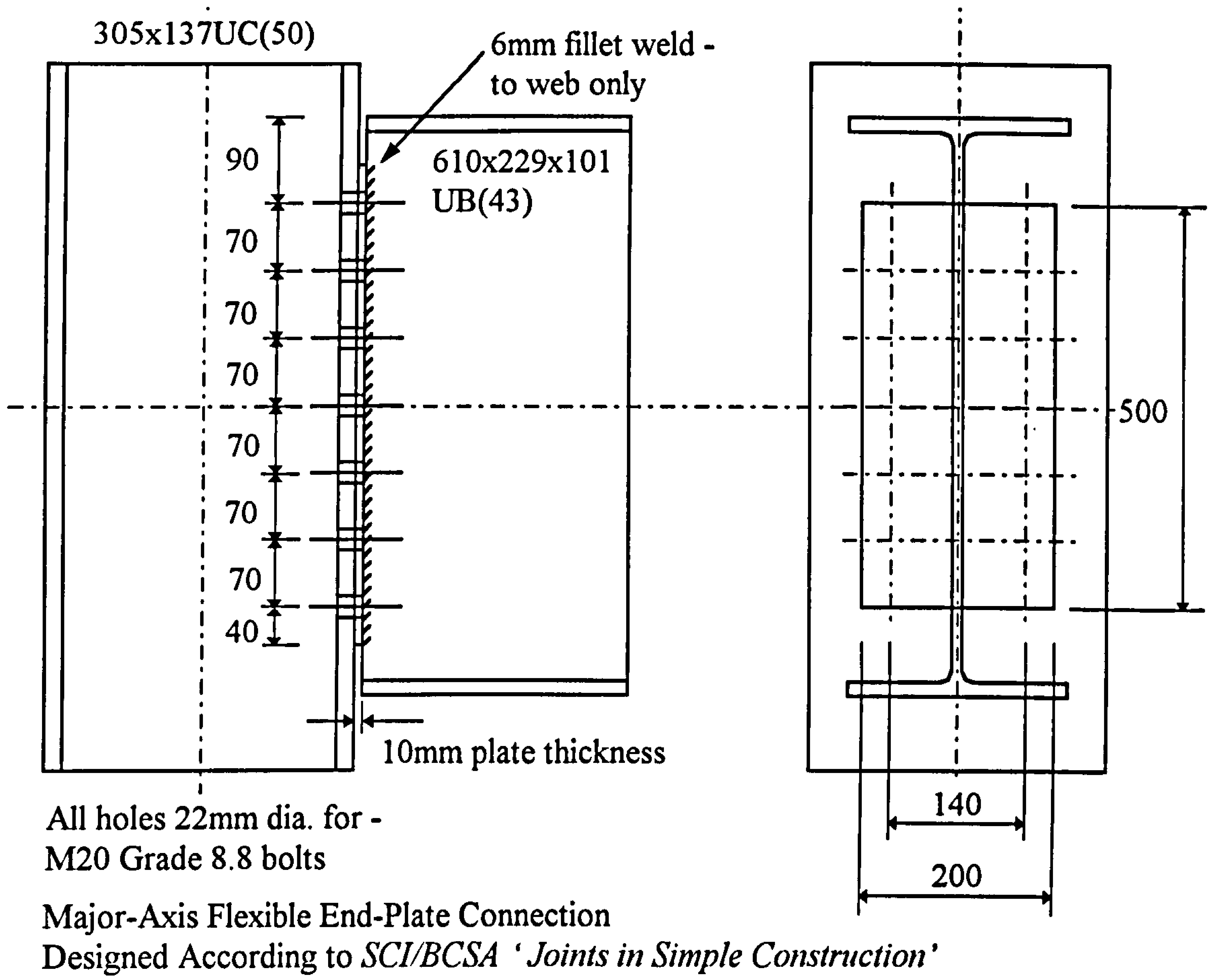


Figure D.3. Ambient-Temperature Moment-Rotation Results for CANT3



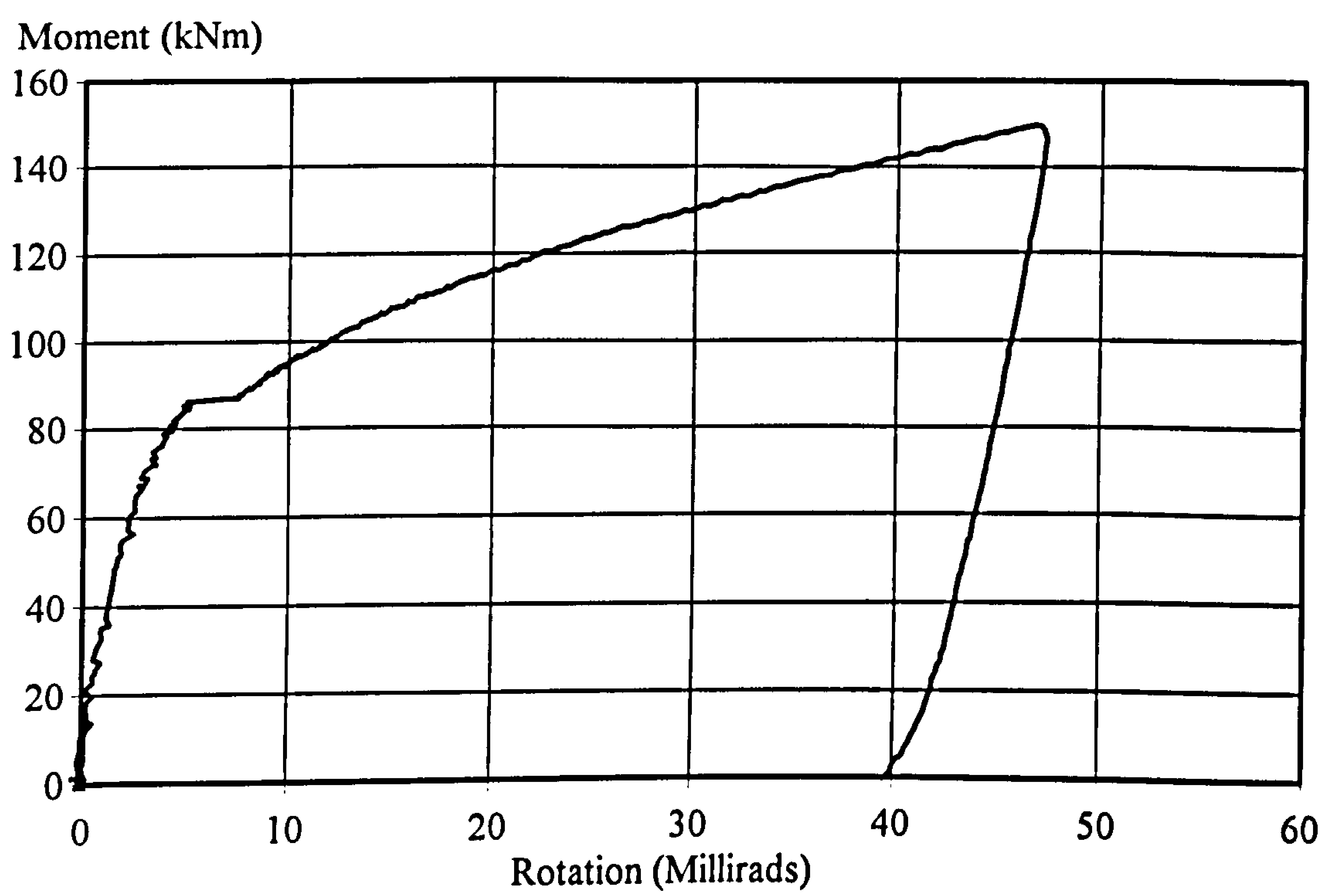
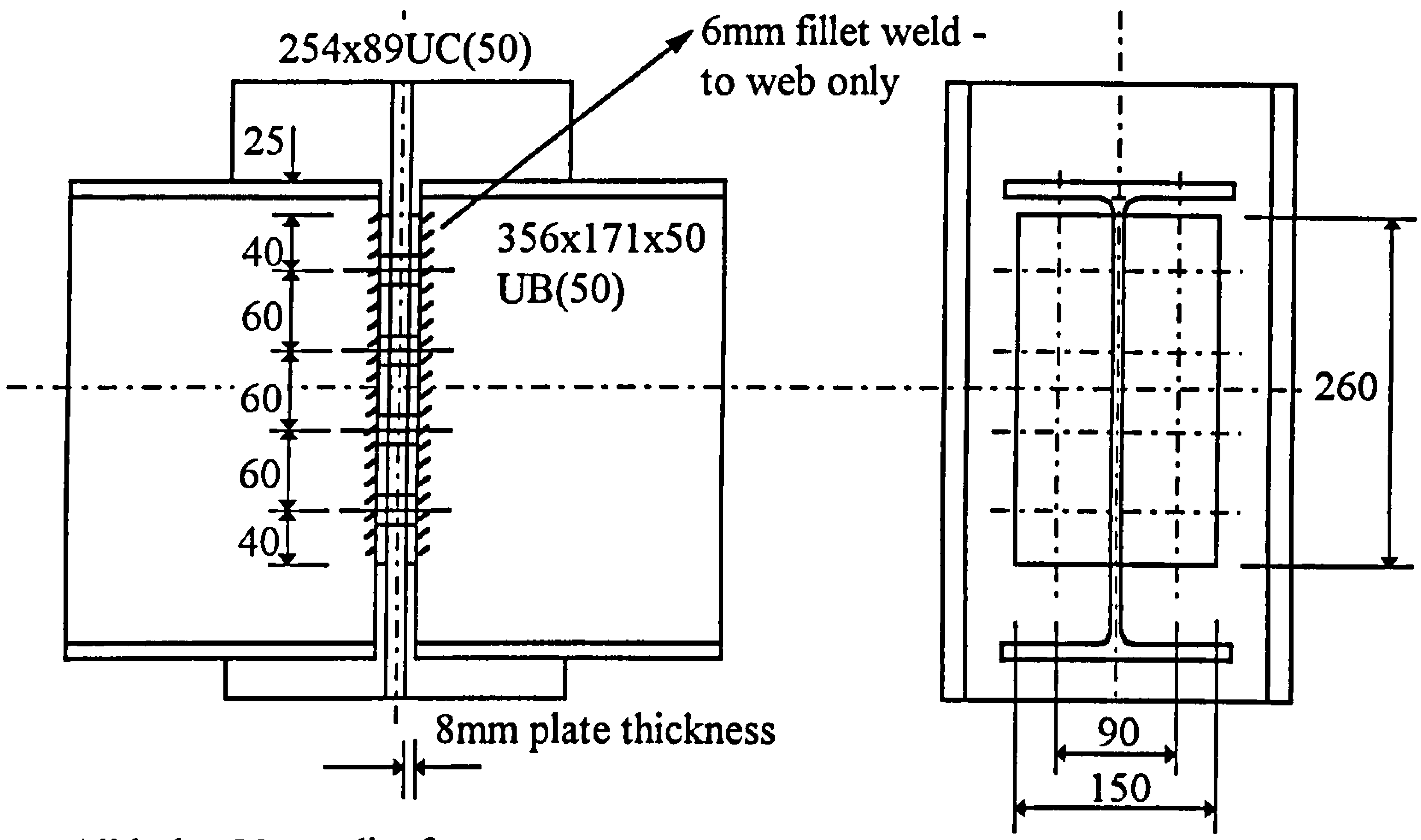


Figure D.4. Ambient-Temperature Moment-Rotation Results for CANT4



All holes 22mm dia. for -
M20 Grade 8.8 bolts

Minor-Axis Flexible End-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

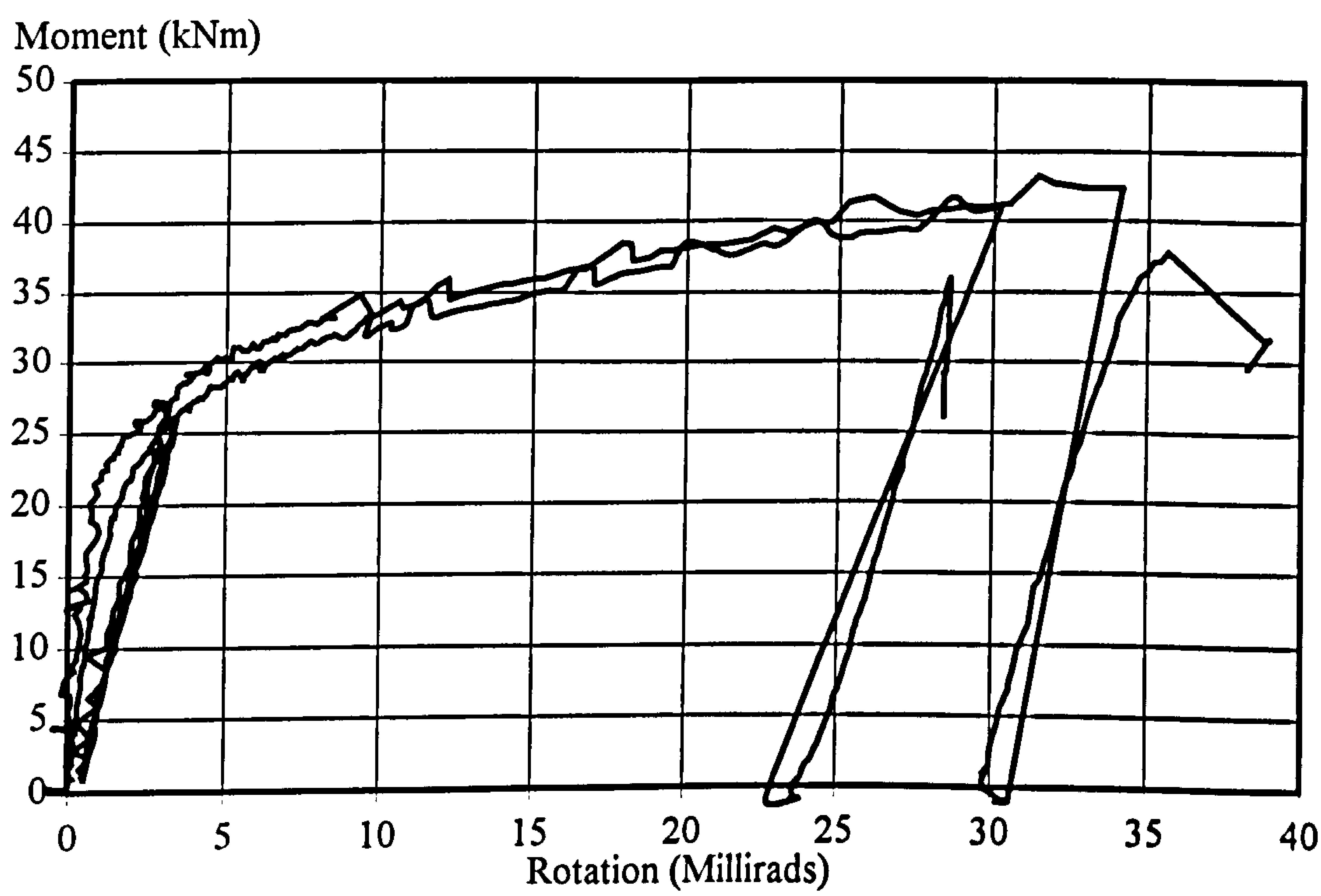
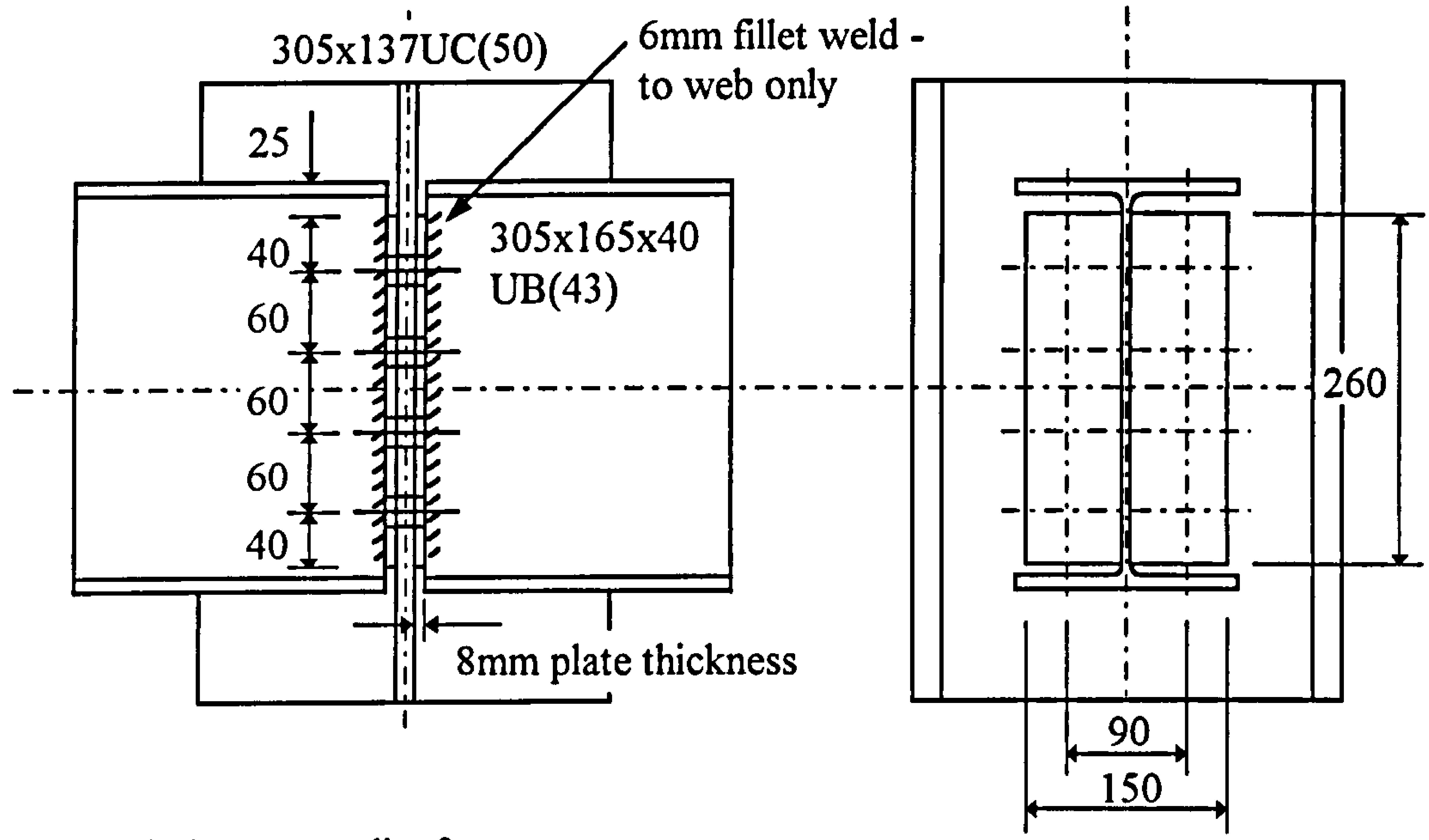


Figure D.5. Ambient-Temperature Moment-Rotation Results for CRUC1



All holes 22mm dia. for -
M20 Grade 8.8 bolts

Minor-Axis Flexible End-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

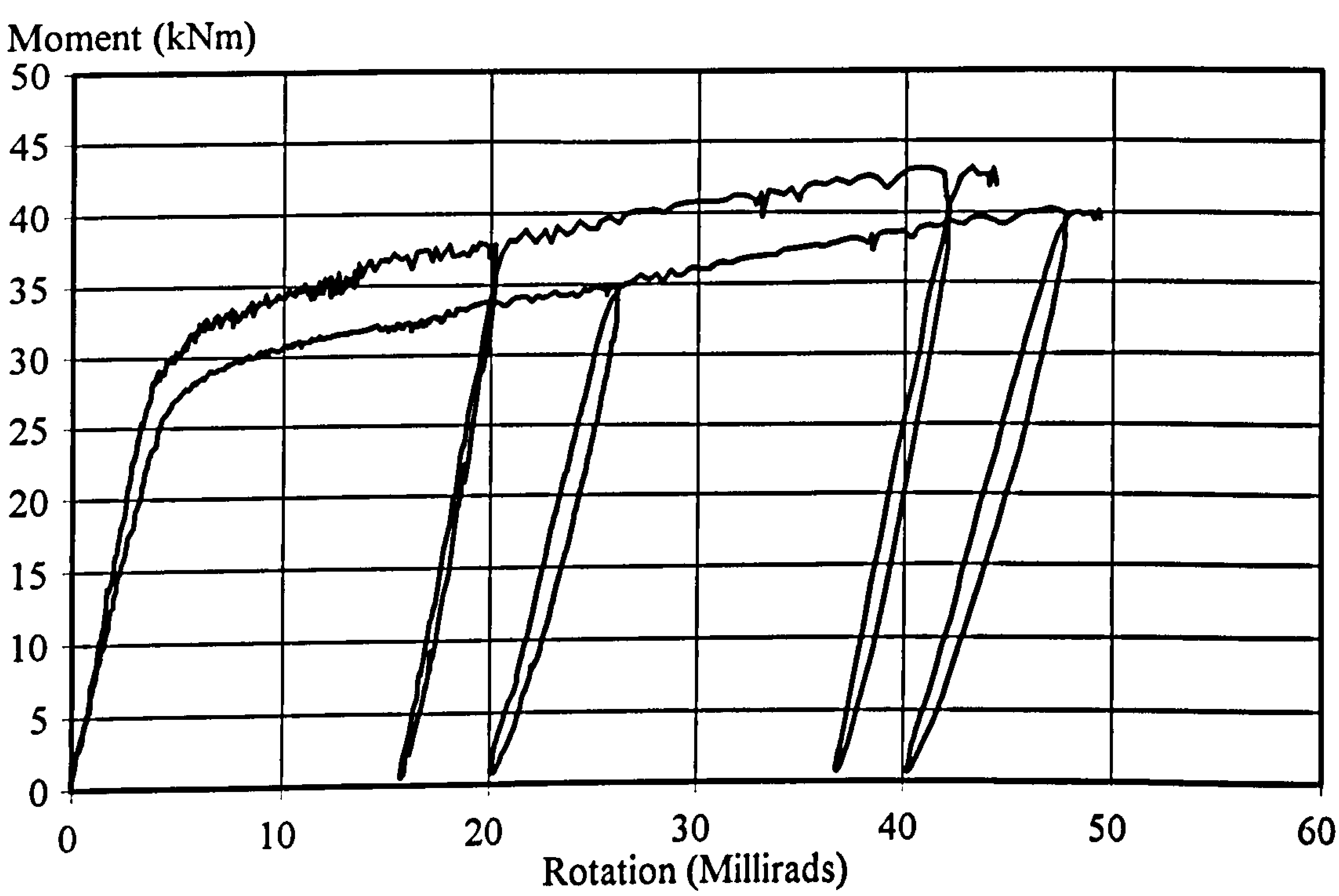
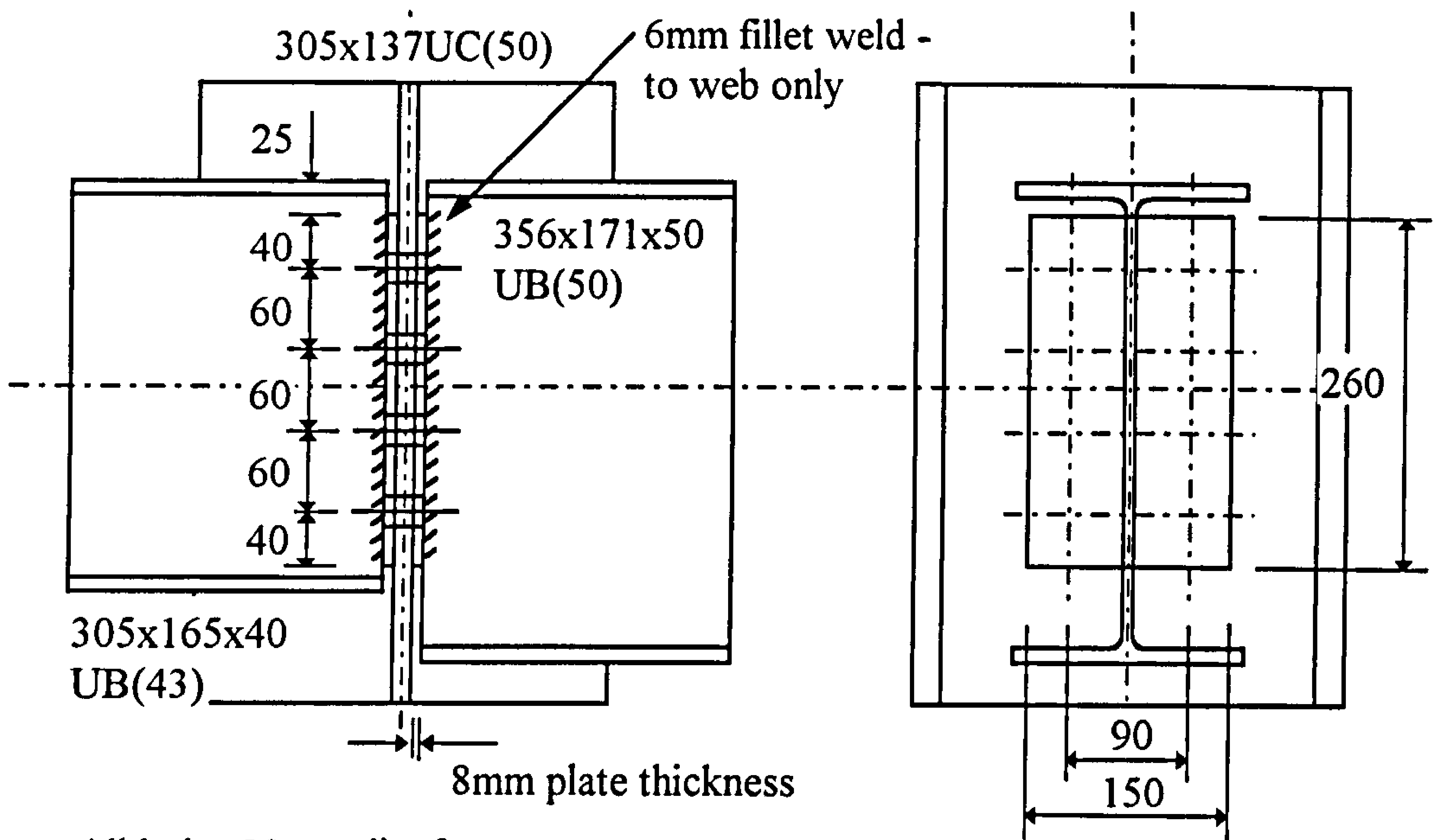


Figure D.6. Ambient-Temperature Moment-Rotation Results for CRUC2



All holes 22mm dia. for -
M20 Grade 8.8 bolts

Minor-Axis Flexible End-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

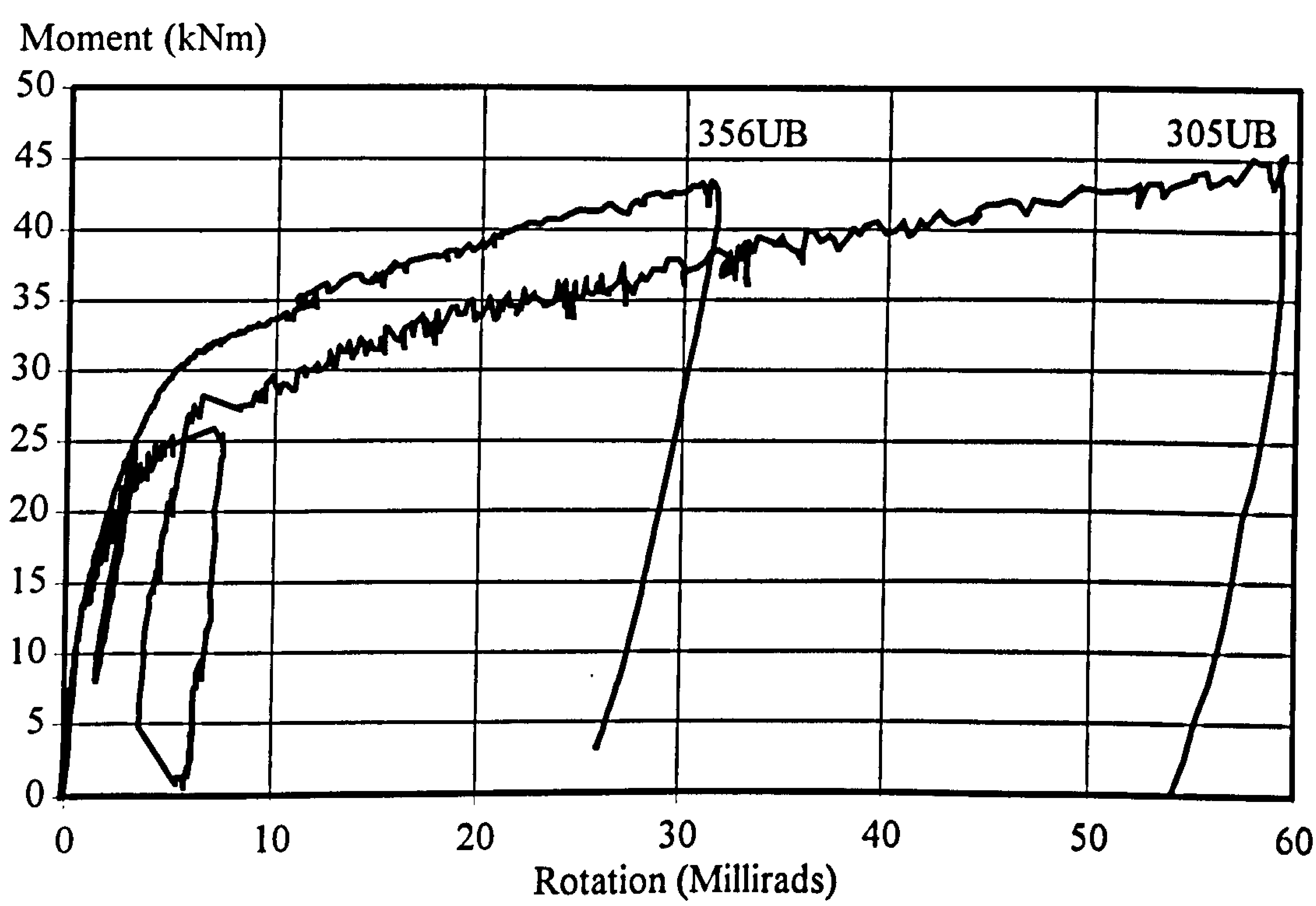
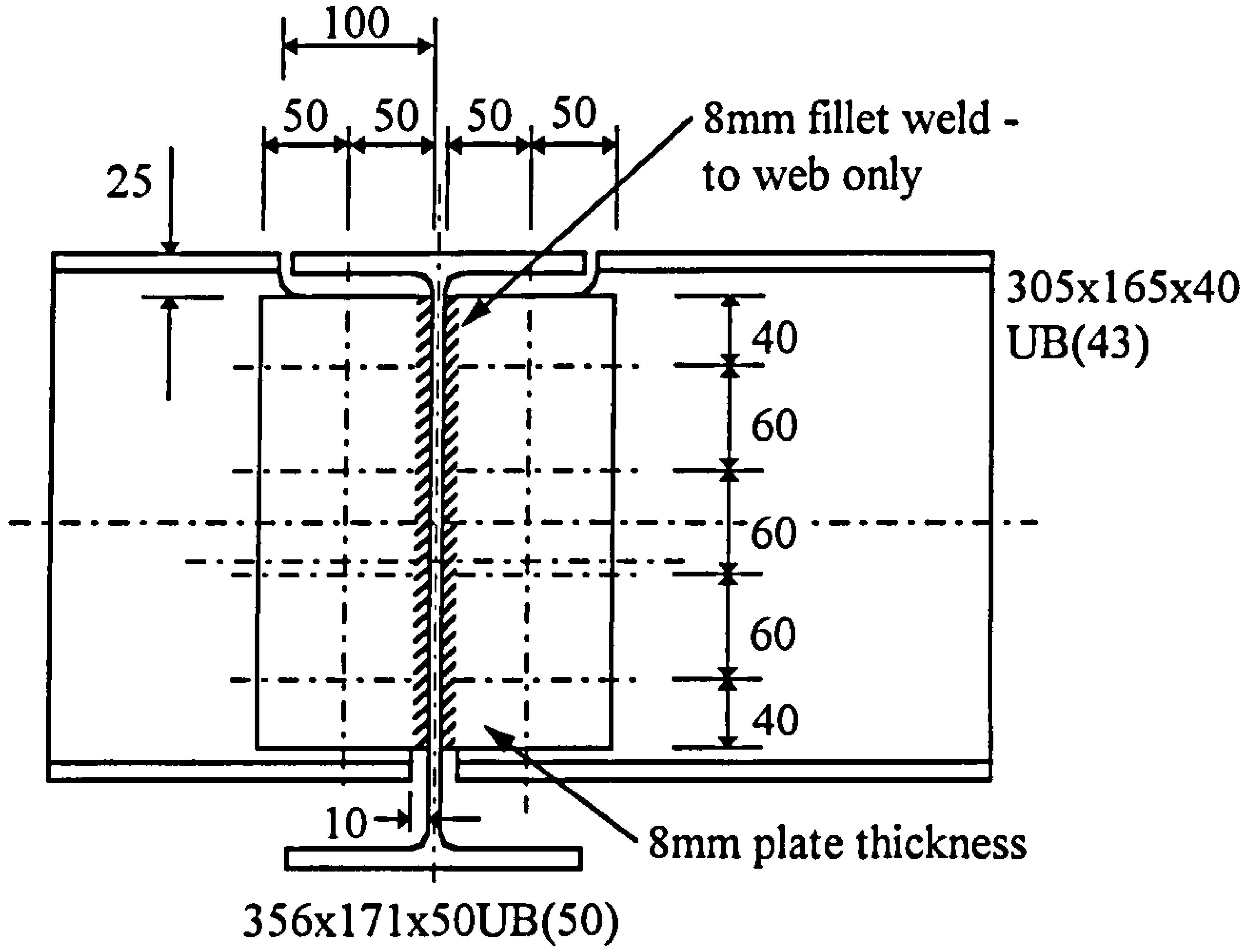


Figure D.7. Ambient-Temperature Moment-Rotation Results for CRUC3



All holes 22mm dia. for -
M20 Grade 8.8 bolts

Beam-to-Beam Fin-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

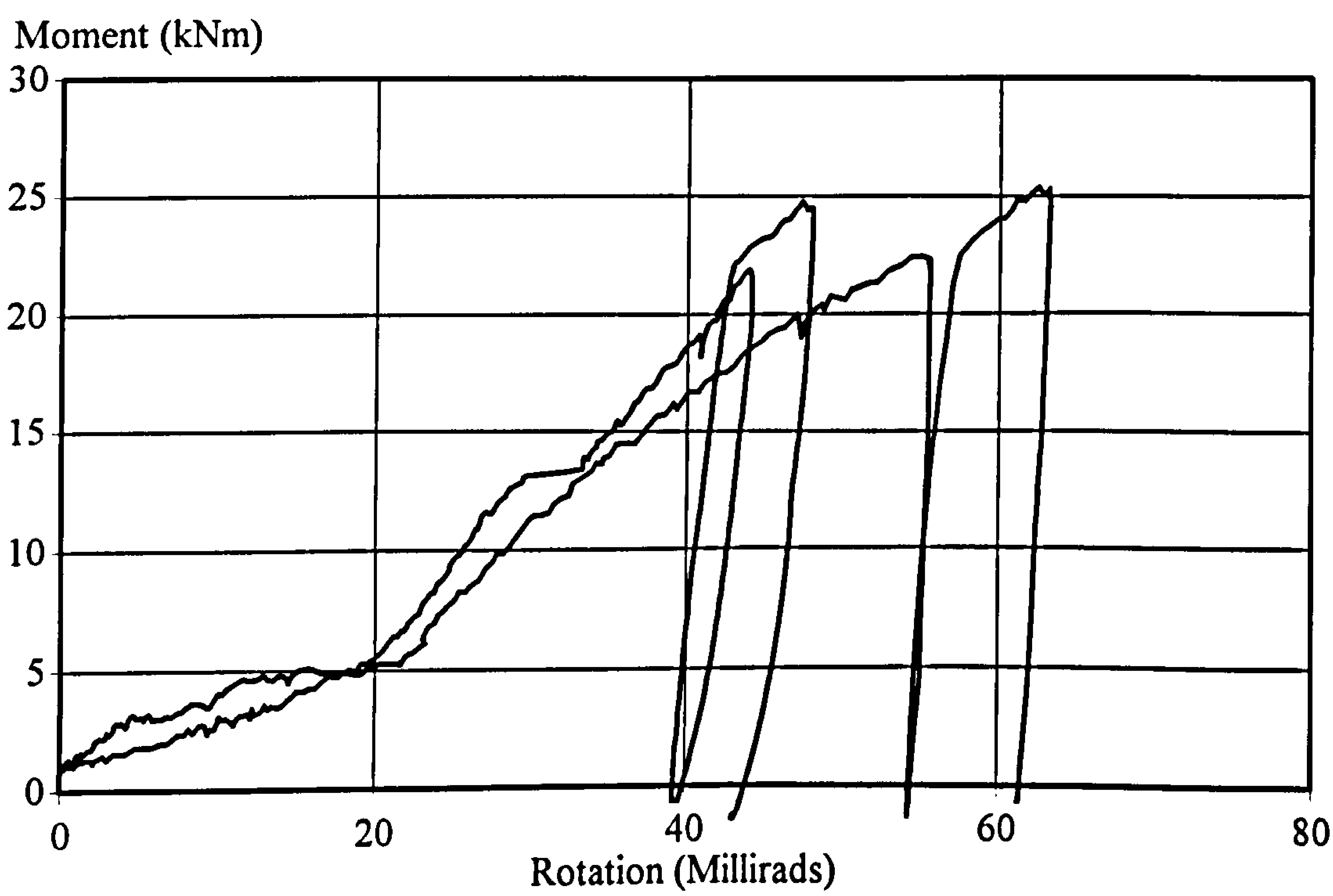
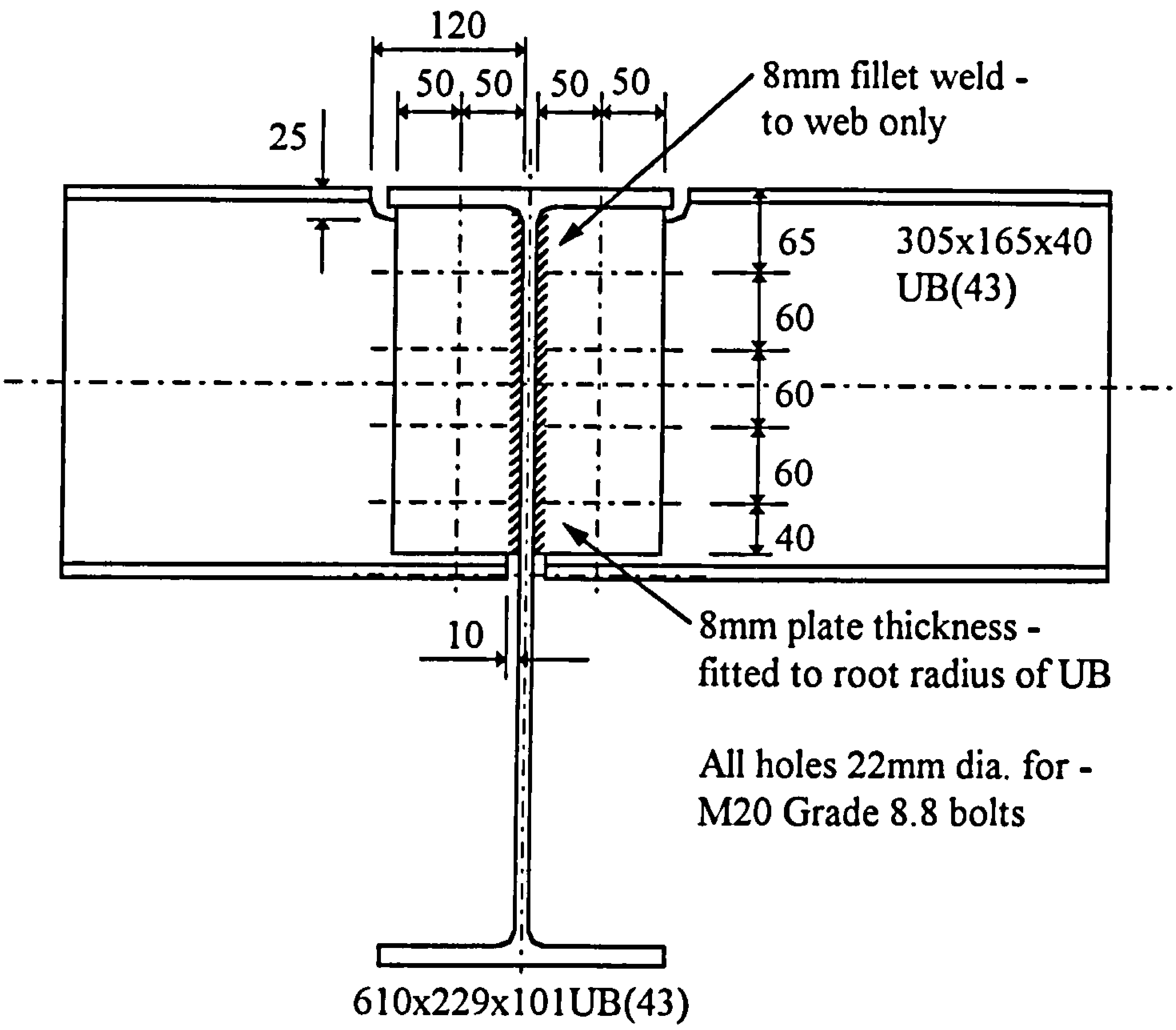


Figure D.8. Ambient-Temperature Moment-Rotation Results for CRUCB4



Beam-to-Beam Fin-Plate Connection
Designed According to *SCI/BCSA 'Joints in Simple Construction'*

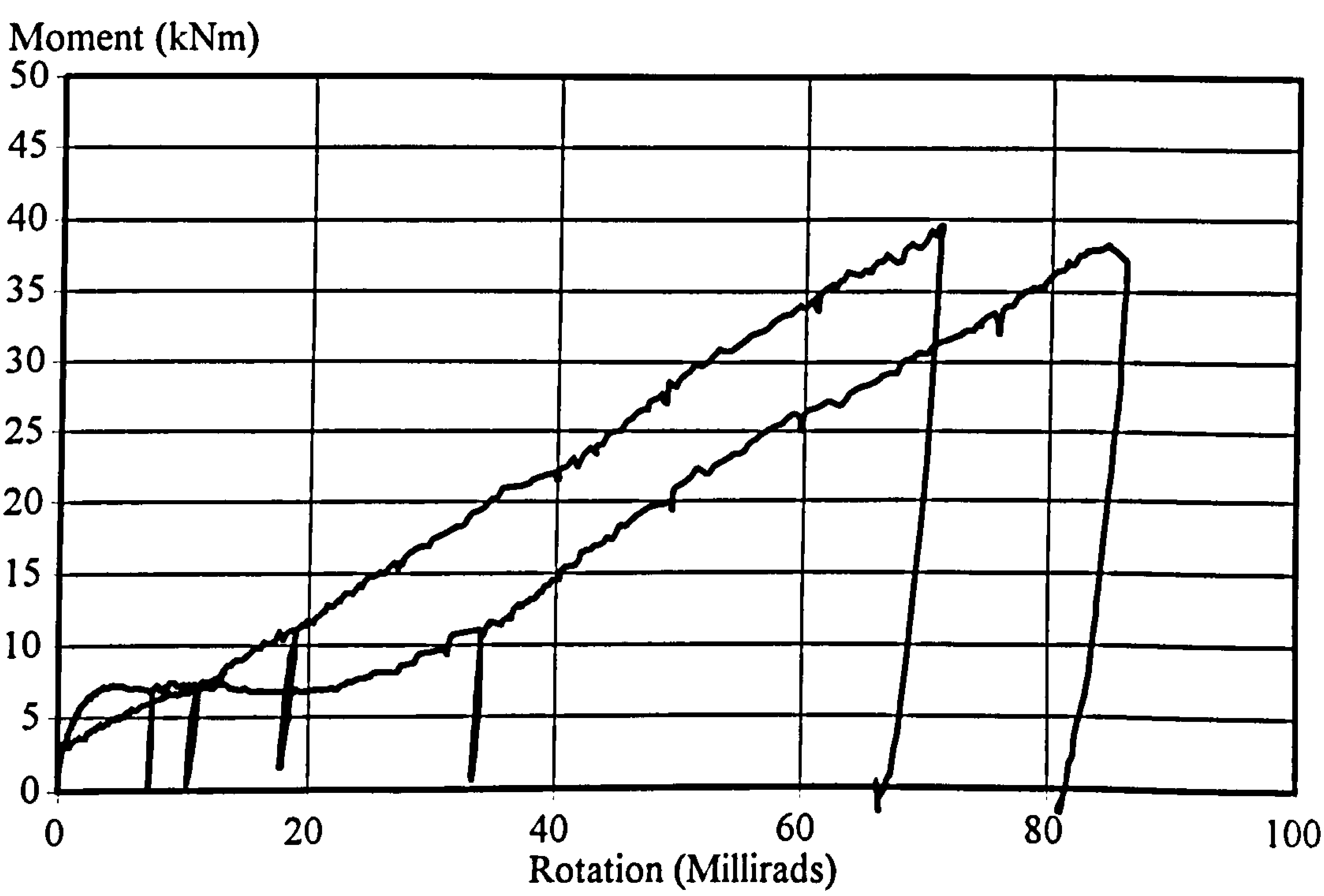


Figure D.9. Ambient-Temperature Moment-Rotation Results for CRUCB5

authors lends weight to the supposition that this was one of the works she was using. Another work which would certainly commend itself to the nuns was The Life of Bernard Overberg, translated from the German by George Spencer in 1844. The German author was Crabbe; the translator, like Cornelia a convert, and since 1845 a member of a religions order new to England, the Passionists. Spencer was something of a personality in the small Catholic community, and his work of translation was the second. The first life in English had managed to suppress most of Overberg's Catholic background, and Spencer in his preface indicated that he wished to give the full picture. As he was a significant figure in the Normal School movement Overberg was also mentioned in some of the editions of The Catholic School. In Mr Jones' library there were quite a number of other works on the theory of education, especially for women. One by Le Texier was a product of the Revolution, being printed in London in 1799, but presumably intended first for the French exiles; L'Ami des Mères, Journal D'Education, et Des Spectacles. The work included a play. Among the works which the nuns acquired are the monthly papers of The National Society for Promoting the Education of the Poor for 1855; the Minutes of the Committee of Council on Education, 1839-40, which have very clearly been used. By contrast there is an edition of Principi della Scuola Rosminiana esposti in lettere famigliari da un prete Bolognesese in an edition of 1850; the pages are uncut! Later works in this library of the nuns (and too late to have influenced The Book of Studies) are Fitch's Lectures on Teaching (1885), Thring's Theory and Practice of Teaching (1894) and Evan's Pupil Teachers' School Management (n.d.). These merely witness to the continuing interest in the Society in keeping up to date in education matters, and suggest that The Book of Studies was not the end of all development in their thinking. The

Jones' Library is an interesting and wide ranging collection, and as other volumes could help with the teaching of individual subjects, there is an extended note on its contents, and it is clearly wise that it has been kept as a separate collection.

While it is clear that Cornelia Connelly was aware of some of the trends in education in England, her main source of inspiration was unquestionably from the Continent. It was specifically the tradition of the Jesuits in education and her own first hand experience of the Sacred Heart nuns. The relationship between *The Book of Studies* and the Jesuit *Ratio studiorum* has been studied in an unpublished thesis.[63] Mother Buckle probably translated the *Ratio* in 1856, and although this translation has been lost, the Latin text which had been given to Cornelia by Father Gallwey, SJ is probably the one still in the SHCJ archives. The *Ratio studiorum* is one of the most famous documents on the curriculum, and certainly the one which was the longest in gestation. The early Jesuits were developing colleges and schools by 1550 in Italy, and then France, Spain and Portugal, and finally in some of the German states. This experience forced them to consider some of the basic questions both of curriculum and school management. All the members of the first group of Jesuits were alumni of the university of Paris, and Ignatius himself had met Louis Vivès in Bruges, so that they had some training in renaissance humanism and some experience in education. Nadal was one of the first to actually draft a curriculum, which looked back to the Parisian course of studies, and behind that to the mediaeval trivium and quadrivium, but it was their apostolic purpose which gave final direction to the whole enterprise of education; the first principle was *in studiis primum locus pietas obtinet*. Goodness was of more lasting value than learning, but learning could contribute to goodness, and Ignatius in his writings on the Constitutions couples the two together. This was clearly continuing the outlook of the devout humanists of the Renaissance, but giving to it much more force by the provision of teachers who had all experienced the Spiritual Exercises.

It was in 1551 that Nadal, then Rector of Messina, produced his ordo studiorum, which eventually became a contributory document to the projected Ratio on which James Ledesma worked from 1560 to 1575. In 1584 the General, Cladius Aquaviva, convened a committee of six who in the next two years produced a new Ratio for wide discussion and consultation. As a result of the comments there was a revised draft produced in 1591, which after yet further consultation and revision led to the final draft in 1599. This was formally promulgated as the definitive version by Aquaviva. As by 1586 the Jesuits had one hundred and sixty-two colleges upon which to call for experience and comment the range of consultation was great, nor was it restricted to Europe with schools in Mexico at Tacuba since 1573, and in India since the time of Francis Xavier, 1543. The committee itself which worked upon the proposed Ratio was an international one with John Azor from Spain, Gaspar Gonzales, Portugal, Peter Buys from Austria and Anthony Guisani, Upper Germany, while Stephen Tucci came from Rome, and a Scotsman, James Tyre, represented France.[64] They repeated the traditional basis of their work, that it was concerned to aim at "ardens pietatis studium et praestans rerum scientia", an ardent pursuit of piety and eminent degree of learning. The general content of a middle class boy's curriculum in the sixteenth century was hardly open to question; it had to be a classical education. But there was much variety as to how that training should be given, the textbooks to be used, and the structure of a school. It was in these areas that the Ratio developed its strength. The

Jesuits produced their own grammars by Alvarez, Frustius, Ledesma and others. Some of these were still in use in the nineteenth century, and there was an English translation of Alvarez in 1847, which went through a number of editions. The Latin Prosody of Emanuel Alvarez, S.T.P., Provost of the College of St Roch, with the explanations in English by the Rev. E.J. Geoghegan, 1874; a new edition in 1853 was the work of G.B. Wheeler, who claims in his preface that "the following treatise has long been a favourite in the Public Schools of this Country". In addition to the basic grammars and studies of poetry, the Jesuits were soon engaged in editing both Latin and Greek texts of classical authors, often expurgated editions, and when they came under criticism for teaching the classics they made available St Basil's letter to a young man on the study of the classics. This was edited by Fr Hieronymus Brunello in Rome in 1594. Their work in the classics led quite soon to an extensive development of the use of theatre in the school, and by the turn of the century it was normal for a Jesuit college to have a theatre, and drama was very much a part of their education.[65] From purely classical plays their work developed both into the vernacular and into ballet. As has already been mentioned, they developed the confraternity into a form specific to their schools, the Sodality, which also had its place of importance in the Ratio studiorum. And as their colleges built theatres, they also normally had not only a college chapel, but also a special sodality room or chapel.

Although the classics were the staple fare of education at the time, the Jesuits also introduced some mathematics, and both history and geography, taught to support the classical programme. The balance and directions of these various studies was one of the concerns of the Ratio. It has often been presumed that once the Ratio was produced, it was used with slavish fidelity and without any development. But some of the work which has been done on Jesuits colleges challenges this assumption.[66] Not only was the Ratio the result of the longest period of gestation and consultation in the history of education, but it is certainly the longest surviving curriculum, as there are people alive today who were educated on this plan.[67] Its influence was very great; the French Oratorians produced their own Ratio; the Piarists also used the model to develop their own plans; even John Baptist de la Salle a century or more later was influenced in writing his Conduite à l'usage des Ecoles chrétiennes.[68] The influence was first in what was appropriate for a boy's secondary education, but also in the important question, which was a vital one in the nineteenth century, of method.

The Ratio studiorum has thirty sets of practical regulations for administrators, teachers and pupils, which cover also three distinct curricular areas, the humanities, philosophy and theology. The Jesuits' schools were concerned with secondary and tertiary education, while The Book of Studies deals with primary and secondary. But common to both is the attempt to delineate the areas of responsibility of head teacher, prefect, form teacher and pupil. In all this Cornelia depends very extensively on the pattern set by the Ratio studiorum. This is particularly true of the later part of The Book of Studies with its common rules for the Mistresses of the School, the Rule for the Mistress of the Order and the Rules for the Prefect of Studies. These are the rectores, praefecti and professores of the Ratio. So too is the stress on motivation, not by chastisement, but by the attraction of honours, and also on the need for variety in the teaching, which the Ratio advises is "good because satiety is bad". Equally the system of regular examinations and of academic contests is taken direct from the Ratio studiorum. It is quite clear that the fount of method for Cornelia is to be found in the Jesuit tradition, and specifically from their educational handbook, which she had had translated.

But if the Jesuits could supply the method, they really had little to offer on the content of a girls' curriculum. But even here their influence is to be found indirectly. The Institute of the Blessed Virgin Mary founded by Mary Ward early in the seventeenth century was but one of the many congregations which sought to provide for girls just what the Jesuits were providing for the boys.[69] And the second or third generation of the Ursulines as they developed in France also produced a plan of studies clearly dependent upon the Ratio studiorum.[70] But in neither case was a classical education seen as appropriate for girls' education, so that as early as the seventeenth century the content of a female education was being developed under the general inspiration of the Jesuits, but by the direct influence of nuns who were dedicated to teaching girls. It is not clear how much Cornelia Connelly knew about the early work of Mary Ward and the French Ursulines. Her own immediate experience was seven years of association with the Sacred Heart nuns at Grand Coteau in America and the Trinità in Rome. Sophie Barat the foundress of the Sacred Heart and her early companions were influenced by the Fathers of the Faith, who were would-be Jesuits, as the Society was suppressed at the time. Once it had been restored in 1814 there was considerable contact between the Sacred Heart nuns and the Jesuits, and in education specifically with Father Loriquet who was an outstanding teacher and author of many text books.[71]

The Sacred Heart nuns developed their own plan of studies over half a century. Various manuscript documents from 1805, 1806, 1810, 1820 and

1833 all eventually led to a published work in 1852, Réglement des Pensionnats et Plan d'Etude de la Societie du Sacre-Coeur. This clearly contributes to The Book of Studies. When previous work was done on the sources of The Book of Studies in 1953 by Mother Mary Conrad at Gonzaga University in the United States an attempt was made to extend the work to cover the Sacred Heart plan of studies, but this work was not available.[72] As far as is known the plans of studies published by the female orders have all been privately printed, and access to them has been restricted. None of them, including The Book of Studies, seems to be in any of the major bibliographies. However, although the basic documents were not circulating among the female Teaching Orders, they did know a great deal about each other's methods and what was being taught in the various schools. I am convinced that Cornelia Connelly had not seen the Sacred Heart Réglement ... et Plan d'Etude, but from her seven years of contact with the nuns she both knew their method and the content of their curriculum. Obviously while she was in immediate contact with them in Grand Coteau from June 1838 to the June of 1843, and in the Trinità from April 1844 to 1846, there existed only the manuscript copies of the various revisions. And I am sure that if she had been fortunate enough to obtain the printed work in 1852, there would have been a word of this. The actual order in the two documents is different, but many conclusions agree. The resemblance in the two plans lies in similar attitudes and approaches, in the generous bibliographies of textbooks, the system of examinations, the general rules for the pupils and the organization of the classes. There are notable differences. However as the Réglement ... et Plan d'Etude is a significant work, and an early one in the nineteenth century development, it deserves to be considered before the resemblances and differences are noted.

Internal evidence suggests that the Sacred Heart document is composed of two separate works which were eventually published as one. The Réglement des Pensionnats is composed of four numbered chapters, Ordre des Exercises, Discipline et Usages du Pensionnat, Des Etudes and finally Moyens d'Emulation. Each of these chapters is carefully broken down into various articles, also numbered, and there is finally a short conclusion. Although the pagination carries on into the Plan D'Etudes, there are no chapter numberings. Nor are the main sections, such as objets de l'Enseignement Des Classes, and Notes so carefully broken down into numbered articles, and the work finally concluded with briefer statements on foreign languages, music, drawing, deportment and two pages of notes. The first chapter of the Réglement, the Ordre des Exercises devotes seven pages to the timetable of the day, the week, the month, the quarter and the year. Over twenty pages in chapter two, Discipline et Usages du Pensionnat, is concerned in seven articles with the rules of rising & going to bed, of the practice of religion, study, rules governing the refectory, recreation and finally the infirmary. Only five pages are devoted here to the studies, covering, in four articles, religious education, reading and writing, needlework & domestic economy and finally, Des Arts d'agrément, refinement & accomplishments. If this seems a very sparse treatment of a curriculum, the second half of the work has considerable expansion to offer in this matter. The final chapter of the Réglement is Moyens d'Emulation, and in eight articles and twenty-nine pages covers punishments, merit systems and honours, compositions and competitions, exercises and examinations, rewards for the quarter and the year, positions of honour and finally promotion.

The Plan d'Etudes returns from a number of different angles to the consideration of what is taught in the schools. So while in the first section six pages are devoted to some of the subjects, these are considered again in the second section on the classes especially through the lists of textbooks. This is a much longer treatment, taking up twenty-eight pages. The third section is concerned with the general method of teaching, and the final five pages are further notes, which look a little like an afterthought on foreign languages, music, drawing and deportment.

Common both to this document from the Sacred Heart nuns and The Book of Studies is a very similar timetable, great similarity about some points of discipline, the system of regular examinations, though The Book of Studies had monthly exams. Also alike is the way in which the school was to be divided up into classes, and the interesting lists of textbooks, some of which are common to both documents. There was clearly basic agreement about how to run a convent boarding school.

The common ground in the curriculum is the provision of a humanities programme in which vernacular and perhaps also foreign language literature replaced the Latin and Greek classics of the Ratio studiorum. The method of teaching this course with compositions, contests, regular examinations and the use of the theatre is basically the method which the Jesuits developed in the second half of the sixteenth century, and the structure of the schools is likewise from the same source. But whereas initially at least both history and geography had been disciplines which supported the study of the classics in the Jesuit plan, in both the Sacred Heart Plan d'Etudes and The Book of Studies, these became more important and were recognised as having a value in themselves. By the nineteenth century, if not before, the Jesuit teachers were devoting more attention to history and geography, and moving away from merely studying Greek and Roman history, and the Sacred Heart nuns were using history textbooks produced by Fr Loriquet SJ.[73] The aim of the classical curriculum had been to produce the mature development of a mind through contact with the ancient literature and the effort required to master it. Both the Sacred Heart and Holy Child nuns were also seeking to use literature, basically the vernacular literature, to achieve the same development. They did also teach languages, and certainly in the Holy Child schools developed a programme of both French and Italian literature; and both orders did some Latin and Greek, though this was for a minority of pupils.

While the curriculum was well developed in literature, it was weak in the sciences. The actual balance in the Holy Child schools will be made clear in the next chapter on the textbooks which they used. The specific development in The Book of Studies, for which there is no comparable development in either the Ratio studiorum or the Sacred Heart Plan d'Etudes, is the importance attached to art. This was to be no mere accomplishment, but was regarded as a means of communication second only to reading and writing, and in some ways more international than these. It was an integral part of the curriculum, and with it Cornelia Connelly associated geometry, so that part of the art programme led naturally into architecture, and it will be possible later to consider some of the examples of pupils' work which illustrates this. The strength of the art course also supported the theatre by the provision of stage scenery and the design of costumes, and its influence is also to be found in needlework in the design of tapestries. There is a very marked contrast here to the Sacred Heart curriculum, where 'musique, dessin et maintien" are subjects which collect just a few pages at the very end of the work. While the book of the Sacred Heart nuns is impressive, The Book of Studies is a better work on method as it concentrates on this, and although the philosophy of Cornelia Connelly is eclectic, and certainly benefited from both the Ratio studiorum and from her personal contact with the working of two Sacred Heart schools, I consider that The Book of Studies also has a more definite philosophy of education. This is remarkable since the Sacred Heart nuns by the middle of the century had founded a considerable number of schools, certainly over fifty and were working in France, Italy and America.[74] They had considerable experience upon which to draw, and they had taken time to develop their own curriculum. A major contribution to Cornelia Connelly's outlook on curriculum was the experience of the Teacher Training College at St Leonards, but while this obviously developed her knowledge of textbooks and government requirements, an appreciation of standards, and gave her more experience of the inspectorate, the whole concept of the art programme eventually came under attack in the Training College.

A study of the design and contents of the Sacred Heart Plan d'Etudes and the Holy Child Book of Studies supports the theory that Cornelia Connelly was using her knowledge and experience of the Sacred Heart schools, but had not actually seen their draft documents, nor the Réglement ... et Plan d'Etudes of 1852. This accounts both for the considerable similarities, down to even a few identical textbooks, and also for the different balance in the two documents. A teacher working at Grand Coteau would necessarily know the timetables, the rules, the general line of the curriculum, and all the other items which made up the Sacred Heart system. And at one time Cornelia was considering joining the Sacred Heart order, so that she was acquiring what, at the time, she would regard as a working knowledge of the system. A number of factors resulted in her change of mind with regard to the Sacred Heart order as her own vocation, among them a crisis in the development of the Society at the time she was in Rome and an uncharacteristically harsh attitude on the part of some of the members.[75]

That Cornelia's approach was eclectic was certainly true in the way in which she developed her Rule, and the same applies to the growth of The Book of Studies.[76] The author of the first published life, Mother Gompertz wrote in 1932 to Mother M. Amadeus Atcheson;

> I remember being strongly impressed with CC's power of adopting and adapting the best ideas of others, rather than her own originality. I should be inclined to say that she had very little originality, but a perfect genius for selecting the best from other people's ideas.[77]

More recently a student of the principles of character training in The Book of Studies came to the same opinion;

> I think you will find that Mother Foundress rather adapted than originated, though she had a faultless intuition in dealing with concrete circumstances and with individuals, and a great personal influence. Those who knew her used to dilate upon her brightness, vitality and joy, and how she could make anything "go" by her presence and persuasive energy.[78]

While basically agreeing with these opinions, which in regard to the growth of The Book of Studies are amply supported by the material in the Ratio notebook which Cornelia used before the publication of the work, I consider that the insight with regard to the place of art in the programme is entirely hers, and does show great originality. While she was using all her considerable experience, and wide knowledge, she also added to it finally, which made the ultimate work considerably more than just a collection of even the best of other people's ideas.

Two final glimpses of the way in which she worked may be obtained from her notes. Ten lines in a small pocket notebook tell how she had lately visited "in a large town a boarding school containing 40 girls" and gives her conclusions about their health. The town remains anonymous and the note is undated.[79] But as her own regulations concerning the diet and health of pupils occurs early in her Ratio notebook, it may be convincingly argued that this was early in her career as an educationalist. Also among her papers is the prospectus for Queen's college for 1859-60. This twelve page pamphlet is heavily endorsed in her hand. The Bishop of London was the official visitor of the college, and it had a substantial council which included the Bishops of Lichfield & Oxford, two Lords, an MP, two Knights, the Dean of Canterbury, the Chairman of the Committee of Education, and six other notabilia. There was yet a further committee and a list of honorary fellows. It is clear from the notes she made that Cornelia was dreaming of founding a Catholic ladies' college on similar lines at 44, Upper Harley St., and she pencilled in her own provisional list of patrons including her own bishop Dr Grant of Southwark, five clerics, Sergeant Bellasis, Colonel Towneley, and among the educationalists, Allies, and Marshall the HMI. For her lady visitors she proposed two Duchesses, Leeds and Argyle, and four Ladies. She has obviously studied the courses which Queen's college was offering, and she fills a few pages with her own subject headings and possible lecturers. These she carefully classifies as charity lecturers and paid lecturers. At this date, 1860, her own plan of studies was operating in about twenty schools at a primary and secondary level, and she had the Training College at St Leonards. But with all this she was still looking around at the various developments in women's education. In fact this dream never materialized, but the indications of the way in which she worked are revealing. She was wide in her scope and prepared to venture. She would build upon the best she could find, and she had her own insights to add to the vision of others.[80]

Cornelia Connelly had wide experience gained in a number of countries. All this she brought to bear upon the subject of girls' education, and much of the result is to be found in The Book of Studies. As its origin is clear, it now remains to consider the textbooks to which it refers. These also give an indication both of the standards sought and of the lines of the curriculum. At the moment much work remains to be done in the field of nineteenth century English school books, but enough has been achieved to enable a judgement to be made upon the worth of those chosen by Mrs Connelly for use in the schools of the Society of the Holy Child Jesus. Although a few were produced by the Society, again Cornelia's eclecticism is the decisive factor.

CHAPTER 7

THE TEXT BOOKS

Both from the tables at the end of The Book of Studies, and from Cornelia Connelly's notes, a long list of text books which the Society used may be compiled. To set these in context is difficult because of the incomplete state of the study of such works here in England. But there have been a number of important articles on the teaching of various subjects,[1] and a first bibliographical index of the school books by Dr Higson, so that a substantial start has been made.[2] Not all schools abounded in books. In Dames' schools they were something of a rarity. In the report on education in Manchester in 1832 it is stated that "in the greater number of schools there were only two or three books amongst the whole of the scholars".[3] Occasionally the books were provided by the parents and Kay Shuttleworth argued that this sort of provision, which he notes as common in Scotland, need not actually require the selection of the book by the parent.[4] In 1855 Matthew Arnold speaks of the common practice in his district of scholars buying their own books, and of some being entirely without any.[5] And he argues for the need for a public stock of text books. This custom of pupils bringing books from home was very common in a number of countries at the beginning of the century, and in some lasted till the twentieth.[6] A happy contrast is the report by Marshall, writing of the poor school at St Leonards, commenting on the excellent building, furniture, playground and "abundant books and apparatus".[7]

1820 to 1835 was the first era of cheap popular literature, and this coincided with the growth of labourers' and mechanics' institutes. The publications ranged from penny magazines, cheap encyclopedias to the works of the evangelical and educational societies. Political science became a subject of popular interest. 1827 saw the birth of the Society for the Diffusion of Useful Knowledge, and it is claimed that when Constable began to issue his first cheap volumes about 1828 he looked for a million buyers.[8] But although there was a lot of material in print, this did not provide immediately many good text books. In 1831 an anonymous reviewer in The Quarterly Journal of Education declared that there was "only one thing more in need of reform than school-masters, and that is school-books".[9] Ireland was probably better off in the early nineteenth century for school books of a good standard. The Kildare Place Society had been producing text books, and in 1814 another society was formed to edit non-religious ones for the poor. Two years later they merged, and between 1816 and 1824 the Society was responsible for 52 new books, 88 reprints, and 30 revised or improved texts.[10] This output in Ireland was increased by the work of the Commissioners of National Education and by the work of the Irish Christian Brothers.[11] The Catholics in Ireland thought that some of the texts in use were biased, and knew that few if any had Catholic authors.[12] And concern in England by the Catholic body led to a Catholic Book Society as early as 1828 which sought to "diffuse useful knowledge", and once the Catholic Poor School Committee was formed, text books were high on the list of priorities. By this time the Christian Brothers were spreading in England, and gaining a reputation for opening boys' schools for the poor in the most economic fashion. They imported many of their own texts from Ireland, and fortunately a manuscript account book provides a detailed picture of the sales.[13] It covers the period January 1849 to February 1856 in one hundred and seven pages. While most accounts are relatively small, some do accumulate into five or six hundred pounds. Apart from schools, parishes and convents two firms are listed; Burns and Lambert, and Charles Dolman.

Irish text books were also being used extensively in the National Schools. The minutes of the Committee of Council on Education provide an interesting list of the works used in King's Somborne National School in 1847-48, as an example to other schools.[14] It includes all the Irish Board readers, grammar and arithmetic and Sullivan's Geography Generalized. And when the Committee decided to subsidize an approved list of school books in 1847 there were seventeen works of Irish origin, eight from the Scottish School-Book Association, and only one set of readers from the British & Foreign School Society; three are traceable to the Society for the Promoting of Christian Knowledge, and there were works from a dozen or more of the authors who had won recognition like Allen & Cornwell, Latham, Tate and Hullah. The Committee's list is intended to be broad enough to include most of the current works in use, and illustrates the wide complexity.[15]

Most of the early inspectors have trenchant comments on the problems created by this diversity of texts. F.C. Cook reported that he was being pressed for complete sets of text books and for a general plan of instruction, but that he could not bring himself to recommend one more than another.[16] Henry Moseley requesting to see the stocks of books had his faith in the future of education challenged by "the tattered assemblage of miserable pamphlets", which often had to serve twice the number of pupils.[17] Mitchell looked at the problem as it affected the pupil teachers, and so the future staffs of the schools, and wrote about the questionable contents and presentation of the works.[18] To some he even objected on religious grounds.[19] Some of the inspectors list the text books used in the better schools; thus Longueville Jones for example.[20] Dr Woodford reported on the situation in Scotland; even though the parents were supplying books there was a shortage, and the diversity is "injurious to order and attention".[21] Fitch is able to report the complaints of parents about the diversity.[22] Matthew Arnold found this diversity an "extreme" problem, and a serious prejudice to the learner.[23]

> The diversity of these is at present truly embarrassing. Almost every educational society has its own school books: these are by no means universally adopted by the schools in connection with it, and a recognised text-book on any subject is nowhere to be found. To this state of things Your Lordships alone can supply a remedy.[24]

This report of Arnold's for 1854 provides a useful summary of the situation at the time when the Holy Child schools were beginning to expand, and they were forced to make decisions about the choice of texts.

They shared the reservation of the Catholic body, who considered that seemingly innocent books could hide deep prejudice. Entick's Spelling and Pronouncing Dictionary looked innocuous enough; but "Anti-Christ" is defined as "one who opposed Christ - THE POPE". In 1830 the Associated Catholic Charities in London had looked into the possibility of printing their own lessons, but concluded the matter would have to wait till the financial situation improved.[25] Catholic schools often used the Irish texts, either those of the Christian Brothers or of the Irish

Commissioners. A manuscript of the Sisters of Charity, of about 1841, directs teachers for their books to try the Catholic Book Society at 5, Parliament St. Essop Bridge.[26] Ten years later Marshall, reporting on Catholic schools, noted a "growing disposition to use the works of the Irish Commissioners", and criticised one of the readers of the Christian Brothers. This started an acrimonious correspondence in The Catholic School and The Tablet.[27] Marshall thought that parts of the readers were too difficult, and considered that this was especially true of the Third Reader, which he considered "in many instances ... to be nothing more than a lesson in the pronunciation of difficult sounds; no instruction whatever being derived from the text, nor any faculty save that of articulation being brought into exercise".[28] He allowed for different circumstances in Ireland, and concluded that the children who used the Christian Brothers' readers were at a disadvantage both in their progress in reading, and in the knowledge they accumulated.[29] It has not proved possible to see a copy of a first edition of the Third Reader, but later editions would not support this criticism.[30] Although there was an angry reaction to Marshall's comments, which could be seen as a closing of ranks, the general unease about school books was shared by the Catholic body.

The Catholic Poor School Committee took three steps. They negotiated with the Privy Council for the inclusion of some Catholic books on the list of those on which grant might be sought; they produced a list of works on which they would give a grant, and they commissioned some publications of their own.[31] For a number of years the Rev. Henry Formby appears in the accounts, before the eventual publication of an illustrated bible history and a number of books of songs for school.[32] It was 1860 before Burns and Lambert brought out their readers, Elementary Books for

Catholic Schools, and then other firms followed. With this slow rate of progress the few works which the Holy Child nuns wrote became of some significance in Catholic circles. In 1850 or 51 Emily Bowles produced, anonymously by a custom of religious sisters, a History of England for Catholic Children, from the earliest times to the present day.[33] Later in 1870 the nuns actually printed a work of Mother St Peter, who later worked in the American schools of the society, Legends of Our Lady and the Saints.[34] There had been a printing press at St Leonards since 1866, and I think that The Book of Studies might even be evidence to earlier work of this nature. They also in 1871 produced an Interlinear Commune Sanctorum, which included notes, a Latin vocabulary and a little grammar.[35] Probably of much more significance to the work in school was a series of cards for use in teaching French and German grammar. While little is known about these, a few specimens do remain in the archives.[36] With this background on text books it is possible to look at those which the Society used in its different schools across a range of ten basic subjects. The intention in this chapter is merely to consider the text books used, and in the following one to look at any further evidence as to the quality of the teaching.

Basic literacy involved the use of first readers, some apparatus and eventually both spelling and writing books. In the background as works on the method of teaching reading Cornelia had the various works of Wilderspin, Chambers and Mayo.[37] Reading was based upon a Look and Say method, and this involved the apparatus. Letters were first taught, and then children could pin a letter on a board, or place it in a letter case.[38] This involved a certain amount of movement which Cornelia recommended especially for the little children. There were reading cards, often in large print, which a group could look at and repeat word by word. Lancaster had helped to develop these as being less expensive than individual text books. A reference in The Book of Studies to Mayo's Models, refers to the model lessons by Elizabeth Mayo such as Lessons in Objects, Lessons on Shells.[39] Some of the works of the Mayoes might have been suitable for starting reading, but these readers are for the more advanced. There were simple works like A Peep at Grammar for children, and the stories of Maria Hack, Stories of Animals intended for children between five and seven years old. This work of 1820 was in the library, but not listed in The Book of Studies. Cornelia also used a religious first reader called The Peep of Day. Given the tendency of the Catholic body to scent heresy anywhere, this was a courageous choice as the work came from an evangelical background.[40] It is perhaps the evidence for the use of apparatus which underlines Cornelia's activity methods rather than any choice of text books.

In the poor schools the choice of a series of readers was important, as the information contained could be the main body of instruction in a short school life. In addition to The Peep of Day, and Line upon Line, the list certainly included Formby's Bible History and the Catholic Reading Books. Also McLeod's First Poetical Reading Book (1849) and his A First Reading Book or his Reading Lessons. It is also very likely that Emily Bowles' History of England was also used as a reader in the poor schools by the Society with the higher classes. The SHCJ library also contained The Dublin Reading Book of 1840. A reference in The Book of Studies to Lindley Murray, could be to either his grammar or a reader. Sullivan's Literary Classbook; or readings in English Literature of 1850 would have been too advanced for most of the classes in the poor schools, but was otherwise in general use in the SHCJ schools. The only other reading book mentioned in The Book of Studies is Gordon's. This means that the readers of the Christian Brothers, mentioned and criticised by Marshall, were clearly not in use in these schools. What is significant is that according to the Inspectors Marshall and later Stokes, the SHCJ poor schools were amply stocked with reading books, unlike many of the schools of the day.[41]

A curious reference in the time tables to citolégie eventually proved to be a reference to a method of teaching reading quickly. An early edition of Larousse describes it as "méthode particulière de lecture",[42] and eventually other sources reveal the Manuel de la Citolégie published by H.A. Dupont (1767-1855).[43] It was a phonetique method, and in his career Dupont had eventually taught in Paris, and attracted some attention there. One is left wondering whether this was something which Cornelia investigated while staying in Paris on her way to Derby in 1845. There is no means of assessing the value of the method, which is forgotten in the histories of education. Its presence in the SHCJ schools is a tribute to the international outlook of the foundress.

Reading did not cease to develop once basic literacy was achieved. Sullivan's text book included an introductory treatise on the art of reading and the principles of elocution. The reading course looked forward to school dramas, and there were some of these in the poor schools, and also benefited from the example of some of the sisters who were highly professional entertainers. So school journals reveal Sister M. Joseph reading parts of Kenilworth to the pupils,[44] and Mother Mary Ignatia, known to the pupils as "Reverend Mother's Shadow" was a favourite reader. A pupil records that this caused problems;

> She was a captivating reader, and used to be sent to read in the School Hall whilst we were occupied with needlework: but she read too well, and the Prefect complained that instead of being working listeners, we were gazing listeners.[45]

Reading and writing were studied together. This was not universally so in Victorian days. F.C. Cook in his report for 1853 noted, as something new, that the mistress in the Home and Colonial Model school had adopted a plan, already proved to be successful in Germany, of teaching reading and writing simultaneously.[46] For writing The Book of Studies refers to Mulhauser's method and books, which had been favourably commented upon by T. Wilkinson in his report for 1853, and by the Irish Commissioners in 1848.[47] But also listed are Darnell's writing books, and these were still being advertised in 1869, and were perhaps seen as an English improvement on Mulhauser. Significantly in his report of 1853 Marshall states categorically that writing is better taught in the girls' schools than the boys. "The penmanship of the elder girls is equal to anything which could be produced in much more ambitious seminaries", he concludes listing five schools, one of which is the St Leonards poor school.[48]

Used in conjunction with both basic reading and writing was The Spelling Book Superseded of the Irish Commissioners. And some of the readers also included spelling lists. Although only one such book of spelling is listed, it is likely that others were used as there was an enormous number of "spellers" produced, some of them better known by their colour than their author, editor or printer, such as the famous American Blue Backed Spelling Book.

Literacy also included grammar. The Book of Studies specifies one of the most famous works of the day, the grammar of Allen and Cornwell.

By the middle of the nineteenth century this had challenged established names like Lindley Murray and Cobbett.[49] There was almost no end of English grammars as may be seen in the work of Gould Brown.[50] But giving evidence to Taunton, Fitch claimed that he could find little or no evidence of grammar "as a science" in Ladies' schools.[51] By contrast Cornelia Connelly in a letter comments favourably upon Bromby's grammar because "it is such a logical thing".[52] The plans of the Victorian grammars produced a multitude of rules and a system which was often deeply laden with etymology. Another grammar listed in The Book of Studies by professor Latham is really a text book for tertiary education, with a great history of the language, and much etymology. It is hard to see how, especially in the poor schools, grammar could be anything other than a burden. While the texts of Bromby, Allen & Cornwell and even Latham are not the only ones referred to, they do seem to have been the main ones in use in the SHCJ schools between 1850 and 1870, and as such they represent a reasonable choice.[53]

Literature was a major subject. According to Kearney English literature emerged as a successor to the classics in the secondary curriculum from the 1860s, when a new importance was given to the teaching of modern subjects in the educational debates of the day.[54] Fitch considered that the New Code introduced English literature without enough definition of the subject, and he found in his experience that the use made of the subject was often unintelligent; "one of the most unfruitful parts of the school-work".[55] Most of the major series of publications of English literature belong to the final quarter of the nineteenth century, and there was a shortage of texts to bridge the gap between basic reading and grammar and mastering the masterpieces of English literature.[56] Some of the readers gave generous extracts, though not ones which would be recommended nowadays. McCulloch's *Course of Elementary Reading in Science and Literature* includes rhetorical passages from worthies like Lord Chatham, Burke and Southey, a trifle from Macaulay and a generous selection of poetry.[57] Indeed poetry was better served, and Palgrave's *Golden Treasury* began its considerable career in 1861. Matthew Arnold thought literature was an essential key for the pupil in that it could open up a whole culture.[58] In addition to this Cornelia was concerned about the ability of the pupils to express themselves effectively. So the literature course was related to the drama produced in the schools. For this reason the two are best considered in the one section. Five Shakespeare plays occur regularly in the theatre programmes; *King Lear*, the *Merchant of Venice*, *Julius Caesar*, *Macbeth* and *A Midsummer Night's Dream*. The first play ever produced was Milton's *Comus*. In contrast to this more classical drama there were farces such as *Caught by the Ears*, and *The Bashful Man and the Man of Nerve*. *The Jacobite* and *Frederick of Prussia* were among the historical plays produced. A particular favourite was Cardinal Wiseman's *Fabiola*, a novel which one of the sisters had turned into a drama. This with his *Hidden Gem* remained for forty years or more a popular part of the school repertoire.[59] Dr Braun wrote a *St Cecilia* specially for the SHCJ schools, and the nuns themselves seem to have written quite a number of dramas.[60] The more classical theatre included extracts from Homer in English, such as the parting of Hector and Andromache, the death of Hector, and the petition of Priam for his body. It is possible to list over seventy different items produced on the SHCJ stage, from the most classical theatre to sheer farce.[62]

In addition to drama the theatre was also used for poetry recitals, and this also gave direction to the study of literature in the schools.

Apart from the reading books of which most contained at least some verse there were a number of poetry books in use which included Daniel Scrymgeour's A Class-Book of English Poetry and Aikin's British poets, Biographical Sketches of the British Poets. Cowper's Task, and Goldsmith's Traveller and also his Deserted Village together with Milton's works provide but part of the variety.

While it is known that a number of authors, especially Walter Scott, were read to the pupils, and while it is possible to identify other likely authors in the library, it is not easy to say what authors the pupils themselves were actually reading. Once the sort of definition which the school theatre provides is no longer used the actual content of the literature programme becomes indefinite. Items which are frequently referred to by Cornelia include Lingard's History of England and also his History and Antiquities of the Anglo-Saxon Church, a copy of which was found with a note in Cornelia's characteristic hand directing that it be read in certain circumstances in the refectory.[63] Agnes Strickland's The Queens of England was another favourite. It can also be argued from the foreign literature which the students are known to have studied that similar works in English literature were very probably in use. So after considering in the next section the foreign languages which some of the schools studied, some attention will be paid to the foreign literature as well.

The choice of foreign languages was probably made by Cornelia on religious grounds, and also because of her own knowledge of both French and Italian. Towards the end of the century an inspector, King, was reporting that parents considered that Italian and Spanish were the two languages of commercial value, though he personally favoured German.[64]

Dorothea Beale opted for French and German prior to Latin. At the time of Taunton very few schools were doing Italian, and I think the one mentioned, but not named, in Lancashire may well have been the SHCJ school at Blackpool.[65] In Catholic circles some were urging the value of church Latin and the production of the Interlinear Commune Sanctorum by the Society might be regarded as a gesture in this direction. In the schools both Latin and Greek were occasionally studied by the brighter pupils in the top forms, but they were not a regular part of the curriculum. By contrast French certainly was. From The Book of Studies some thirty-two French texts may be listed, seventeen Italian, six Latin and one German.[66] Two methods of teaching foreign languages are among these books, that of Ahn for Italian and Ollendorf, which was very popular at the time for a number of languages, seems to have been the one used for French.[67] There was also a copy of the Magazin des Enfants of Mr. Le Prince de Beaumont, which at least suggests the possibility of a gentle introduction to a foreign tongue for the pupils. The inspectors reporting to Taunton found French common in girls' schools, but nearly always badly taught, so that Giffard described it as a "mysterious jargon of English words with a French termination".[68] Cornelia had a succession of mistresses from France, and eventually made her own foundation in that country to provide a finishing school for the senior pupils, and also to give the novices an opportunity to win a brevet in education.[69]

An indication of the languages is to be found in the theatre again. The little pupils produced La Reine des Fées and the seniors some of the dramas of Racine and Moliere. Esther and Athalie were especially popular. This serious drama was also balanced by farces such as Ici on Parle Français, and there were also religious plays such as Le Martyre de Sainte

Eulalie and more general theatre in *Le Secretaire et le Cuisinier*, *Richelieu*, *Monsieur Jonson* and the *Bourgeois Gentilhomme*. Italian plays seem to be especially those of Pietro Metastasio, who is mentioned by surname only in *The Book of Studies*, but the school library included a copy of *Cinque drammi sacri*, printed in Chelsea in 1801. Programmes name particularly his *Giuditta* and *Temistocle*. His work would probably appeal to the nuns as being of a religious bent. Again the theatre cannot tell of the whole of the studies in foreign languages, but the number of works listed in *The Book of Studies* and the number of dramas performed in the schools do serve to suggest a reasonably wide programme of literary studies. Works in the library such as Manzoni's *I Promessi Sposi*, dated Paris 1843, used and rebound, and A.F. Ozanam's *Dante et la Philosophie Catholique au Troisième Siècle* which is inscribed Rome Ap. 13, 184- would seem to point initially to Cornelia's own reading, but the amount of use which the Manzoni volume has had suggests that at least the teachers were also reading it. Other works in the library which would be complementary to the much loved works of Walter Scott are the little known publications of Kenelm Henry Digby who had become a Catholic in 1825 from a study of mediaeval antiquity and wrote, anonymously, *The Broadstone of Honour*, and later *Mores Catholici, or the Ages of Faith* in many volumes. These were probably used by the staff, and parts of them read to the pupils.[70]

Geography came first into the elementary syllabus as an item in the readers, but unlike some subjects from an early date there was a considerable number of geography texts available. Kingsmill Moore listing some seventy-nine text books of the Kildare Place Society includes in this list forty-six concerning geography, a remarkably high percentage.[71] Equally the list issued by the Committee of Council on Education of books on which grant could be claimed provides for an abundance of geography texts.[72] Fitch makes the point that it was a subject favoured by teachers, but adds a rider that it is favoured "chiefly, I believe, because in it the maximum of visible result is attainable at the smallest expenditure of teaching power".[73] In most schools it was no more than a memory test with lists of rivers, mountain ranges, ports and towns to be learnt by heart. An experienced inspector, Fearon, writing as late as 1879 saw the danger in geography still as that of its tendency to degenerate into lifelessness, with a cramming of unmeaning names.[74] It was the work of two German scholars Humboldt and Ritter to produce better order into overcrowded text books, and to outline the principles which showed the interdependence of human life and natural phenomena, and so to make geography a science with universal laws.[75] In England the Royal Geographical Society in 1886 produced an important report on the teaching of the subject,[76] so that Sir Archibald Geike could speak of the "growing recognition of the extremely unsatisfactory position of geography in the general educational system of the country" with the hope that matters were at last improving.[77] Oxford was the first university to establish a readership in the subject in 1887, and by 1910 a writer in The Journal of Education was claiming that perhaps no subject had changed so much in the method by which it was taught or in the regard in which it was held.[78]

It will be remembered that The Book of Studies provided for a very vivid approach to geography, beginning in the playground, and then the neighbourhood. This was very much oriented in the direction of maps and plans, and some of these remain. The list of text books included Humboldt's Views of Nature which suggests that the SHCJ were in contact with the most up to date views on the subject. A reference to Hugh's (sic)

Physical Geography and another to Hughes' Geography does not permit of absolute identification, but I think it is probably the work of William Hughes, A class-book of physical geography of 1861 which was revised and reissued for the rest of the century.[79] Although it was an authoritative text, it is mainly a catalogue of facts with very little to relieve the overburdened student. Other text books are listed by Arnold Henri Guyot, Robert Sullivan, who wrote one of the most popular ones of the day, and James Cornwell.[80] A number of atlases are indicated including one to support classical studies and a bible atlas. Among the works in the library of Mr Jones were a number of the publications of the Royal Society and several folio volumes with maps. Among these William Guthrie's A New System of Modern Geography of 1795 is marked "science library" and may be a clue as to how the works were used in the school. In Cornelia's Training School Journal there is a copy of a list of text books which she had supplied to an inspector Morell in September, 1862. The eleven listed under geography include four atlases by Johnson, McLeod, a bible and an ancient atlas, and seven text books by Guyot, Sullivan, Homboldt, Chambers, McLeod, Hughes, and Cornwell.[81] This is probably as good a list for geography as was possible at the time.

In turning to history we find one discipline in which the text books have received some considerable attention.[82] By 1860 there was an abundance of books and a division of opinion as to their worth. The purpose of history in the curriculum was presumed but not defined. For many writers it obviously had a political significance, and Valerie Chancellor has found that towards the end of the nineteenth century history text books became more jingoistic, and the British Empire became even more the subject of both history and geography.[83] In Ireland after 1835 history was extended first to the middle and then to the working class to defend the British constitution, according to the researches of H.E.H. McHugh.[84] As a corollary to this, other histories were regarded as virtually treasonable.[85] This style of writing history often led to the whole of the middle ages being regarded as dark ages, and to most of the incidents in English history which involved the papacy being regarded as a loss of liberty.[86] The heroes chosen were significant; Drake, Grenville, Marlborough, Wolfe, Clive, Nelson and Wellington. Hannah More thought that the study of history could provide moral benefits by "judicious perusal" designed to give a clearer insight into the corruption of human nature, and into the workings of providence. History was almost a branch of ethics.[87] It could also be a sectarian issue.

The extent of the problem is highlighted in Gladstone's Irish University Bill of 1873 which proposed the establishment of a Catholic university on the impossible condition that theology, history and philosophy would not be taught there, a condition described by Matthew Arnold as "simply ridiculous".[88] While such a suggestion was doomed to failure, it well illustrates how sensitive a subject history was in the eyes of the authorities in Victorian days. For English Catholics a certain level of respectability had been won by the authority of Lingard's historical writings. His History of England was abridged and revised into a whole series of school texts by Burke, Townsend, Young and in this century by Norbert and Belloc.[89] There were other Catholic works; T. Flanagan's A Short Catechism of English History, published about 1850 and Miss A.T. Drane's History of England for Family Use and Upper Classes of Schools. Both these are identified by Chancellor as obviously Catholic writers.[90] In spite of this the SHCJ produced their own text, which they also used in America, and which had a second printing in 1866. The Society used over a dozen histories and the work in school covered English history, church history, the history of art and both classical and bible history. A pictorial history of England by E. Knight was in use, and also the formidable Blackstone's English Constitution.[91] While a list of all these is in the notes, it is worth adding that copies of Burke's Peerage were in the school library, and the nuns, if not the pupils, had the twenty-nine volumes of René-François Rohrbacher's History of the Church. The range of text books covers all the needs from the poor school, through middle schools and training college to reference material for the staff. Some consideration of how they were used is possible in the next chapter.

Perhaps significantly the shortest list of text books which Cornelia provided for an inspector is that on arithmetic. All were standard texts used to the end of the century. There was James Cornwell and Joshua Fitch's The Science of Arithmetic which had reached a sixth edition in 1864, John William Colenso (later bishop of Natal) Arithmetic designed for the use of schools (1843) or perhaps his Arithmetic for Beginners (1858); Barnard Smith's Arithmetic for Schools. It should be noted that although geometry was a part of the course in school, it was classified under art and not mathematics. Arithmetic was not traditionally in England a subject at which young ladies excelled; nor had it proved a popular subject in the boys' grammar schools. In the 1863 unofficial examinations at Cambridge for girls out of forty seniors, thirty-four failed mathematics, and of Miss Buss's twenty-five candidates, ten failed.[92] Sophia Jex Blake is at pains to make the point in her account of female education in America that women were proficient in mathematics, and that one of them was actually a leading actuary.[93] Emily Shirreff was recommending that many girls might begin Euclid at thirteen, and recommended the use of Barnard Smith's text as it included some algebra and Euclid.[94] There was criticism of the standard of mathematics teaching for both girls and boys in England, and French writers thought that the method of teaching was wrong and unscientific.[95] Gordon and Lawton have pointed out the dual tradition in mathematics whereby the pursuit of abstract truth favoured by the public schools led to geometry, while the needs of the elementary schools led to a search for competence in ordinary arithmetic.[96]

The text books used by the SHCJ if few were among the best. The use of them must await the following chapter.

In the nineteenth century science had an uncertain place, if one at all, in the curriculum. Locke, Pestalozzi and advocates of object lessons started a movement which was recognised by authorities on method like Wilderspin and Stow. Perhaps because of this the readers often gave coverage of scientific matters, in some cases very substantial coverage. So the fifth book of the Irish Commissioners in 1838 in its 406 pages devoted 161 of them directly to science, and the Sequel to the Book of Lessons had a section on zoology, half of which is devoted to birds. In similar fashion Chambers' Information for the People included a very similar coverage of astronomy, natural philosophy, hydrostatics, optics, chemistry and electricity, still usually called Galvinism. This was the approach of the day. The work which has been done on science in the school often dates it from the Great Exhibition, which rather disregards what was done prior to 1850.[97] That the Exhibition was significant is not in question. Sir Lyon Playfair said at the time;

> As surely as darkness follows the setting of the sun, so surely will England recede as a manufacturing nation, unless her industrial population becomes more conversant with science than they are now.[98]

In Macclesfield the factory owners J. & J. Brocklehurst were keen to introduce some science into the schools they patronized as no one in England could produce the dye they required.[99] Lectures in science were a significant part of the work done in Mechanics' Institutes, but it has been suggested that the majority of the clerks and shopkeepers who attended were not really interested in the subject, but rather in acquiring a little middle class culture, and that the curriculum was drawn up by the middle class supporters of the Institutes for their own purposes.[100]

Especially in girls' schools the place of science on the curriculum was uncertain. Botany, with some astronomy and even a little geology were considered suitable accomplishments for ladies. Physics was out of reach for most girls as their mathematical training was weak. The lack of suitable teachers was such a handicap that science subjects were very often covered by visiting lecturers. Dr Lyon Playfair in his first report in 1854 of the Department of Science and Art made it clear that his main objective would be to introduce science into the field of elementary education.[101] By 1845 there had been some developments in the training colleges, encouraged especially by one of the inspectors, Moseley. But his work was in effect killed off by Lingen in a circular letter of January 1857.[102] As the Revised Code of 1862 virtually excluded science there was a conflict of policy between what was (since 1856) the Department of Education and the Department of Science and Art. The Taunton Commission discovered little sign of interest in science, and Hammond noted that there were some subjects, "those in fact which rest on scientific principles which females at present cannot teach".[103] More encouragingly Miss Buss had brought in a Doctor Hodgson to give a course of lectures on the structure of the human body, and was given by him a work by Lovett.[104] The Devonshire Commission in 1875 revealed a more encouraging scene in the grammar schools, and most of the really competent school text books seem to date from about 1870. The British Association for the Advancement of Science in 1887 was still demanding the recognition of science as part of a liberal education, and presenting reasons for its inclusion in the curriculum.[105] It ignored the female curriculum.

A first look at The Book of Studies would suggest that the SHCJ offered no science at all. There was Harding's Trees, but this was basically an art book, and the reference to Zornlin's The World of Waters or Recreations in Hydrology is probably intended as an extension of the course on geography. There were however a considerable number of science books in Mr. Jones' library from Marcet's small works on chemistry and mineralogy to large folio volumes from the Royal Society.[106] Some of these give visible evidence of having been used, even over-used; some were moved out of the collection into one of the school libraries. So Henry Phillip's History of the Cultivated Vegetables in two volumes (1822) is inscribed "Training School, St Leonards SHC Jesus" and William Lawrence's Lectures on Comparative Anatomy - the Physiology, Zoology and the Natural History of Man (9th edition, 1844) has a library and SHCJ plate over that of Mr. Jones. Only the first hundred pages have been cut, but the diagrams of skulls have been much used. The school library also has a collection of science works, though some of them were old, and these also give evidence of having been much used. James Rennie's Bird-Architecture (1844) is marked "Boarding School Library"; Lucy Hardcastle's An Introduction to the Elements of the Linnaean System of Botany for Young Persons, (1830) carries the abbreviation St L. SHC Jesus. Even more indication is to be found in James L. Drummond's Letters to a Young Naturalist (1833) which covers both nature and some natural theology; it is inscribed "For the use of the Mistress of the 4th Class". Francis M. Wyndham's Wild Life on the Fjelds (sic) of Norway (1861) was a prize given to Caroline Sullivan, while François Arago's Popular Astronomy in two volumes (1855) was presented to the library by Sergeant Bellasis in January 1867. The pages of the book are all cut, the back broken and some pages loose. Scientific Dialogues (1800) has the name of a possible owner, Maria Martin, and also "Boarding School Library". A possible light on the way in which science was envisaged in the school is to be found in Oliver Goldsmith's History of the Earth and Animated Nature (1779) in eight volumes. This is catalogued as "History No. 260 Training School St Leonards". There is also The Wonders of the Heavens displayed in twenty lectures (1826) which has been very much used.

It would seem that science was not identified as a separate subject in the SHCJ curriculum, but that there was some study of it, probably mostly for its value in general knowledge, but also in history, geography and art, which were strong subjects. Possibly Cornelia Connelly's concern about health and domestic economy also contributed to some interest in scientific matters. I have not been able to find traces of the newer scientific texts from the last quarter of the century, though this was obviously after the time of Cornelia's direct involvement. The general movement in the country was symbolized by the opening of two new laboratories, the Cavendish at Cambridge in 1870, and the Clarendon at Oxford in 1872. What was happening at St Leonards in that year is suggested by a letter which Sergeant Bellasis wrote to a daughter, now a SHCJ nun, and through her sending a message to "dear Monica" congratulating her on the progress of her studies, "especially in the science of astronomy" for which incidentally the convent accounts included an extra charge of nine pence for the half year.[107] Science in the SHCJ curriculum was not entirely absent, but it was either a part of another discipline or an accomplishment. And it did eventually win itself a place in the library of the school.

For Cornelia Connelly art was "one of the most important branches of education, second only to the art of speaking and writing". Her bibliography of the courses is impressive. A basic work seems to have been Rio's The Poetry of Christian Art, and in matters ecclesiastical Pugin's Glossary was her guide. As has already been mentioned she brought into the art course geometry and the text used was Richard Burchett's Practical Geometry (1855). For models she used James Duffield Hardings' Lessons on Trees (1850) with its thirty plates and also his Landscapes. There was a Manual of Painting in Water Colour (1854) and Overbeck's Illustrations of the Gospels. Her own artistic training had been under a master sent by Flatz, who himself was a pupil of Overbeck.[108] Retzsch's "outlines" are referred to without any other identification. I think this is Friedrich A.M. Retzsch who produces a number of sets of outlines, but among those which the school may have used I think his Gallery of Shakespeare (1828-32 and later reprints) may be safely identified from existing work by the pupils.[109] A reference to the method of Tate will refer to the Drawing for Schools (1854) of T. Tate. Burchett in addition to his geometry had also produced a Practical Perspective which was both used in school and given as a prize.[110]

Together with these text books, and other works which were available in the library of Mr Jones, there was a lavish amount of equipment, boxes of crayons, of water paints, oil paints, drawing boards and T squares. A whole page in the tables at the end of The Book of Studies is given over to "materials required for the drawing course", and it is clear that models were used in addition to the examples given in Harding and Retzsch. Mathematical instruments and maps are also in the list, and here again existing examples of both coloured maps and perspective drawings remain.[111] A number of letters of Cornelia's concern the binding of some of the pupils' work in art into permanent volumes, which they would take home for their parents' inspection during the summer holidays, and exhibit at school. Some of these which have survived included diagrams to illustrate astronomy. So it is possible that the art course was so strong in the early days at least as to absorb geometry, astronomy, map making and to provide designs, on occasions, for needlework. It also collaborated with drama in producing stage scenery and helping with the design of costumes. There were globes as well as maps for geography and sheets and cards to illustrate astronomy. The school acquired a printing press, possibly even before the publication of The Book of Studies, and it is certain that some of the nuns became proficient. It is not so clear whether "practice - printing" which occurs on Tuesday and Thursday afternoons and alternates with "practice - maps" means the use of a press or just improved calligraphy. A number of the models for sketches "after the great masters" have survived, and the number of items which remain from the art course witness to its popularity.

An early issue of The Catholic School in 1849 reveals Wiseman writing an open letter "on the importance of introducing music more effectually into our system of education". He gives three reasons; its value as recreation; its usefulness in providing the basis for good church choirs, and finally its cultural and educational worth.[112] There was an editorial response and eventually a reply by bishops Brown, Hogarth, and Ullathorne, who wrote twice. Music was obviously dear to the hierarchy, and was going to receive the patronage of the bishops.

A recommendation was made that Mr Crowe be hired by six of the larger London poor schools to raise standards there. He was considered a good choice as a follower of the method of Wilhelm, which the editor thought Hullah had tampered with to its detriment.[113] Crowe was given a grant of a hundred pounds, and the Journal set out to encourage music publications. The interest was echoed in other Catholic journals, such as The Rambler, and the bishops looked forward to a time when ability to read music, to teach singing, and to play the organ "will be reckoned among the ordinary qualifications of a Catholic schoolmaster".[114] In 1849 this was distinctly optimistic on the part of the hierarchy as at the time there was not a single Catholic training college in the British Isles.

There was however quite soon a considerable production of music books both for Catholic churches and schools. The Oratorian Frederick Faber was a prolific writer of hymns and Henry Formby produced some successful books for schools, most of which found their way into the Holy Child establishments. He contrived to show something of the erratic genius of Pugin in his own sphere, claiming in a published sermon that there was an "actual correspondence" between the Latin plain chant and Our Lord's humanity, and that persons singing it never grew tired of it.[115] More modest and practical were his The Young Singer's Book of Songs, School Songs, Easy Part Music for the use of Schools and Choral Societies, Sixty Little Songs for Little Singers.[116] By 1854 the Catholic Poor School Committee was offering various small grants to encourage singing in the schools, and book grants to reduce the cost of the purchase of some of the Formby publications.[117] Apart from the provision of the Formby texts, Cornelia also provided for apparatus a Sol Fa Modulator, a music drawing board, listed as distinct from an ordinary drawing board, sheets of music paper, and a piano or concertina. At one period at St Leonards there were three separate choirs, the nuns', the boarding school's and the training college's. There was obviously a lot of sheet music to support all the church activities, which is not listed in The Book of Studies, but was very much part of the life of the school.

Although the term used in the SHCJ tradition was Christian Doctrine, the Society really offered a course of religious studies which was wider than this term might at first seem to imply. It included doctrinal instruction based upon approved Catholic catechisms, but also both bible history and church history, and there was considerable use of works of devotions. So a reference in the bibliography to "Guillois, Ch. hist." refers to Ambrose Guillois, L'Evangile en Action, ou histoire de la vie des Principaux Saints dans l'Eglise catholique in two volumes (Paris 1852), and this was in use with other devotional works like The Imitation of Christ of Thomas a Kempis, the nuns' own edition of the Interlinear Commune Sanctorum, F.-X. Gautrelet, Nouveau mois du Sacré-Coeur de Jésus (1850 etc.), The Rules of the Sodality of the Children of Mary, and a Whitsuntide novena book, which the nuns had translated. There would also be plenty of the small lives of the saints, which were in popular use in the confraternities and sodalities, and also missionary journals or reports which circulated in these circles too.

The more formal instruction was based upon catechisms. These had become a prolific species of publications since the sixteenth century, and although the major catechisms have been studied, the multitude of smaller, diocesan catechisms remain an inviting field for exploration.[118] Local bishops could insist upon their own choice being followed. In England there was a series of catechisms which followed from the Douay catechism, and they are not yet completely collected or classified.[119]

The influence of the devout eighteenth century bishop Richard Challoner in this matter has been investigated.[120] Significantly, it is clear that Cornelia Connelly favoured and used French catechisms. Her list included An Abridgement of Christian Doctrine, which may be the work of H. Turberville, or possibly William Gibson's A Short Abridgement of Christian Doctrine. Although the Irish Christian Brothers' First Book of Doctrine is mentioned, it does not seem to be listed in The Book of Studies for use in the schools.[121] The Manual of Instruction in Christian Doctrine published in 1861 by Burns and Lambert was in use, and likewise John Perry's Full Course of Instruction for the use of catechists of which there was a second edition in 1852. These were all substantial works either for use in the senior forms or with student teachers.

For the little children something brief and easy was required. And it would seem that little really suitable material was available in English Catholic circles. For the very little children Cornelia was using David Blair's First or mother's catechism, which by 1847 had reached its ninety-sixth edition. This simple work could probably have called down episcopal wrath upon the Society as the author was not a Catholic and his work would most probably have been disallowed by the authorities. The teaching at infant level especially included many stories, and a liberal use of pictures. These are listed in The Book of Studies, but only generally; "the Holy Mass, the Rosary and the Angelus from pictures". For the older pupils there is frequent reference to the Catéchisme de Persévérance. This French text was for the pupils who had made their first Holy Communion. The Christian Brothers in 1886 produced a translation in four volumes, but until then it seems to have been available only in the French, and in the SHCJ papers the French title is always given. There was also another edition of its abrégé, and this too was in use. Also mentioned, though not seemingly used by the pupils, and so probably a mistress's book is the two volume work of Henri J.A.T. Icard, Cours d'instruction religieuse à l'usage des catéchismes de persévérance et des éléves (Paris, 1846). Gaume is mentioned on a number of occasions without further reference. The abbé Gaume was the author of a number of works including a catéchisme de persévérance, and this may be an indication as to which of the senior French catechisms the Society was using. Two further French works both eventually became available in translation, which may be an indication of the sureness of Cornelia's selection. Joseph de Harbe's A Complete Cathechism of the Catholic Religion was translated and published in 1877 by John Fander, as was his Complete History of the Catholic Religion (1862). The first is usually just known as Fander's catechism.

There were a number of bible histories in use, those of Formby, who was also publishing the music for schools, Capes's Bible History, and Overbeck's Gospels Illustrated. A reference to "Fleury, Cours d'Hist." could refer to the abbé Fleury's Histoire du Christianisme in six volumes, but is much more probably the work which was translated and published as A larger historical Catechism; containing an abridgement of sacred history, and of the Christian Doctrine in Newcastle in 1786. This was reworked by Henry Formby in 1871 into The Complete Historical Catechism; or Fleury's Short Historical Catechism revised, enlarged and continued down to ... Pius IX. The book list includes a bible, and this would be the Douay version, but in the revised form which was the work of Bishop Challoner, which virtually represented a new translation.[122] Also listed as required for the classes were Scripture History Cards. No further indication is given of their origin. Finally it should be remembered that some of the more gifted pupils actually worked through St John's gospel in the Greek, taught by Mother M.Joseph Buckle.

A list in the appendix gives over two hundred of the books which were used in the SHCJ school by pupils or mistresses. The vast majority of these are from The Book of Studies and so represent a choice made before 1863. Even with all the reservations about the present incomplete state of research into the nineteenth century English school text books, it is still possible to say with conviction that the choice of text books is a good one, wide-ranging, balanced and showing an interest in both the youngest and oldest of the pupils. In addition to the text books there is ample evidence of an unusually generous selection of apparatus in use in the schools which corresponded to Cornelia's stress on the visual. The presence of a printing press at St Leonards suggests other more ephemeral works of their own which have since completely perished. The only actual example which I have been able to find was a card with an exercise in German grammar. But as they printed a number of books, and this text card, it seems reasonable to suspect other small school pamphlets of their own were in use. It would appear from the almost general absence of the texts produced by the Irish Christian Brothers that the nuns accepted the criticism of Marshall of some of these. He was a great friend to the Society and his word carried weight. There is a useful knowledge of French text books, and some Italian texts are also in use.

All this points to an educational society which was very much alive to the possibilities. It is not on its own a guarantee of good teaching. As Marshall had commented about the poor school at St Leonards, there was an excellent building, furniture and playground and "abundant books and apparatus". The following chapter seeks to probe into the use of all these resources and to find out whether the combination of a defined method, an educational philosophy of some character and a good supply of books and apparatus did in fact produce a variety of good schools.

CHAPTER 8

THE BOOK OF STUDIES IN ACTION

However interesting The Book of Studies is as an early girls' curriculum, and however well equipped the SHCJ schools were, the final acid test was the ability to educate girls successfully. There are various sources of information which help to give some picture of the system in action. The most professional are the series of inspectors' reports on the poor schools for which the Society was responsible at St Leonards, in London, for a while in Liverpool, and in Preston; and with these the reports on the short-lived training college. There are also other sources which are to be regarded rather as pointers, and glimpses of the system in action. They are fragmentary. From Cornelia's educational directives it is possible to obtain an idea as to how the mistresses in a school were to report on the progress of their work, and the sort of control over this which the nun who was headmistress had. In this case it can be shown that this did happen in some of the convent boarding schools but it is not safe to conclude that all were conducted with the same efficiency. Also among the school papers which Cornelia used are examination results from St Leonards together with the comments of some of the mistresses upon the pupils. These reveal the normal school problems and serve to show that a successful school was not built out of exceptional pupils. There are also a few recollections of both parents and former pupils. It must be presumed that only the flattering ones have been preserved, but the features of the schools which they comment upon are significant nonetheless.

The school inspectors at first were allowed more liberty in their annual reports to the Committee of Council on Education and used the opportunity to try to encourage various aspects which they regarded as beneficial. Eventually the secretaries to the Committee are to be found restricting this.[1] In 1858 Lowe and Lingen decided to put an end to the publication of the reports of the inspectors in an unabridged form, and as a result a good deal of the interest goes out of the material.[2] But in spite of this there was much adverse comment on the policy of the Revised Code from the inspectorate, and they were by no means muzzled.[3] But the suggestions about teaching methods, and the amount of detail about some of the schools declines after 1858. The rising number of schools may have in part contributed to this, but the financial constraints imposed by the various governments resulted in secretaries to the Committee who all looked for value for money, and tended to see the inspectorate as their watchdogs. The inspectors on the contrary saw their vocation as that of raising educational standards. Mary Stuart considers that George Kekewich who became secretary to the Department of Education in 1890 was

> the first Secretary since Kay-Shuttleworth who really believed in education, (and) saw in the teachers not instruments to be degraded and harried, but partners in a work to which they would give intelligent and faithful labour if they were trusted and encouraged.[4]

The Catholic inspectors, at first Marshall, and then Scott Nasmyth Stokes and the others who followed were committed to their denominational schools. The inspectors in general were the main agents in breaking down the monitorial system, and the Catholic inspectors were no exception to this.[5] They encouraged class teaching, and the reports of Marshall and Stokes are alive to questions of the efficiency of the methods used in the poor schools. It is also clear that the SHCJ had great confidence in the advice of Marshall, and he must have contributed to the formation of Cornelia's philosophy, possibly by advice about text books though details here are lacking.

At first Marshall was the only Catholic inspector of schools, so that he was responsible for England, Wales and Scotland. An initial report on St Leonards' poor school in 1848 merely indicates that a start has been made towards furnishing books and founding a school. The school is to be under inspection; buildings are in the course of erection, and although a group of pupils are already receiving instruction, it is recognised that the foundation is still being made.[6] But by 1851 the situation has changed and Marshall is able to give the highest of praise.

> All the conditions of complete success are now united in this admirable school, in which the teaching is of the highest order, and the supply of school requisites ample in quantity and of the best kind. New buildings have been erected during the past year, which are now occupied by the scholars, in which the most effective arrangements have been adopted. The influence of the teachers is of the happiest kind, and the deportment of the children peculiarly pleasing; the condition of the school is one of steady sustained progress, and nothing seems to be wanting to the gradual attainment of all the highest results which such institutions are capable of accomplishing.[7]

The following year Marshall was able to confirm his prediction in a report which could not be bettered.

> It is impossible to witness without admiration the results obtained in this interesting school in which consummate skill in the art of teaching, unwearied

> patience and the most persuasive personal influence have combined to accomplish all the rarest fruits of Christian instruction; the school is now probably one of the most perfect institutions of its kind in Europe.[8]

This continues to be the tone of Marshall's comments upon St Leonards, and is outstanding among his reports.

> (St Leonards Girls) continues to be one of the most remarkable schools I have ever seen. I have only to express my admiration of the completeness of the results obtained in it by the rare skill, judgement and patience of the teachers. St Leonards, Infants. Ability of mistress, highly qualified. Taught by the most approved methods; amply supplied with every requisite, and effecting all that should be aimed at in a school of this class.[9]

The St Leonards poor school continued to obtain good reports, and in the new and expanding order it would provide a standard for the poor schools of the Society in London, Liverpool and Preston. It remained a small school, probably never topping a hundred. By contrast some of the schools in the big towns grew to be large. It could be that a school attached to the centre of an order might be particularly favoured in the choice of exceptionally good staff, supported with additional assistance and generally promoted to be a show place. So it is necessary to look carefully at the reputations of the other schools.

Many of the reports of the inspectors are abbreviated and are often also given in a tabulated form. The inspectors use numbers to comment in order upon (1) desks and furniture; (2) books and apparatus; (3) organization; (4) instruction and discipline; (5) methods; (6) master and mistress; (7) special items.[10] In 1851 Marshall is able to comment upon the Gate St. school in London which the SHCJ had only taken over during the year and were beginning to reform.

> 230 examined, av. attendance, 240.
>
> 1; good and ample. 2; good and abundant; books of Irish Comms ... 3; complete and effective; parallel desks and benches; gallery for younger children; classes formed with great order and method; 4; very satisfactory. 5; mixed, unusually good in writing and arithmetic. 6; eminently qualified in every particular. Great efforts have been made in the past year to raise this school which had been most disorganized into an efficient state; buildings have been enlarged and fittings renewed; teachers possessing the highest qualifications and performing their duties with admirable judgement and devotedness have been provided. Finally an adequate supply of well selected books and other requisites have been furnished. The results are such as might have been anticipated from measures adopted with so much intelligence and liberality. The character of the school is in all respects satisfactory, the deportment of the children wonderfully improved and steady progress is making in the several depts. of instruction.[11]

In the following years Marshall was able to repeat the verdict upon the Gate Street school; in 1852 he wrote that

> the judicious efforts which have been made to improve this school by new organizations and by securing the services of highly qualified teachers have been attended with great success and whatever can be accomplished by patient and practised skill may now be anticipated with confidence.[12]

The following year brought similar comments.

> The same judgement and zeal which has characterized this school under the present teachers has been displayed this year, and excellent progress has been made in the various branches of instruction. The general condition of the school is in all respects satisfactory and its efficiency cannot fail to be sustained by teachers so eminently qualified for their office.[13]

The nuns had only taken over the Gate Street school in the February of 1851; when they took over the school in Bunhill Row, Marshall came on his yearly inspection a mere fortnight later, which hardly left time for miracles. Marshall criticised the buildings and furnishings, but then added that the present teachers "have been skilfully trained and are perfectly competent".[14] And in later years he is able to report good progress.

It might be thought that Marshall was specially kindly disposed towards his Catholic schools, and perhaps painting a less than accurate picture. It is only by reading his reports on all the schools for the year that it is seen that those of the Society HCJ are among the most outstanding. Of others he comments that "a gallery is still wanting", or "writing from dictation and numeration have apparently been somewhat neglected", and of some children, "Irregular attendance"; and of a teacher that his "want of familiarity with methods disqualifies him for his office".[15] Neither Marshall nor Stokes are lacking in critical judgement, and although the reports on the poor schools of the Society in London, Liverpool for a while and in Preston are usually between good and excellent, both inspectors occasionally have some criticisms to offer.

A society which was expanding steadily with an increased number of sisters engaged in teaching was bound to have a variation in the quality of staff. The number of the nuns in the 1850s grew towards the hundred mark; not all were engaged in classroom teaching, but helped the school in a variety of other offices in administration, cooking, cleaning and staffing the infirmary. Some nuns survived initial difficulties to become good teachers. So one young sister remembered the instruction from the days of her novitiate that all should be done for the love of God, and that as long as the intention was good, the results were of secondary importance. The devout novice as a young class mistress took this spiritual doctrine to heart, and when asked about the results in her class was able to claim that all had been done with the highest of intentions. It took some prompting and an encouragement to better method before she settled down to become a highly successful class teacher.[16] Even more striking is the case of Sister Mary Christina. She was a daughter of Coventry Patmore, the poet, and perhaps herself had more of a poetical and mystical outlook on life than a practical one. As a teacher she suffered from an utter inability to maintain discipline, and might have been regarded as a danger to good order in school and a weak link in the teaching system which could destroy the efficiency of the method of the Society. But in spite of obvious defects she was allowed to continue as a class mistress at St Leonards in the convent school, and after her early death a memoir was published in which it was recognised that while she was helpless before a class of merry youngsters, she had left a profound mark on a whole generation as being recognised by the children as someone who was clearly holy.[17] But perhaps it was not a view which the inspectors would have taken of a mistress in one of the poor schools. In such a school she could have been in charge of three or four pupil teachers and a hundred pupils, and one bad report might have jeopardized the school's future under the Revised Code.

In addition to the government inspectors, eventually the diocese began to send round clerical inspectors to look at the religious teaching which was not otherwise a subject of inspection. The benefactory of one of the London poor schools, St Anne's in Little Albany Street, had become a Carmelite nun, and as such Miss White was known as Sister Theresa. In 1873 Cornelia wrote to her telling of the work of the school.

> The Schools are very flourishing and well attended and the reports of the Ecclesiastical Inspector most satisfactory. If you will not find it an interruption,

> it will be a great pleasure to send you an annual account of the works done there, and of the reports given after the Examination.[18]

The reference to schools is merely a recognition of the separate departments as it was common at the time to list the infants as a school on its own. And boys and girls were still often separated, so that a full primary school in modern terms might then be classified as four schools. In this letter I think that Cornelia is referring to one of the diocesan inspectors who had been examining the religious knowledge of the pupils. But what is abundantly clear is that the Foundress is confident that the work of the school is evident in the inspector's report. The schools in Preston would support the same confidence.

The Holy Child nuns had gone to Preston only in 1853, but at an inspection later in the same year their presence was already noted for its influence in the schools.

> Preston. St Ignatius Girls.
>
> 1. 2 fine rooms, properly lighted, ventilated and furnished. 2. Desks 2 double rows down the middle, furniture excellent; Books ample supply, apparatus good. 3. Perfect. 4. Disc. perfect; inst. solid and extending in range. 5. Those of the SHCJ St Leonards. This school must soon attain the first rank of instruction for elementary education. Conducted by teachers whose accomplishments are excelled only by the devotion which placed them at the service of poor children; actively superintended by the clergy and liberally supplied with requisites, with a carefully prepared staff of pupil teachers, it remains only to raise the character of the institution and extend it to all subjects. This object all concerned in the school will heartily concur in promoting.[19]

The accent in this report is very much that of Marshall, but the report was actually made by Stokes who had just relieved Marshall of the northern half of his district. Marshall covering all England, Wales and

Scotland had written in a recent report of the "unmanageable dimensions of the district previously entrusted to me". An illness on his part, and the growing number of Catholic poor schools under inspection had led to the appointment of Stokes who took over all north of a line from the Mersey to the Tees plus the counties of Cheshire and Shropshire and the northern counties of Wales. A note in The Preston Guardian (13th May 1854) both welcomed him and commented upon the success of the schools in which the SHCJ were working.

> S.N. Stokes Esq. Inspector of Catholic Schools in the North of England and Scotland, is pursuing the labours of his office with the greatest zeal and diligence. Of the Catholic schools under his inspection, and lately examined by him in Preston,. he will, we are assured be able to report satisfactorily. The scholars of St Ignatius boys' and girls' schools, who underwent examination, amounted to 1000. His inspection of the schools in Preston occupied him a week, and since then he has visited most of the Catholic schools in the neighbourhood. He will be engaged the whole of next week in Liverpool, and the six subsequent weeks in Scotland. Mr Stokes' affability, gentlemanly manners, and eminent qualifications for the situation which he holds, have gained for him in all quarters, merited respect and confidence.

Although The Preston Guardian did not elaborate, Stokes' eminent qualifications included a Cambridge degree, Bar qualifications and his previous experience as the first secretary from 1848 to 1853 to the Catholic Poor School Committee.[20] The same paper (27th Dec. 1856) contained an account of the ecclesiastical inspection. As details of these are rare for this time, it is worth quoting.

> St Ignatius Girls' School.
>
> The examination of the pupil teachers and children attending the Convent school of St Ignatius was held on Tuesday last, and the proficiency which they exhibited, and the satisfactory manner in which they

> responded to the questioning and cross-questioning of each other elicited marked and unqualified approbation. Indeed it was evident to all that both great pains and great care had been taken by their instructors - the nuns of the convent - in the training and education of the children. The subjects embraced in the programme of the examinations were numerous and varied, comprising not only the usual studies pursued at such schools, but physical geography and grammatical analysis, music and singing. A scene from Milton's Comus was also enacted by the pupil teachers. Different prizes were awarded; and the following clergy were present on this occasion; Revs. M. Cooper, Geo. Clifford ... R. Gillow, dean of Fernyhalgh.[21]

So there is a useful dateline for the extent of the Society's curriculum attracting comment, and for the activity of drama within the schools. The pupil teachers are part of the strength of the system, and in Preston, eventually a number of them, at times up to twenty, shared a dormitory in the convent and taught in four different schools. The inspectors in their annual reports had to examine these pupil teachers so that the grants might be obtained. Eventually the pupil teacher system came under attack. In places the pupil teachers were both neglected and exploited, but in Preston they were well looked after, and most went on to a training college. The inspectors' reports are generally very satisfied with this group of pupil teachers. The system in general was an important part of the growth both of primary education and the development of the teaching profession.

It is possible to look at the Preston schools which were staffed by the Society as a group. They were St Ignatius, St Wilfrid, St Walburga, also called Talbot Street in the Inspectors' reports, and later these three were joined by the English Martyrs. These poor schools eventually developed so that they all eventually possessed infants departments. They grew so that all can finally be described as large and there is criticism occasionally of overcrowding arising from this growth. In 1869 St Ignatius Infants is characterized as having "better arrangement but still overcrowded". St Wilfrid's Infants in 1866 is reported thus; "Infants admitted too young. Fewer scholars with more learning would make a better school". In the same year it is stated of the Talbot Street School that it is "creditable but overcrowded". Four years later the same theme occurs; "care must be taken that the numbers admitted do not outgrow the capacity of the room and the strength of the teaching force. Accommodation for 286, average attendance 306". The same school in 1879 is described as having "large classes". But in spite of this the inspector is able to add that "the whole school shows a cheerful good order which combined with the excellence of the instruction makes one of the best as well as one of the largest infant schools with which I am acquainted". These reports seem to have led to some extension of the premises; so in 1870 of St Ignatius Infants there is no full report with an explanation that "no comment (is offered) because of working amid noise of alterations". This is followed the next year by the statement; "room now ample and well-arranged". After a series of comments on the restriction of space in St Wilfrid's Infants finally in 1871 the words "new building" tells of radical improvement. It was not merely the actual size of space available that was at issue as another comment on St Ignatius Girls in 1873 illustrates; "this department suffers from the noise made by the infants in the adjoining room".

Many of the problems of the school arose directly from the poverty of the people and the parishes. There was an agreement between a parish and the Society; the parish agreed to provide a school and salaries of a number of mistresses. Grants were then claimed by the managers of the school to try to meet the costs. The result was that the parishes favoured bigger schools with fewer mistresses as being the route to solvency, while Cornelia is found writing to support the pleas of local superiors to the managers for an increase in the teaching force. The situation which was always a significant one became more acute with the implementation of the restrictions of the Revised Code. The poverty of the local population was occasionally commented upon by the inspectors. In 1873 of St Wilfrid's Infants the inspector says that "this school is largely attended and doing good service in the midst of a dense and poor population". And it was this poverty which made the night school an important part of the work of the Society in Preston for quite a number of years. Again the inspectors reported on this work. In 1863 of the night school at St Ignatius there is the comment "very satisfactory". The following year; "night - arrangements satisfactory and instruction unusually good". And this same year the Talbot Street School won an almost identical comment; "night schools conducted in a very satisfactory manner and are very useful departments".

Over the years the schools received the highest praise but with occasional signs of some fluctuation. First the praise, which in many ways is reminiscent of the early reports on St Leonards. So a report on St Ignatius Girls in 1879;

> 401 present and 352 examined. School kept in perfect order, and accuracy of elementary work is remarkable throughout all standards. Class subjects as a whole have been well prepared and grammar in 3, 4, 5, 6 is very good. Sewing is excellent and singing nicely done.

Likewise St Wilfrid's Infants in 1876 also gets a blessing from the inspector.

> This school is small but it has been worked up by the care and skill of its teachers to a state of praiseworthy efficiency. Whatever is taught in the school is well taught. The highest place should be given to the needlework, the writing and the elementary arithmetic. Good discipline and considerable intelligence are also found among the children.

That year St Wilfrid's Girls had too few scholars presented for examination, but two years later they obtained a first class report.

> Behaviour and order leave nothing to be desired, and attainments both in the elementary and class subjects are accurate and thoughtful. The ready repetition and answers of the older girls show superior intelligence and careful instruction. The knowledge of domestic economy and literature is also creditable.

Over the years the Talbot Street School also gained a series of very good reports. Of the Infants in 1872 there is the comment; "one of the most thoroughly efficient schools in the district". And there was similar praise for the Talbot Street Girls' School in 1873;

> All the general features of past years remain and if possible are improved. The school is altogether one of the best and most pleasing with which I am acquainted, and I can hardly imagine an elementary school more thoroughly efficient and satisfying.

In 1875 it "ranks among the highest class of schools". The following year the comment is that "all the good points of former years are fully sustained". Similar comments are made of the English Martyrs' School. Some of the Infants in 1879:

> This is one of the largest and most thoroughly efficient Infant schools I know. 361 for inspection, who are not only kept in excellent order but are taught with minute care and show an extraordinary amount of knowledge. Drill deserves special praise and the fittings and aspects of the room are particularly good and pleasant.

At the same time the English Martyrs Girls were noted as remarkable;

> An excellent school in all respects. Conduct satisfactory to highest degree. Elementary work exceedingly correct and neat and class subjects show accurate knowledge and thoughtfulness. The school leaves nothing to be desired in points of order, good behaviour and neatness.

When ~~occasionally~~ the inspectors do have some criticims to offer, they are occasionally able to offer a reason which is in part an excuse. So in 1875 St Ignatius Girls only achieved a standard of "average merit" and the inspector thinks that it is suffering from a change of a teacher. In 1867 there was the comment that the teaching staff should be strengthened. In 1866 St Wilfrid's Girls had a report which told of the strain on the mistresses working long hours in a very poor area.

> The excellent mistress who with unflagging zeal has for many years taught large schools in Preston is I am sorry to find no longer strong enough to cope with the difficulties attending the management and instruction of numbers by day and night.

This compassionate comment reveals the experience of the inspector as well as the dangers to health in the system.[22]

Cornelia Connelly was well aware of the dangers to health and the strains to which the nuns were subject. In a reply to Bishop Grant, who was concerned about dowries to cover the old age of the sisters, she sadly comments that they are more likely to die young of overwork.[23] In her correspondence she is often to be found offering advice about health, and remedies for illness. "Sulphur has been highly recommended as a cure for rheumatism - taken internally and externally".[24] A sister from Preston left suddenly and Cornelia was concerned that she might have had a mental breakdown, and in a letter to Bishop Grant she discussed the problem of hospitalization of such a case.[25] A decade or so later Sister Angela went insane and was moved to a home run by nuns in the midst of a panic caused by the repeated threats of a member of parliament to have convents inspected.[26] Cornelia wrote to Sister Angela Morley, after hearing that she was in ill health, and suggested a fortnight at St Leonards with the hope that the "change of air and plenty of good food and porter" would set her up for the winter.[27] The boarding school at Blackpool also served as a summer residence for some of the Preston nuns, while the sisters in London could go to St Leonards and later to Mayfield. In the wording of the era Blackpool was considered rich in "dephlogisticated air" while St Leonards was regarded as a health resort. Occasionally the sisters thought they were given heavenly help in health matters. Sister Walburga was seemingly dying at St Leonards from pyloric ulcers, and the doctor, who was not a Catholic, had said that there was no hope. Cornelia gave the sister a relic of the oil of St Walburga, and she was cured and up for Mass the next morning. When the doctor called to sign the death certificate he was questioned, and said that it was a matter of hours at the most and that nothing could be done for her. At a prearranged signal the sister walked into the reception room, and so stunned was the doctor at this unexpected apparition that springing to his feet he rushed, with his chair to the far end of the room. After an explanation of what had happened, he signed a certificate; "cured by a dose of Saint Walburga's oil".[28]

I think that the considerable amount of attention which is given in the papers of Cornelia Connelly to the question of cooking is also a response to this threat to health which overwork made upon the nuns. The rules for the sister in charge of the refectory are very detailed and extensive, and it is made clear that they are seriously binding commands.[29] There is detailed information about making tea, cocoa and soup, and menus for the week. "Good soup makes good soldiers" is a theme argued with reference to French cuisine.[30] The food is to be served hot on plates which have been warmed, and that meat is to be cooked in a fashion which is pleasing to the eye; "a calf's head is not to be served with the teeth grinning at one" and pigs' ears are not to appear without singed whiskers.[31] The whole tenor of the notes for the kitchen show both a continued concern for health, an interest in economy and a mother's appreciation of the likes and dislikes of children.[32]

Looking through the inspectors' reports on the Preston schools for more than a decade, there is never to be found any criticism of the state of the schools, other than those mentioned, arising from overcrowding. There is never any sign of a lack of either school books or apparatus, but these are often listed as being plentiful and well chosen. The skill of the mistresses is usually the subject of praise, and on the few occasions where there is some criticism, there is sometimes, as has been noted, an indication that the inspector realises that a good mistress has literally been worn out by work. The inspectors will often identify the teaching method specifically as that of the Society HCJ and in their reports likewise refer to the methods of the Sisters of Mercy or the Presentation nuns. It is not clear what was particularly characteristic of these other orders, but <u>The Book of Studies</u> helps to provide some definition of the method of the SHCJ. As there is no question here of writing a history of the schools of the Society, it is sufficient for present purposes that the inspectors' reports reveal that the system which Cornelia Connelly and her associates had developed could produce excellence in the poor schools. The reports are not detailed enough to provide any characteristic picture of the system in action, but they do establish the two important facts that there was a distinctive method of the Holy Child nuns, and that the results in their schools were often very good. Before trying to elaborate this picture from other sources it is necessary to consider the one known failure of the SHCJ poor schools.

The Society responded to the invitation of Canon Newsham to go to Liverpool in March 1852 and took charge initially of St Anthony's schools which provided for the needs of the two parishes of St Joseph and Holy Cross in the Scotland Road area of the city. There was an initial problem when the house provided for the nuns proved to be unhealthy and unsafe, so that in August they moved to 115, Shaw Street at an agreed rental of £75. According to the Liverpool superior, Sister Emily Bowles, Canon Newsham had agreed that if the schools did not bring in one hundred pounds a year, he would be responsible for the shortfall. This did not happen. And it was found that Bishop Brown of Liverpool had given his permission for the nuns to be invited on the condition that it imposed no additional burden on the two parishes.[33] So financial problems caused immediate difficulties. Both lack of funds and the continuing difficulty of the economics of the situation caused a new superior in January 1855 to advise that the work be given up in Liverpool. The actual teaching situation in the schools was good. The report of Marshall speaks of an improvement in 1852, and the following year Bishop Brown wrote a formal letter in support of the application by the Society for Roman approval to The Rule.

> By these Presents we certify that the Sisters of the Holy Child Jesus have been established in Liverpool nearly two years and in the Town of Preston about one year; that they conduct the Schools under their care in an excellent manner, that they have an amiable method of training the children to habits of piety and that seeing the valuable fruits of their labours

> we highly approve of their being in the Diocese of Liverpool.[34]

The document is in legal form as addressed to the Sacred Congregation de Propaganda Fidei, and it is not based upon an inspection of the schools by the diocese, but upon their general reputation, and the known comments of the inspector which were published annually both in The Catholic School and in the Report of the Catholic Poor School Commission. There was a similar letter of support from her own Ordinary, Bishop Grant. From late November 1853 to almost the end of April '54 Cornelia was in Rome working for the approval of The Rule. The superior of the nuns in Preston, Mother Lucy came to St Leonards to be in charge of the Society in her absence, and Mother Teresa who had translated The Rule into French for the Roman Congregation went with Cornelia to Italy. Meanwhile the superior in Liverpool had been looking for a house in the hopes of establishing both a middle school and a training college. This had been discussed, and because of the financial problems of the Society a ceiling figure of fifteen hundred pounds had been set. When Cornelia returned, it was to find that Emily Bowles, without any permission, had purchased Rupert House for five thousand pounds and was in process of spending a further fifteen hundred pounds in refurbishing it. Most of the money was a private loan from her brother a non-Catholic. It caused a financial crisis, and eventually Emily Bowles left the Society, and years were spent trying to retrieve the economic situation.

The author of the Annals SHCJ in recounting these details also adds that Emily Bowles had been so involved in the plans for expansion that "the elementary schools in Liverpool had been neglected". The examination results were bad, "failure" is the word used in the Annals. And the conclusion was that "in consequence the schools were withdrawn from the charge of the Sisters".[35] Certainly the schools had been getting good results. How quickly could a decline take place? A school which the nuns had once had in London in Bentinck Mews, after their time in 1863 suddenly slumped, and in this case it is possible to see from an entry in the log book just what had taken place.

> I could scarcely believe it possible that in so short a time (one month) such a change could have taken place. The whole school is so entirely changed. Now nearly all those children who paid 3d. and 4d. per week have left, and in their place a set of children who have been running wild in the courts or at the ragged Schools. Big girls who have left their places of service have been sent by the Lady Visitors and will probably only remain till they can get situations. They are irregular, inattentive, restless and have been the cause of great disorder.[36]

Clearly because of the great poverty in the big cities the number of children requiring special care was vast, and those from deprived social conditions could easily upset the balance of a good school if care was not taken. Possibly in Liverpool, with the superior involved in planning such an expansion, there was neglect, as the author of the Annals suggests, and a rapid change took place in the schools. The sisters left and never returned, but at the same time their reputation in Preston remained undiminished. As Preston was then a part of the Liverpool diocese, it would seem that it was understood that what had happened at St Anthony's schools was not characteristic of the Society. And it was not related to the provisions contained in The Book of Studies.

Perhaps before leaving the reports of the inspectors it is worthwhile finally to consider a late report on a poor school at Blackpool. It comes from this century, 1908, and is an interesting witness to the ethos of the school.

> A striking example of the admirable results which come from the judicious use of liberty and the absence of repression in the management of children. Since the teaching follows as well as guides the inclinations of the scholars, their development is on natural lines and therefore is rapid. While nothing as a rule is done for the children which they cannot do for themselves, the actual instruction is clear and incisive and is thoroughly enjoyed by all.

The liberty in the schools of the Society was one of the criticisms of the opponents of Mother Connelly; the children were said to do nothing but play.

The educational papers of Cornelia Connelly give a fragmentary picture as to how The Book of Studies was administered in a school and they provide further insights into her ideas of teaching methods. As the material does not cover all the subjects in The Book of Studies, it will be treated under just a few heads, the humanities, the art programme, drama, the religious life of the school and the effect which this had on the curriculum for the poor schools. While the details of the curriculum were worked out for the convent boarding schools for pupils from four to eighteen, some of it became available for the poor schools, although the children there did not stay so long. The extent of the connection between the curriculum of one class of school and the other cannot be defined in detail, but some examples of influence are known.

The transition from basic literacy to drama and some appreciation of literature was a major development in the humanities programme. A characteristic note of Cornelia's is found alongside the report of one of the mistresses on the reading which her class had been doing.

> In this Report no observation is made on the Reading. You have all stated what has been read, but there is no notice of the tone, style, pronunciation, analysis

of sentences etc. etc. 3 best or worst in each branch.[37]

The mistresses were supposed both to indicate the ground which had been covered and also in detail the progress which the pupils were making; and for the purposes of emulation they were to nominate the top three and also the three worst. The St Leonards School Report Book which covers the years May 1854 to June 1857 in 128 pages has a variety of matters from lists of prizes, examination questions to the reports of the class mistresses, which often contain such an addition in Cornelia's hand. She directs blackboards to be supplied to a class that is without one, calls for careful control so that pupils who have been out of class for a music lesson will not get behind-hand, answers direct queries for mistresses, deals with problems of the timetable, asks specific questions as to which exercises the children have done and repeatedly insists on detailed reports and not general statements.[38] So a French report on the 4th class reads;

> Sr Veronica. The lessons have been the same as last month. Minnie has applied more this month and has known her lessons generally. Augusta and Emma have been good and attentive. Agnes Fellowes scarcely ever knows her lessons and has often been out of temper and dissatisfied. May has been middling. Mary Kerr has improved and has tried to learn her lessons.[39]

To all this Cornelia proceeds to add, perhaps as an aid to memory for further investigation with the class mistress concerned.

> General remark.
>
> Each report should contain the number of pages learned by heart and define what has been dictated and read: When the composition books are brought to the Community room each mistress of class should decide which of each branch are the 3 best and which the 3 worst of the set, writing it in the report.

An indication of the problems arising from the limitations of the teacher is indicated in the report of one of the mistresses on the third class.

> Latin Roots every day. Douay Catechism every day. They do not learn any Latin because the mistress herself does not know it ...[40]

The Latin roots would be for the etymology which filled the English grammars of the time, made life very difficult for the students and must have been a major obstacle to any enjoyment of English at the very least in the poor schools. Occasionally in these notes subjects are explicitly mentioned which are only treated in a very general way in The Book of Studies; so botany and mineralogy, drilling and dancing, Pope's Essay on Criticism, and Dante all come into the curriculum.

The whole subject of the contents of a study of literature was of interest to Catholics. It had been noted in a report in 1832 by Thomas Daniel that "Catholics were the only religious body known to him to adopt a quite different and distinct school literature".[41] And this question of literature and religious culture was considered in a report of the Catholic Poor School Committee considering the text books of J.M. Glenie. The report looked for a Catholic "tone" suitable presentation and a recognition of the importance of religion. It asked for a "scientific cultivation" of the faith of the young, and continued;

> A Catholic spirit, therefore, should breathe through the whole of such a literature. It is by no means meant that religion should be introduced at every turn, whether to the purpose or not: but that from the first book upwards, the choice and the handling of subjects, their order and relation to each other, the mode in which they are illustrated and harmonized, should indicate that the writers possessed themselves the Catholic faith, and valued above all things the possession of it, as the key to all the works of God, the standard and the crown of all knowledge.[42]

The choice of literature was a sensitive area, and Dante was obviously a choice for a classic which would appeal in this context. This interest probably also lay behind the production of their own book of verse. The Legends of Our Lady and the Saints; or, Our Children's Book of Stories in Verse was actually printed at the convent in 1870. It is a handsome volume of 126 pages plus vi and was distributed by Burns, Oates of London. A readability test is not so accurate with poetry and so the different types produce very different results, with a reading age of 13.08 on the Fog index, but only 6.5 on a Smog grading. Fry would give 13.0. So perhaps a sample of the type of reading is more helpful. The opening poem is called "The Indian's Cloak".

> A Greyhaired Indian Chieftan stood
> Upon his native strand,
> And to an English Wanderer told
> A legend of the land.
> "Stranger," he said in mournful tone,
> And waved his hands around,
> "These hills were once the Red Man's own,
> My father's hunting ground."[43]

In nineteen such verses the legend of Our Lady of Guadaloupe is told; there is no pretension to great poetry, but it is easy to envisage the verses being recited at a concert evening, and the book itself occurs regularly in the lists of prizes. There are nineteen such poems in the work with stories about the rosary, St Francis and the wolf of Gubbio, St Christopher and the restoration of Mayfield which the Society had accomplished. It clearly represents a move towards a specifically Catholic contribution to the literature of the school. While there were plenty of books of verse which would not be too difficult for school use, few if any contained a selection of verses on Catholic subjects. Most of the readers which were used especially in the poor schools had to cram into a few volumes a mass of material on geography, history, basic science together with some religion. The evangelical tradition had tended towards being almost exclusively religious, and was critical, for example, of the works of Walter Scott, so much prized at St Leonards.[44] The nuns, under the watchful eye of their bishop, were more Catholic in their taste, and excluded material either because they regarded it as anti-Catholic or immoral. And in these matters they were on occasions to experience difficulties with episcopal authority. So Bishop Grant wrote prohibiting the use in school of Aikin's British Poets, and Cornelia replied that it was required for daily use, as it was part of the curriculum for the teachers' training college, but that it was not read by the students and that the mistresses merely used passages which had been approved. And what was she to do?[45] A further letter reveals that the books had been burnt at the bishop's direction.[46] Had the bishop known the contents of Mr Jones' library he might well have been asking for bonfires, as Aikin's British Poets seems innocent enough.

The literature which was read in school was both prose and poetry, from Walter Scott to Shakespeare. In the memory of former pupils some of the novels of Scott lingered as the highlights of the reading programme, while Shakespeare really came to life in the dramatic productions. Apart from reading, which at the level of the top forms included some of the Latin and Greek classics in translation, there was the inevitable work of grammar and paraphrase. An example of the sort of exercise which was set for the senior girls, and possibly also used in the training college is to be found among the educational papers.

1. Write out a paraphrase of the following passage.

"Though various foes against the truth combine
Pride above all opposes her design;
Pride of a growth superior to the rest,
The subtlest serpent with the loftiest crest

Swells at the thought, and kindling into rage,
Would hiss the Cherub Mercy from the stage."

2. Parse fully the words underlined in the following sentence.

True Piety is cheerful as the day
Will weep indeed, and heave a pitying groan.
For other's woes, but smiles upon her own.

3. Make out a table of the declensions of the English pronouns, personal, relative and demonstrative.

4. Give examples of English words in which difference of number, gender, person, case, mood and tense are marked by changes in the form of the word.

5. Show in what respect the English Alphabet is deficient and in what respect redundant: and enumerate the elementary sounds distinguishing vowels, mutes and liquids.

6. Name five of the principal English writers in each century beginning at the 16th and relate what you know of their works.[47]

While no examples remain of students' examination papers, there are a few surviving copies of students' notes. One of these is an analysis of The Wasps of Aristophanes, and it appears from the text of this that it was only one of a number of such analyses. The notes do not include quotations but cover both the dramatic action of the play, and the irony and sarcasm. It is obvious that the satire is appreciated, and the poetical imagination of Aristophanes is carefully noted. The students' work has an increased significance in the theatrical tradition of the school.[48]

The black leather manuscript from which the reference to The Wasps of Aristophanes is taken is a one hundred and fifteen page survey of Greek literature. It commences with a general sketch of Greek history, which is little more than an eight page table analysis. But this is followed by substantial sections on seven various divisions of literature. Eleven pages are devoted to the principal bards, and of these a full seven are given to Homer. The lyric poets are covered in eight pages with specimens in translation of Simonides, Pindar and Bacchylides. The extracts are short, and the final one is Bacchylides' Lines addressed to Peace, translated by Bland. Drama, naturally, is given the most space, some thirty-six pages, with extended analyses of the works of Aschylus, Sophocles, Euripides; and Aristophanes is treated in the next section of twenty-five pages on comedy. The historians are covered briefly in six pages, eloquence even more so in a couple, and finally philosophy in thirteen. The real strength of the work is its coverage of drama and comedy and the general view which it gives of the range of Greek literature.

It would be creditable as sixth form work, and the tradition of the Society is that it was done as such by a girl who afterwards joined the SHCJ and then used the manuscript for teaching purposes. There is a similar work on ancient history and another on architecture. They are all illustrated in the appendix. It is likely that there were similar works on French and Italian literature, geology, astronomy and other epochs of history which have not survived. But fortunately there are sufficient remaining examples of work to support the claim that high standards of achievement were attained by some of the pupils, and to suggest a range of work which was unusual for early Victorian girls' schools. The main relic from the theatre is a good collection of programmes.

To turn to the theatrical productions which were the highlights of the school year, and are always mentioned in recollections by former pupils, is to touch another point of controversy. This time it was with the staff, as a note on the dispute among her papers reveal.

> The opinion of the Sisters is that the children are rather injured than improved by the plays - Little Gertrude only a fairy full of vanity and not attending to her lessons - full of airs - Carry Rogan, assuming the naughty Lolo in Beauty and the Beast, "who cares for a snub - what are words" etc. Agnes Parker - full of conceit - full of her Beauty. Therèse de Laubenque hitherto so good now full of her imagined beauty because she was made so by dress and paint - If the plays are sowing the seeds of vanity are they to be upheld or to be put down? Again if they are properly used are not the children led to know their own vanity at a time when correction can be applied, and when they are safe from the snares of the world? Again are they not thus prepared to meet the temptations of the world and to know how to conquer them? Let us examine the past effects on our children before we come to any positive decision.[49]

The plays stayed, and it is clear from Cornelia's notes that she saw them not just as a part of the literary course, but also as a laboratory for moral training. And at least one pupil later commented that "I never knew myself until I acted the character of others in the St Leonards plays in my happy school days".[50] Cornelia is to be found referring to the Holy Child Theatre, and in spite of all criticism the theatre continued.

Opinions about this were divided in the hierarchy. Wiseman, a literary figure himself, was pleased, and perhaps flattered when his novel Fabiola was presented as a play. According to his biographer, Cardinal Manning disapproved. So Purcell notes that "the fact that Bishops drank wine or encouraged theatricals in convent schools were 'Hindrances to the Spread of the Catholic Church in England'", in the eyes of Cardinal Manning.[51] Perhaps realizing that the situation could cause controversy, Cornelia had prudently sought the support of her bishop, and was even pressing him to write works for her. He produced a song for angels in a play for one of the middle schools.[52] And his biographer revealed that any doubts he may have had about the propriety of the school theatre had been solved by an Italian cardinal.

> Being once asked if he approved of plays and similar entertainments in boarding schools, he replied: "An experienced Italian Cardinal encouraged them, and on being asked why, answered: '1st. It is an innocent recreation for children when used in moderation, and when the play is well chosen. 2nd. It improves their deportment, and gives them ease of manner." The Bishop (Grant) would sometimes provide the mistresses with copies of plays that he thought good for the children, and desired that great care should always be used in the selection of them. It was not enough that they should be harmless: he wished them to be profitable and to convey noble sentiments and useful lessons to the minds of the little actors. He often deplored the dearth of good and amusing story-books for children in English. He liked Canon Schmid's: but used to add, when praising them, "What a pity it is that they all end in temporal happiness".[53]

The tradition of the school theatre had been established first by the Jesuits, and was very much a part of their system.[54] Newman was encouraging the production of strictly classical dramas in Latin and Greek. The question of propriety was a serious one for the Victorians. Queens College had trouble about a charade and the suitability of ladies appearing in a costume performance. This dispute seemed to have to be a set-back for the development of drama at the College.[55] Dorothea Beale eventually found great relaxation in the guild plays which were produced by her former pupils, and there were outstanding performances of Comus in 1896, Griselda in 1904 and Hatshepset in 1909.[56] But these productions were comparatively late. At the North London Collegiate School of Miss Buss works like <u>The Faerie Queen</u>, <u>Coriolanus</u> and <u>Richard II</u> were produced. And there was a notable performance of Browning's <u>Stafford</u> at which the author himself was present.[57]

Among Bishop Grant's thoughts on the theatre was the hope that it might, if well directed, help to "convey noble sentiments". As a pupil Freda Bellasis took the role of Cordelia in Lear. Sixty years later as a Holy Child nun on the eve of her death she revealed that she had used some of the words of the play as a prayer throughout her life. The words spoken by Cordelia to her royal father, she addressed to God.

> What shall poor Cordelia do?
> Love and be silent? I love your Majesty
> according to my bond, nor more nor less.
> You have begot me, bred me, loved me;
> I return these duties back as is right and fit,
> Obey you, love you, and most honour you.[58]

A similar incident was noted of yet another of the sisters, Teresa Laprimaudaye, who a couple of days before her death, was heard repeating lines from Athalie as a prayer; "D'un coeur qui aime, mon Dieu, qui peut troubler la paix; il cherche, en tout ta volonté suprème".[59] The dying nun was singing, and the nurse at the bedside was Cornelia. The plays of both Corneile, Moliere and Racine were studied and performed, and in addition to Athalie and Esther there were lighter French pieces. Cardinal Wiseman and Bishop Grant both came for the plays; in later days Cornelia is to be found writing to Grant's successor, Bishop Danell to know whether he would stop for the three nights of theatricals.[60] Bishop Butt, a former chaplain, also attended.[61] And even Cardinal Manning, in spite of his reservations, was present at least on recitation and musical evenings, and at distribution of prizes.[62] As the recitations were in a number of languages he thought the audience might have missed the point of an Italian piece, and proceeded to explain it to them. When the Society opened its first school in the United States at Towanda, dramatic productions were presented within a few months, and the local people rallied round to help to build a stage. The nuns there were rather flattered that one of the gentlemen who assisted was a member of Congress.[63]

The presence of French and Italian theatre at St Leonards may indicate a pinnacle of achievement. The educational papers of the foundress reveal the daily work which was necessary. There are instructions about learning verbs, there were days in school when only French was to be spoken, examination papers show the different levels of progress expected in the various forms. When Queen Marie Amélie was in exile she was a frequent visitor to the convent; prompted by Mother Connelly the children asked the queen for her blessing. But instead of "daignez nous bénir" they came out with "daignez nous baigner" to the queen's amazement.[64] At times there were French mistresses at the convent, and a certain amount of correspondence concerns the terms for young ladies from French convent shcools who were to teach in England. Eventually Cornelia made her own French foundations with the idea of providing a finishing school in which the French accent could be perfected. There were also a number of French hymns in use in some of the SHCJ schools.

There is less information in the educational papers about Italian in the school, but The Book of Studies alone is sufficient to make it quite clear that it was studied. It occurs less frequently in the programmes of concerts and plays, but it does occur in both from time to time. The study of literature, however, was designed to cover English, French and Italian, and this gave the pupils a broader view than the vast majority of the Victorian girls, and supports the thesis that the basis of the curriculum in Cornelia's plan was to replace the Latin and Greek of the Ratio studiorum with English, French and Italian to replace these classics. This provided some contact with great literature on an international basis. It provided for the possible enlargement of the pupils through contact with fundamental themes as expressed by writers of genius. At the same time it was a programme of studies which called for expression as well as reception. While the curriculum is clearly centred upon the humanities, it remains open to both the sciences and the arts. Indeed the fundamental training in reception and expression may be the first reason why Cornelia ranked drawing so high on her curriculum.

While the educational papers do not devote as much space to the art programme, it can be argued convincingly that more of this got into The Book of Studies than of any of the other disciplines. Not so many text books were involved, so it does not figure as much at that level. But in terms of expertise it is provided for at length in The Book of Studies, and there is sufficient additional material to indicate how the mistresses struggled to reach the required standards themselves. Cornelia's principle was that it had a "philosophy as well as a poetry". A number of factors combined to give her this outlook. She had natural talent in this field herself, and when she was in Rome she received professional training from a master sent by Flatz, who was a pupil of Overbeck.[65] While she was at Rome the school of the Nazarene painters to which both Faltz and Overbeck belonged was flourishing, and it strongly favoured religious art.[66] This appealed to Cornelia who was able to combine the natural aptitude with which she was gifted with a strong philosophy. But this was also reinforced by her Ignatian spirituality. The meditations of the Spiritual Exercises were of a graphic nature, and led to a form of contemplation based upon the mysteries of the life of Christ. As a preparation to more formal prayer the person was encouraged to imagine vividly a gospel incident, to picture himself present, perhaps as one of the crowd, to see what Jesus was doing, to listen to what was being said. It is a very concrete approach to meditation and appealed to the artist in Cornelia, and in return it enhanced the position of art, which was then seen as Christian and as one of the "most important branches of education, second only to the art of speaking and writing".[67] One of the text books which she provided for the schools, Rio's The Poetry of Art had made a considerable stir in the contemporary artistic circles. It spread the influence of the Nazarene school, and in England it was significant in the development of both Lord Lindsay and Ruskin.[68] Pugin in his Contrasts is to be found referring to Overbeck who was the leading light, though not the founder of the school, as "the great Overbeck, that prince of painters". As the movement represented a movement away from some of the paganism in art which had characterised the period of the French Revolution, it could be seen in Catholic eyes as part of a providential restoration. So her talent, a contemporary movement and her Ignatian spirituality combined to provide the strong basis of the philosophy of art in The Book of Studies.

Various masters were brought down to St Leonards, one REGALI to demonstrate how to make statues from casts, another to coach some of the mistresses in gold-leaf work. Regali and the moulds for the statues eventually proved a failure. The weight of the larger proved to be too great, and the only result of the experiment was a couple of dozen small statues and a couple of St Aloysius about two feet high. But although the attempt was abandoned, Cornelia's comment was both characteristic and hopeful: "if we can't do it ourselves - anyhow we know how it is done".[69] Her principle was that the mistresses and pupils could do anything until the contrary was proved, and with this optimistic outlook she often achieved unsuspected results. She challenged people to draw and paint, and many became quite competent. Her notes provided for a variety of techniques. The gold workers who were brought from London proved to be a better investment than Regali and the statues.[70] Some of the art books which the students produced to take home included some gold work on the fronticepiece, and for occasional ornamental letters in the works.[71]

The same form of control is to be seen in the educational papers over the art teaching as for the humanities. She wished to know exactly what progress the pupils were making, so that a characteristic instruction reads; "Let me know what water colours the children ... have done, whether any illuminations have been attempted.[72] Another directive specifies that Hopley White's lines on the "Relations of Harmonies of colour" were to be learned by heart, and that various pictures were to be copied. Among the documents in the Mayfield archives are a number of sketches after the old masters. They include a lady's head in a Dutch style, a young girl with a spaniel in her arms, a child with a book, a mother and daughter, and a child at prayer. Some of the drawings have a pencil grid across the picture, and one is marked M. Teresa Xavier, Dec. 3rd 1882 Convent St Leonards on Sea. The tradition was that they were actually pupils' work. But professional opinion at the Whitworth Gallery identifies them as reproductions produced for art classes, probably by G. Rowney of London.[73] Some half-size reproductions are to be seen in the second volume, together with some actual examples of different work by the students. The work which has survived and is available illustrates especially the happy marriage of drawing and geometry which has left a number of copies of very well illustrated works on architecture, with a great number of drawings to show all the different forms from Egyptian and Grecian to Chinese, Gothic and Moorish. It is an admirable piece of work from which some illustrations have been assembled for an appendix. And others are to be found in the archives.

Cornelia's educational directives in art were not only very specific, detailing with the mixing of colours, the type of brush, the preparing of paper and canvas, but also providing examples of what was wrong. An instruction reads;

> This water colour of Meinengen 5" by 4" ... is to be kept for the Studio not only as an example of most vile taste, but to shew how easily body colour may produce lights and any mistake be remedied by their introduction. The best artists of the day put in small lights on this principle.[74]

The same authority was revealed when she dismissed one architect as "having no taste or eye for drawing", and corrected some of Pugin's drawings in his presence; "Would not that be more artistic?" And amazingly Pugin agreed.[75] The extent to which art was to be taken may at first have puzzled some of her companions. Not only was the convent, and above all the chapel, to be beautiful, but the principle was to extend to everything. So another directive came down to the level of the pots and pans.

> The tea-pots and all kitchen utensils ought to be kept beautifully bright - first, for the order of the convent: secondly, for the proper teaching and training of the orphans, who ought to be taught to relish the beauty of order, neatness and cleanliness in all their surroundings ... AMDG ever in view! God is the God of order. Such as He is, such should be His house.[76]

Henry Cole, Richard Redgrave, John Ruskin and Prince Albert were all promoting the moral advantage of art at this time. It was seen as an uplifting subject which could improve the lives of the people. Cornelia's approach is slightly different. It is that of a Christian mystic who saw the ascent of the mind to God as beginning from a true appreciation of the creation as God's handiwork and moving on to the contemplation of the creator himself. St Teresa of Avila a favourite author of Cornelia's had written at some length on the beginnings of contemplation in this way, and she was in this repeating an established theme. In both her Life and The Mansions she deals with this subject. Characteristic is her comment;

> For those who would quickly enter into Recollection a book is useful. I also found gazing at fields, water or flowers a great help, for they spoke to me of the Creator, and served as a book in bringing me to a state of Recollection.[77]

This was a great distance from a mere development of good taste. Erasmus Darwin in his curriculum saw drawing for girls as "greatly facilitating the acquirement of Taste". The capital is significant. Presumably it was because it was just a matter of taste that in 1858 at Cheltenham under Miss Beale the treasurer in lowering the fees put both music and art on the list of extras.[78] Almost half a century later Pauline M. Randerson, reporting on drawing and painting at Cheltenham does not offer anything like the extensive programme to be found in The Book of Studies. It was 1889 before a clay modelling class was opened there under a Miss Stirling.[79] And all this was in spite of a friendship between Miss Beale and Ruskin. There is nothing in the Taunton report to suggest that art was flourishing in the girls' schools at any real depth. Wiseman however, who had a high regard for Overbeck, was criticising some paganism in art and commenting that "God seen in Nature, becomes the obvious preception of its greatest beauty".[80] This was more the feeling of Cornelia who regarded the potential for finding God in nature as part of the justification for artistic training. She saw a close connection between art, religion and worship, and the idea of art as a totally independent discipline was completely foreign to her concept of its place in her curriculum.

The extent of the art programme given in The Book of Studies is such that it is not likely to be attempted today except in a college of art. Ten sections comprise the full course; free hand drawing; flat model and model; geometry; perspective; model connected with perspective; Harding's Trees and Landscapes; water colours including Illuminating; heads and figures with chalk shading; sketching after the Ancient Masters; oil painting. And if this was not comprehensive enough The Book of Studies in its seventeen pages on art gives detailed notes on guache, and a long section on ivory miniature painting. And the history of the school at St Leonards with the visits of Regali and the workers in gold-leaf, and accounts of the production of stage scenery and vestments and embroideries for the chapel all shows art flowing into the life of the school in every direction. This was most unusual at the time, and the extent of the programme was only achieved in the colleges of art in England in the last decades under the influence of William Morris.[81] A note in Cornelia's hand in a copy of The Book of Studies which was in use at Mayfield provides an interesting indication of the way in which the detailed programme of art education developed for the private schools was given some scope even in the poor schools.

> The children of St Michael's school are not to begin the course of Drawing until they are in the 3rd class. They then begin on the 1st yr. of the 2nd course. On Sundays and holidays the lower class may have an Elementary Drawing and also the 1st course. C.C. Sup. 1868.[82]

It is rarely possible to trace the influence of the full course on the more restricted time-table and school life of the poor schools. That it had an effect is quite certain, but there is a lack of evidence for anything like a detailed picture to be established.

Attention must be turned away from the art to the subject of the ethos of the school, which was essentially religious, but at the same time very light and far from oppressive. While the religious instruction has been considered and some of the text books listed, the actual religious life of the school remains to be discussed. The chapel was both kept beautiful in its decorations, and kept alive for the children by the amount of music. The sisters wrote some hymns of their own, and in a letter Cornelia tried to encourage Bishop Grant, who replied; "I fear I shall fail in English and cannot attempt Latin".[83] There were a succession of music masters to teach instruments, almost exclusively the piano; Signor Guglielmo, Herr Kloss, Herr Kummerman, and J. de Jasienski.[84] At Blackpool the music master M. Pierre Garnaud was not a practising Catholic, and the nuns were very worried when he died.[85] There were various choirs, and apart from the more ordinary hymns there were special pieces for the choirs like Lambillotte's Pastorale and his Lauda Jerusalem. Haydn's third Mass was used and a variety of Latin motets. In the Holy Week of 1877 the Lamentations were sung to the accompaniment of a harp.[86] At St Leonards there were quite a number of different choirs which were given different roles and between whom there was a certain amount of competition; the nun's choir, that of the upper class school, the choir of either the middle school or before that of the training college. On occasions the children of Mary would have a special benediction of their own and sing as yet another group.

In addition to a great deal of music associated with the liturgy, there was also music for recreation. As late as 1877 Cornelia, writing from Paris, reveals that she is giving singing lessons to the pupils and "often goes to night recreation to sing with them".[87] She was also known on such occasions to waltz around the room with a pupil while another played the piano. This caused dark suspicions on the part of her bishop.

Lucy Mary Barrett who was a pupil at St Leonards from 1863-67 remembered in particular the beauty of the place, her piano lessons and singing, objectionable rice pudding and the great influence of Cornelia.

> At recreation time Mother Connelly would often come in, and if a child was at the piano playing a waltz, she would whisk one of the children round on the "light fantastic toe" regardless of her voluminous habit. When Mother Connelly came back from a journey, we would all gather in the grounds, dressed in white, ringing little handbells, and would cluster round her carriage to greet and welcome her.[88]

From a child's point of view this was all innocent merriment, and the atmosphere in school was such that in a letter in 1866 Cornelia could claim that the pupils returned joyfully after the holidays. But dancing, and even card playing, were open to misinterpretation, especially in a Victorian society. In 1865 Bishop Grant wrote to Cornelia.

> Confid.
>
> Enquire prudently, as it is said that in one of your Houses (either St. L. or Harley St) the pupils have been taught to waltz and to dance the polka as well as to play whist.
>
> If you discover this to be true, stop it quietly.[89]

A similar incident occurred in one of the Preston schools: Bishop Goss of Liverpool heard stories of a live Christmas crib, and responded with a thunderbolt.

> Live Bambino.
>
> My dear Sister Superioress,
>
> I am told that for the last two years, perhaps longer, there has been exhibited in the Fox Street School a live infant lying in a crib to represent the Birth of the Son of God, and that incense was used on the occasion. I wish to know whether this impiety really occurred, or whether I have been cruelly hoaxed by a false statement. I wish therefore to have from

> you a full and circumstantial account of what took place; if such an account be at variance with what I have heard, I shall feel it my duty to name a Commission to examine into this strange affair ...
>
> Alexander Goss.[90]

Manning once referred to him as "Goss with his usual rough violence - the crosier, hook and point". Later preaching a panegyric for Goss he was more diplomatic, saying;

> He had known how Dr Goss was sometimes strong and resolute, almost to vehemence, in decisions which he thought truth or justice required, but no man was more forbearing, more considerate or more equitable to others, or more ready in balancing justice, to change his conclusions when facts or reasons could be adduced against him.[91]

It is not recorded whether the superior at Preston reminded the bishop how St Francis of Assisi began the custom of Christmas cribs with a midnight Mass in a cave at Greccio with a live crib, ox, ass and baby. The live crib at Preston stopped, but the theatricals continued.

Apart from religious instruction, the religious life of the school was built around the liturgy and the ecclesiastical calendar which called for processions, celebrations of first communion days, confirmation, and in addition to these, retreats, and the work of the various confraternities. Probably the retreats were for the more senior girls, and a note in 1860 when Father Zanetti gave a school retreat in February added that "those who did not follow it read part of the Poetry of Christian Art, worked and drew the whole week".[92] Retreats were part of the preparation for first communion, and the educational papers contain the outline of the preparation for this sacrament. While there was thorough instruction in Christian doctrine, the final six weeks were much more concerned with the moral preparation. Significantly in the fourth week the children were chosen for the sodalities.[93] The link between the Christian doctrine as taught in class and religion as lived was very much established through the work of the various sodalities. They were voluntary, and had a measure of student control, so that a different relationship was established with a mistress through working together in a sodality than through the classroom situation. The commitment to a sodality by a member resulted in certain duties of both prayer and work. For the children in the middle and upper class schools this could possibly mean helping with the instruction of the children in the poor schools in catechism. In needlework they made garments for the poor. Sodality members collected for the foreign missions and certain offices in school, such as prefect of the dormitory, were reserved to the Children of Mary. A sodality was a society which in many ways resembled a religious order, but without the vows and lifelong commitment. But because of the resemblance, it was a point in the life of the school through which much of the spirituality of the Holy Child nuns could filter through to the pupils. At the same time the sodality was not adult, nor repressive, and when it was functioning well it could be suited to the age of the pupils. Certainly at St Leonards there were four different sodalities through which the pupils of different ages could graduate to the final heights of being a child of Mary.

I think that it was the combination of Cornelia's philosophy of trusting the pupils with the strength produced by sodality membership which combined to produce an atmosphere in the schools which was at once very free and also responsible. The French pupils found the amount of freedom remarkable, and even more so the fact that it was not abused.[94] Catherine Harper was in the school from 1855 and later became a Sister of Charity. She recalled how Cornelia spoke to her before her first communion, and went on to say of the foundress;

> She had great sympathy for children, and did not try to force upon them wisdom beyond their years. We all loved her and thought her very holy, and would consider ourselves honoured by a smile and a few words from her. Often I came in for rebukes for bad behaviour, and at times she could be very stern. But the general atmosphere of St Leonards was one of joy and contentment. There was no spying on the part of the nuns, but we were greatly trusted, and trained to a high sense of honour - a method that completely achieved its end. There was a sense of freedom and broadmindedness about the school that was delightful.[95]

While past pupils sometimes wear rose coloured spectacles, there is enough evidence from various sources to indicate that this is a realistic appraisal. The honourable response on the part of the pupils was particularly developed through the system of the sodalities. The fact that the schools were small at first, under fifty pupils, gave better scope for the development of a particular ethos. But at the time of the Taunton Commission most of the girls' schools were noted as being small, less than fifty, and it was thought that this restricted the curriculum.[96] The numbers in the poor schools tended to be greater, and the sodality, at least the Children of Mary, was often on a parish basis, but with one of the sisters helping.[97]

It might be thought that with such a good atmosphere in the private schools, the result was obtained by careful selection of candidates for admission. The St Leonards school journal for the higher and middle school covers the years 1857-1876. Much of it is taken up with marks of examination papers, but occasionally there are comments opposite a pupil's name. These soon dispel the notion that the pupils might somehow be naturally rather good; various students are characterised as rude & bold, idiotic, nonchalant, idle, giddy, weak & bragging, uncharitable, reserved and sly, insolent, boorish, talkative, given to calling names, insubordinate, a greedy bear. But only once the note that she "wishes to go home".[98] Clearly the pupil population was very normal, the convent atmosphere was not stifling the young, but through the system they did eventually respond to the trust which was placed in them.

The children normally all attended morning Mass, and this too provides an example of the balance between a very liberal school programme and religious training. In the summer time the pupils, with parental permission obtained, were allowed to go sea bathing at six o'clock in the morning. This healthy exercise was seen as one of the advantages of the site at St Leonards, as they virtually had their own beach. But seemingly some were known to return late for Mass and in 1860 a school regulation dealt with the situation.

> It was decided that for the future, the children should not lose Holy Mass during the bathing season, but that they should get up about 1/4 6, leave the house at 6 o'clock and return in time for Holy Mass at 7. Those who stay too long in the water, or are late, or cause others to be late for H. Mass are not allowed to go the next time, as a penance.[99]

The importance of the Eucharist was always made clear to the pupils. A similar incident after a picnic illustrates Mother Connelly's sense of the importance of the Mass.

> Once after a picnic, a sister went to Reverend Mother and asked whether all the children might have a long rest in the morning, as they seemed very tired. "Long rest?" said Mother Connelly, "till when?" "Till breakfast", answered the sister. "And miss Mass for enjoyment? What about the balls and the parties and the theatres when they leave us? Will they get up for daily Mass, or are they to remember rests after picnics at St Leonards ... No child should have been taken to so tiring a picnic who is too delicate to get up to-morrow for Mass. If there is such a one, let her rest all day".[100]

Picnics were very much a part of school life, but there was no doubt about the importance of the Mass.

It must have been easier to achieve this type of training in a boarding school with only one holiday at home in the year during the summer. The poor schools presented a different and more difficult problem in training. Often, because of poverty children were leaving at eight or nine. The state of their health made education more of a problem. Matthew Arnold wrote of the London children, eaten up with disease, half-sized, half-fed, half-clothed, neglected by their parents, without health, without home, without hope. And in both London and Preston the nuns faced grim poverty. The inspectors noted that in the matter of poverty the Irish were in a class of their own. Typhus, the poor man's disease only disappeared in Manchester in the 1890s.[101] The Preston log books often tell of pupils carried off by the plague. In 1862 Cardinal Wiseman's pastoral letter on distress in Lancashire was reported in The Times.[102] The SHCJ nuns in Preston ran soup kitchens in these times of crisis; the British and Foreign Bible Society prided itself on distributing testaments to the poor in the slums of the great cities "in anticipation of the visitation of cholera".[103] The sisters were round the homes trying to help with food and clothing. Preston had known lock-outs, and the cotton famine caused by the war in America which either closed mills or placed them on half time. In 1861 there was a relief committee in the town giving aid to twenty-two thousand. Cornelia, at this time herself struggling with the gravest of financial problems for the Society, sent ten shillings each week towards relief. The chaplain from St Leonards, Father Searle, visited Preston in 1865 and wrote back to St Leonards in glowing terms of the good work being done; "I am charmed with my visit to your houses and schools in Preston. What a glorious mission to labour in".[104]

From the log books of the poor schools it is possible to establish that many of the features of the private schools were brought into the life of these other schools. The theatricals and confraternities, the art programme, the music, and above all the respect on the part of the mistresses for their pupils. All the sisters received the same teacher training, and looked to The Book of Studies for their principles. The two restrictions in the poor schools were the fact that the pupils never stayed on for anything like the same length of education, and eventually the pressure introduced by the Revised Code. In 1861 the government grant to the poor schools was placed upon a different basis through a formula which combined the year's recorded attendance and the results of the inspector's examination.[105] A failure in the examination could result in a drop in income, and perhaps even in the closing of a school. As the examination was based upon a few basic subjects, these tended to loom large in the teaching. Memory work was stressed, and the wide range of The Book of Studies could be regarded as a utopian dream. Robert Lowe who introduced the Code agreed with the view that "any attempt to keep the children of the labouring classes under intellectual culture after the earliest age at which they could earn their living would be as arbitrary and improper as it would be to keep the boys of Eton and Harrow at spade labour".[106] The Code was aimed at obtaining value for government money invested in education, but there was also possibly a hidden bias against the poor. It certainly made life much more difficult in Preston. The inspectors had problems in understanding the Lancashire accent; "the children's dreadful pronunciation made the reading marks not so good". In 1866 one of the schools very nearly had its grant reduced by the Privy Council because of failures in the examination, and the danger was averted because "the school has for so many years enjoyed a high reputation".[107] The clerical school managers were concerned about the financing of the schools, and this resulted in stress on the teachers. The log books tell of the resulting situation; "greater part of the morning spent in exercising the gallery babies to answer their names". If they failed to do so an inspector might become suspicious, and an examination begin badly. This led to some of the teachers in Preston being severe and even using some corporal punishment contrary to The Book of Studies. So it was said of Mother Lucy at Preston that "she was very hard on the pupils in the school".[108] This situation at Preston is confirmed by some verbal evidence; one extremely old sister could quote a grandmother from St Walburgha's parish, Preston who commented that the "punishment was not excessive" and of a Sister Joseph that "she did lick us and we did love her".[109] I think that at times the regime at Preston was more severe than Cornelia would have wished, but at the same time it was probably much kinder than the average Victorian poor school.

The general picture of The Book of Studies in action is confirmed by a number of surviving works of students. These are mostly in the archives at Mayfield and at St Leonards. They include a number of map books, and some illustrations from these are in an appendix to this work. There is a very beautiful book of heraldry, some drawing books and some school note books. Again some extracts from these are in an appendix. A study on architecture in almost equal parts of text and drawing is a particularly fine piece of work, and could nowadays be presented as part of an A level project. There are also some coloured programmes for concerts and plays. History notes give reference to one of the texts which the school was using, Fredet's Ancient History and there is a chapter on the divisions of the empire of Alexander the Great. Similar notes exist on astronomy, and are concerned with the history of the science as well as the picture of the heavens. Finally quite a number of texts of the plays still survive. The surviving plays include both printed texts, and also some manuscripts. But not, alas, the Society's version of Wiseman's Fabiola. Printed texts of two of Wiseman's other works do exist, The Witch of Rosenburg and The Hidden Gem, but these were actually written as plays for various schools.[110] The St Leonards collection does include Metastasio's Giuditta, Beauty and the Beast and Fridolin.[111]

There were constantly rumours about Cornelia Connelly, and they included the suggestion that the children in her schools were just playing and receiving no education. So in 1860 she wrote to Bishop Grant about a number of problems, and mentioned the stories

> that the education of the children here consisted in running about the fields - By another that half the year was spent in playing at study. By a priest that Holidays were the rule and Study days exceptions. But many say that no children in a mass ever looked so healthy and so happy.[112]

Probably one of the reasons why the children produced project books of art and history to take home was to combat these wild rumours. They were often bound in half leather, and were part of an exhibition before the schools broke up for the summer holidays. So directives of Cornelia's are concerned that they should come back from the printer and binder in good time for the exhibition.[113] So the author of a manuscript life of Cornelia, Mother Mary Francis Bellasis wrote;

> The standard of education rose rapidly 1856-66 in great measure through the system of regular examinations organised by our Mother. These papers the children took home with them, and they served to remove much prejudice against the School.[114]

But if there was criticism there was also the general success in examinations for the poor schools, and the growing reputation of the middle and upper schools. And for Cornelia there was the occasion when Wiseman visited St Leonards towards the end of his life, and delighted with the sight of many of the families like the Allies, Bellasis, Charltons turned to Cornelia to tell her that she had fulfilled the dream of his heart.[115] Certainly the Holy Child nuns came to occupy a place of excellence in girls' education within the Catholic community.

As a final test of The Book of Studies, the following chapter looks at the training college at St Leonards, and the way in which the Holy Child curriculum fared in the specialized area of teacher training. The short life of the college provides a simple check on the curriculum, its potentials and the problems which it posed.

CHAPTER 9

THE TRAINING COLLEGE AT St LEONARDS

The nineteenth century saw the rise of the teaching profession in England. It was a rise from virtually nothing. In the past the grammar schools and public schools had taken graduates from Oxford and Cambridge, usually with a degree in classics, but with no particular qualifications in teaching. Other schools were mostly unlikely to obtain the services of graduates, and more or less took anyone. As late as 1847 Macaulay was expressing dissatisfaction with the standards of teachers in the House of Commons. He considered that teachers were -

> The Refuse of other callings - discarded servants, or ruined tradesmen; who cannot do a sum of three; who would not be able to write a common letter; who do not know whether the earth is a cube or a sphere and cannot tell whether Jerusalem is in Asia or America; whom no gentleman would trust with the key of his wine cellar and no tradesman would send on a message.[1]

While the atmosphere of the House of Commons does occasionally inspire eloquence rather than accuracy, there is no reason to think that teachers were recognised as a profession with any real status early in the nineteenth century. Dickens too paints a picture of their incompetence. To gain a social position and win some public confidence teachers needed to be seen to be professionally trained, and while this had begun abroad in the seventeenth and eighteenth centuries, it was not so in England.[2]

The Jesuits, the "schoolmasters of Europe" had a long tradition in philosophy and theology, but had also developed their own manuals of paedogogy and their own system for the transmission of classroom skills. Authors like Jouvancy, Possevino, Sacchini had produced a number of works designed to supplement the Ratio studiorum in the matter of teacher training, so that the Ratio may be seen as a curriculum and an administrator's handbook, and the Paraenesis and the Protrepticon, and Jouvancy's De Ratione discendi et docendi as the teacher training manuals.[3] With the restoration of the Jesuits in the nineteenth century many of these seventeenth century works were reprinted.[4] The other teaching orders had followed this example to some extent, and the most significant development was made at the very beginning of the eighteenth century by John Baptist de la Salle who provided the first forum for the training of lay teachers, especially for poor schools.[5] In France all efforts to train teachers were halted by the revolution, but in Germany there was less of a break and normal schools continued to spread throughout the country. Prussia had required a professional examination of would-be teachers since 1763, and in theory by 1819 every district in Germany was responsible for supporting a normal school. After the revolution in 1808 Napoleon created the University of France and at the same time planned a Higher Normal school for men. The whole question of appropriate qualifications for teachers was, from 1828, the concern of the Minister of Public Instruction.

In England the stimulant to change came from the social problems arising from the industrial revolution, which forced upon politicians a realization of the urgent need for a better system of popular education, and therefore the need for an adequate supply of efficient teachers.[6] The monitorial methods of Lancaster and Bell required the services of a person who understood how the system worked, and short courses were available. These were often only about three months, but many of the applicants failed to complete even that brief training, and the standard of the applicants was low.[7] Pickton, giving evidence to the Select Committee of the House of Commons on education in the Metropolis in 1818 suggested that the course would be six months for those who themselves had been educated in a monitorial school, and a year for others.[8] But Borough Road had its problems; in 1825 there seems to have been only one man in residence, so that the country could hardly hope to find a solution to the problem of untrained teachers there. Some teachers were gaining a similar brief introduction to the art of teaching at the Kildare Place Society in Dublin; masters were trained there from 1814, and in 1824 women began to benefit from this establishment.[9]

A major influence for change in the country was Kay-Shuttleworth. A minute of the Committee of Council on Education, to which he was secretary, on 21 December 1846 established the pupil-teacher system; there were to be grants to the instructors of these pupils, and once the pupil teacher had passed through this apprenticeship there would be an exhibition of twenty to thirty pounds to be held at a normal school for three years or less.[10] It was Kay-Shuttleworth's policy of encouraging at the same time both the training colleges and the pupil-teachers that really opened up the possibility of professional training. It provided both for a suitable intake into the colleges, and for the development of a curriculum which the inspectors could help to mould. By contrast the art colleges suffered from a lack of applicants who could draw, and some of the men's training colleges experienced difficulty in attracting boys who were suitably developed in their education. But the students who had been apprenticed in this fashion, and then completed a course as a

"Queen's scholar" could normally on the successful conclusion of two year's training gain a headship almost immediately.

Kay-Shuttleworth was effective in preaching the need of training colleges, and in the eighteen forties many were opened. By 1850 sixteen had been established, providing places for almost a thousand students.[11] The majority of the colleges were provided by the various denominations, with the Church of England well in the lead. An outstanding exception was Battersea Training School which was intended to provide for the needs of teachers for pauper children; this was especially the work of Shuttleworth and Tufnell and was established by private liberality. It was also the first attempt to establish such a school on a continental model, in this case Vehrli's school at Kruitzlingen.[12] The inspectors, like Shuttleworth, were looking both abroad and to Scotland for inspiration and guidance. The work of David Stow and the training colleges in Glasgow and Edinburgh were known and imitated.[13] But the curriculum in the English colleges was in part defined by the ability of the staff. As one inspector reported, the presence of "gentlemen in orders" from Oxford and Cambridge often meant that the colleges were compelled to use as a means of education for the students the subjects the masters happened to be qualified in.[14] Classics were offered to future poor school teachers. Standards and curriculum varied. In 1867 Matthew Arnold was reporting that uniformity in standards in the training colleges was very hard to attain, and he suggested the need of an examining commission.[15] As variations in standards between colleges and differences in approach are part of the history of the St Leonards training college, it is to be noted that the inspectors were finding this a problem elsewhere, and that it was inherent in the growth of the system.

But while in the forties training colleges were rapidly developing in the country, the Catholic body was entirely without any such facility in the British Isles. The bishops in England seemed at first to envisage that all poor schools would be entirely staffed by religious, nuns and brothers, and they dispatched a number of young men to Plöemel in Brittany to train for the freres de l'Instruction Chretienne.[16] Eventually these novices were moved to Brook Green, London to join Stokes, then secretary to the Catholic Poor School Committee, and later to become an inspector. This, in embryo was the future St Mary's training college for men, now at Strawberry Hill. But in its first years it was intended only for religious brothers, and was making little progress. Manning, the future cardinal, on his return from Rome in 1854 realized the impracticality of the episcopal dream, and wrote an anonymous paper in The Catholic School on "The Necessity of Training Schools for Lay Teachers". He urged the admission of laymen into St Mary's, and added that this "is only a transient provision to remedy a grave and extending evil".[17] This was obviously a sop to those who opposed the idea. Estimates suggest that at the time there must have been about three hundred lay teachers in Catholic poor schools, far outstripping the number of religious, but, unlike them, almost entirely without any professional training. Manning was right; "a grave and extending evil".

During the eighteen forties the Catholic body was struggling to gain some share in government grants to poor school education, and this meant that the question of a training college was in the background. But not forgotten. Sir Edward Vavascour swore to the Pope in person that he would build such a college at his own expense, but he died before anything was accomplished.[18] The negotiations which the Catholic Poor School Committee were making revealed that the Privy Council was very much against any grants going to Catholic religious teachers; thus the desire of the bishops and the intentions of the government were entirely contrary.[19] In the absence of any suitable college, and with little prospect of financial support, the Catholic Poor School Committee itself gave some financial help to support some student teachers in convents which were thought to have a sufficiently high standard so as to be able to train future teachers. This move in 1849 was to convents in Birmingham, Northampton, and to the SHCJ at Derby. It is not clear from the documents whether the students supported were actually novices or not.[20] The problem of grants to religious remained, and later Bishop Grant is found writing to Cornelia to instruct her that any students who wished to become nuns should not be admitted as novices until they had passed their final examinations.[21] The reason for his concern was obvious.

Among the first twelve Catholic schools in England to apply for the apprenticeship of pupil-teachers was that of the SHCJ at Derby.[22] And in 1848 there were five pupil teachers in the group who moved from Derby to St Leonards, so that in 1849 the Society received £125 for these students.[23] And at the same time the old priest at St Leonards was reporting that the Holy Child nuns were coming to found a training college.[24] It was presumably as part of the same policy that the CPSC salaried some skilled teachers to visit various schools, for a few months at a time, and on request, to demonstrate method.[25] So Miss Margaret Gaynor, officially described by the CPSC as an "organizing mistress" was with nuns in Birmingham in August 1849, and seems to have gone on to St Leonards before Christmas to stay there, perhaps through to September 1850. Some years later in June 1853 she herself was professed as a nun in the Institute of the Blessed Virgin Mary at York, and worked in the poor school there. She had at least one successor as an organizing mistress, a Miss

McCormack, who in 1852 was appointed head of the Galway Model School.[26] It would appear from this that Cornelia was known for an interest in teacher training, and at the same time was taking every opportunity of improving teacher skills in her own school.

The Catholic Poor School Committee was financed by an annual collection, but the first annual report indicated that the income of four thousand pounds was "not a fifth of what is absolutely required".[27] It remained an average collection, so that the burden of building training colleges as well as meeting all the other demands made upon the CPSC looked impossible. With various charitage helps it eventually undertook the financing of St Mary's College for men, and at the same time recognised that it could not provide a college for women. It was then hoped that one of the orders of nuns would accept the challenge and financial burden. A number of plans were under consideration, and the Sisters of Mercy at Nottingham were involved.[28] It was at this stage that Scott Nasmyth Stokes, since 1853 a second inspector to Marshall, supported Sister Emily Bowles in her venture in Liverpool, during Cornelia's absence in Rome. The financial disaster which that involved has already been noted. Perhaps equally important was the fact that Stokes had been involved in the matter, and although there had been talk of a grant from the CPSC none was ever made. In Liverpool the challenge to found such a college was taken up by the Sisters of Notre Dame de Namur. Stokes had approached Sister Aimeé in the autumn of 1853 but she had been withdrawn to Belgium. Eventually Allies, who had succeeded Stokes as general secretary to the CPSC was sent by the bishops to negotiate with the Superior General of the nuns at Namur, and eventually Mère Constantine agreed to undertake the financial burden of the foundation.[29] The nuns were concerned that if they provided the buildings and then accepted government inspection their ownership might be jeopardized. Significantly it was Stokes who called on the Secretary of the Committee of Council for Education to clarify this point. This led directly to the foundation of Mount Pleasant as the first Catholic training college for women. In December 1855 Stokes reported favourably upon the buildings there. He was well involved in the college which became a great success.

In spite of the Liverpool failure Cornelia Connelly had also responded to the appeal of the CPSC, and, encouraged by Marshall the senior Catholic inspector, she obtained permission from her local bishop, Dr Grant in September 1855 to found a second college for women for the south of England, and to begin building.[30] As this was to be on the St Leonards site it was necessary to gain the agreement of Colonel Towneley, the principal trustee of the property. As an encouragement the CPSC made a grant of thirty-one pounds, together with a public acknowledgement that a college was being founded at no expense to them. The temporary arrangement with the Sisters of Mercy at Nottingham was to cease on the opening of St Leonards.[31] Buildings were designed by W.W. Wardell for sixty students and were completed by the end of 1856. Private students paid twenty-five pounds per annum, pupil-teachers who had passed their examination came as "Queen's Scholars" on a government grant, and others who had not been so apprenticed as student-teachers might obtain a grant if they won a certificate of merit. The college was in operation by February 1856 according to the Diary kept by Mother Mary Ignatia Bridges,[32] and provisional authorization by the government had been forwarded through the CPSC with a covering letter from Allies on 2nd February.[33] At the time of the first examination of the 17th July the college was used as a centre for mistresses from other schools in the south who were seeking their certificate.[34] The regulations of the Committee of Council for

Education were causing increasing costs to the SHCJ, as they required total separation of the training college from the other buildings at St Leonards and asked for a separate kitchen.[35] But the July examination brought good results and praise from Marshall who reported that he was delighted with all that he saw.[36] So at the end of 1856 the annual report of the CPSC was celebrating the fact of three training colleges. They also gave a class list of the students in the Catholic Normal Schools from the Christmas examinations of 1856.

> Liverpool: First year students - 4 second class; 14, 3rd class; 2 schedule.
>
> St Leonards: First year students - 2 first class; 6, second class; 4, third class.
>
> Prizes for Drawing. Hammersmith, 1. Liverpool 0. St. Leonards, All received prizes for Drawing.[37]

Marshall's comment that "it must be regarded as very satisfactory" hardly seemed adequate. Interestingly he expressed his disappointment that Mother Lucy, who he says was sure of a first class, was actually rejected for not finishing her paper.[38] The CPSC recorded its thanks to St Leonards, and Allies, as secretary, wrote to Cornelia to say that compared with the other institutions, St Mary's,Hammersmith and Mount Pleasant, Liverpool, St Leonards did not receive a grant that was proportionate to its contribution in teacher training.[39] She herself in a letter of March 1857, summarized the progress to date; about three and a half thousand pounds in expense, and twenty-one students who were achieving good examination results.[40] An annual grant from the CPSC was agreed upon in April 1857, perhaps through the good offices of Allies. Such a grant had already been made to Mount Pleasant for the support of students there.[41] But Bishop Grant raised a problem that while St Leonards was undoubtedly the healthiest of sites, it had a major disadvantage for a training college in being so distant from a major centre of population, so that it was very difficult to find suitable schools in which the students could practise. And it was impossible to find Catholic schools, with the one exception of the small school which the SHCJ had on the site.[42] This tended to be about the hundred mark, though in 1852 it had 137 children.[43] Bishop Grant raised this problem in 1857, and it was one which a number of the training colleges shared. F.C. Cook's report of 1853 on the Church of England college, Whitelands touches the same difficulty.

> It is however, much to be regretted that the total number of children in attendance is barely sufficient to give the students practice in the art of teaching. There is no model school such as I have had elsewhere occasion to describe.[44]

By contrast the Wesleyan training school at Horseferry Road had five practising schools with a total accommodation for 2,339 pupils, and an average attendance, according to Cook, of 700.[45] The practice school was to prove to be the Achille's heel of the St Leonards college, an intractable problem.

The arrangement for examinations was that the Catholic HMIs appointed by mutual agreement between the Committee of Council on Education and the CPSC representing the bishops would examine only secular subjects. This principle of denominational inspectors had been established before the Catholic poor schools had become eligible for grant, and was basically due to Anglican influence. The corollary was that the various dioceses were to provide inspectors of religious teaching. But for the Southwark diocese Canon Wenham was one of the earlier appointments, and shortly before Christmas 1857 he decided to hold an examination of the training college at St Leonards. Bishop Grant thought that if this was to take place before the secular examination it would be seen by the students as of secondary importance. There was a mix-up about the date, and eventually Cornelia wrote to the bishop to protest against any invasion of the students' holidays.

> My Lord Bishop,
>
> You are mistaken in saying that I named the 29th. I have your lordship's letter before me dated Decr. 11th written to Mr Wenham in which you say "Will you write to Revd. Mother to fix Decr. 29th & 30th as the days for the Queen's Scholar. Ex.? etc.
>
> 2ndly Your Lordship is also misinformed or mistaken in saying that I left three letters unanswered. I left one unanswered, because I could not answer it. I did not know that I had the least right to detain the students after the end of their year, nor do I now think that I could have exercised any such authority.
>
> I named the 21 & 22 as the latest time. But I did my best to meet your Lordship's wishes, and the poor students and ourselves also have been kept in a state of anxiety or indecision for the last fifteen days and we and they have lost the repose of the holidays which we feel needful for us. Everybody has been expecting Mr Wenham all the day as it is the 29th, but we shall be equally ready next Monday. Theresa Hinds is the unfortunate girl we took in at the door about six months ago - Miss Hanmer's poor drunkard.[46]

This forceful letter both illustrates the problems of day to day administration, and also the firm character of the foundress. The final reference to a drunken Irish woman touches an incident which was to cause yet more rumours about the Society. The convent had befriended her, and she fell through an upstairs window without, remarkably, injuring herself. Rumour turned the principal in this incident into either a student or a mistress. The following year Bishop Grant was writing about another rumour which told of the Queen's scholars doing their own laundry and even providing some of their own food. Cornelia replied in detail and included a number of certificates signed by the students in an attempt to scotch the rumours before they got out of hand.[47] Then the drunkard story came back in another guise with the twist that a student had jumped out of an upper window, no doubt crazed with overwork. Victorian society fondly believed that the weaker sex were constitutionally incapable of sustained intellectual labour. Both Miss Buss and Miss Beale had this battle to fight, and as late as 1884 Dorothea Beale was trying to stop a rumour that she had turned a music room into a cell.[48] In the case of St Leonards Cornelia was able to reply to Bishop Grant that the current rumour was just the drunken Irish woman suitably adjusted in the telling.

In spite of the trials of administration the general report for the Catholic training colleges in 1858 was a success story in that all the students from the three colleges had passed. The report noted one disparity which was to remain throughout the century.

> At Liverpool there are 15 students of the second year; 8 obtained a first, and 7 a second class. There are 24 students of the first year; 19 rank in the first class and 5 in the second. At St Leonards there are seven students of the second year; five obtained a first and 2 a second class. There are 14 students of the first year of whom 6 rank in the 1st class, 4 in the second and 4 in the third. Every student in both these colleges has a drawing prize, while Liverpool has 1, and St Leonards 5, complete drawing certificates. Both at Liverpool and St Leonards the success may be said to be brilliant. Indeed in the whole list of male and female training colleges under the Privy Council Inspection there is nothing this year approaching to the proportion of high places attained by Liverpool, which with 39 students takes 27 first and 12 second, without one third class, one schedule or failure; or by St Leonards where of 7 second year students 5 obtained a first and 2 a second class.[49]

The disparity to which the report referred is the difference between the results in the female colleges, and the languishing state and poorer results of St Mary's college for men at Hammersmith. The crux of the problem for that college was the lack of suitably prepared candidates. In his reports to the Lords of the Privy Council Marshall also included the results of the religious examination of Canon Wenham, in terms of the prizes which had been given by the CPSC. Here St Leonards was the only one of the three colleges not to get a first class among the second year pupils. The prizes went twelve to Liverpool and six each to Hammersmith and St Leonards. But Marshall was also able to speak from experience about the quality of the teachers who had been trained at St Leonards, and who were working in his district. Using the expertise and the character of the teacher as his criteria he is high in praise of St Leonards.

> Applying these tests to the St Leonards' College, I may say, without hesitation, that they afford ample evidence of the skill and success with which that institution is conducted. A considerable number of the students are now teaching in various parts of my district, and especially in London - for the most part in large and difficult schools - and it is only due to them that they display with scarcely an exception very valuable qualities. They are especially remarkable for the personal influence which they exert over the pupils, and the improved discipline which always, as far as my observation goes, accompanies their presence in a school. I have hitherto seen no exception. Even the least capable of them is, in these respects, far more successful than the older class of teachers who had not enjoyed the advantage of a similar training. I must say, too, that in addition to the conscientiousness and activity which might fairly be expected from such students, they exhibit a simplicity of character, a freedom from pride and self-complacency and a religious earnestness of motive and purpose, which have often excited my admiration. Others have been much struck with the manifestation of these qualities and several school managers have expressed to me their cordial satisfaction in possessing the services of such teachers and their warm appreciation of the work performed by them. It is to be noticed also, that some whose abilities and attainments are only moderate, are quite as successful in the points referred to as others who have greater natural capacity. This is an important fact, because it indicated, perhaps more clearly than any other, the effects of the moral training which they have received. For this reason it appears to me to deserve special notice; and I congratulate the authorities of the training college upon this decisive proof of the effects of their teaching and example.[50]

Marshall would here appear to be identifying a special quality which was, in his opinion, the result of the training at St Leonards. He finds it in the combination of good instruction with successful moral training, and although he does not specify any further in this passage, elsewhere he speaks of the power of the example of the nuns. It was not so much the cramming of pupils who were naturally bright, but a genuine formation of character. It is necessary to query the extent of Marshall's observation. He wrote of "a considerable number of the students (of St Leonards) ... now teaching in various parts of my district". He is writing this at the end of 1858 of a college which had only opened in February 1856, and whose numbers were comparatively small, ten or fifteen a year. So if he is speaking only of the lay students trained at St Leonards, he is clearly exaggerating. But if he is grouping the nuns who had been trained at St Leonards since 1849 together with the more recent lay teachers, then he could have sufficient numbers on which to be making an observation. He is contrasting these with the teachers who had had little or no professional training, and finding a very notable difference. I think that he saw a close relationship between the professional training in the new college and the more traditional formation of the SHCJ sisters, and found that in both cases the personal qualities, and moral influence were very impressive, and that this had a measure of independence of the cleverness of the teacher in question. Some of the student teachers in the training college did eventually become nuns, and quite a lot joined the Society HCJ, so that Marshall is likely to connect the two groups of teachers. Certainly Marshall thought he had identified special qualities, and it was a subject to which he returns in his report the following year, 1859.

> They display, almost I think without exception, a certain simplicity and generosity of character; they

> work with zeal, but with calmness and composure; they are often singularly unselfish, and though encouraged and rewarded by the approval of others, seem to care more for the welfare of their scholars than for their own credit. I conclude that they owe this peculiar character to the teaching and example which they had the advantage to enjoy during the period of their training. The officers of the college to which this report refers have been successful in many ways, but in none more remarkably than in impressing some portion of their own character upon the students under their charge.[51]

Again Marshall is speaking of former students now working in his district of the south of England. He was a kindly man, and himself very compassionate on the poor; in 1849 he fed a school before examining the students.[52] But it is quite clear from his reports that he was not just sentimental; he could, when necessary, be very critical. And in the context of his reports this is outstanding praise.

To return to Marshall's 1858 report on the training colleges; there is a final point of interest. Seemingly a number of the colleges had expressed concern that the curriculum was to be changed to include some special industrial training as being specially suited to the poor schools. Marshall continues;

> No intelligent person denies the importance of such instruction in the case of female students; but some difference of opinion naturally exists as to the limits within which it should be confined, and especially as to the effect which it should be allowed to produce on the position of candidates in the class lists. If students who have acquired fair skill in needlework, but have not received any special industrial training, forfeit the place to which their general attainments entitled them, it is felt that injustice is done, and that in the long run decisions of the same kind, though they might promote a higher degree of industrial skill, would only do so at the risk of depressing the standard of instruction to a lower level.[53]

And with his interest in moral training as well as intellectual Marshall goes on to suggest that both could be compromised by injudicious stress on industrial training. It will be remembered that needlework at St Leonards almost existed as a hobby in a recreation period with one of the sisters reading a novel to the group. It is probable that the same system was operating in the training college, leaving the time table free for the more basic subjects, but at the same time providing these valuable skills. But Marshall went on to suggest that both the intellectual and moral training might be compromised, and again he has St Leonards in view.

> I have the less hesitation in expressing this opinion in connection with St Leonards Training College, because unusual skill is displayed there in all branches of needlework, from the simplest to the most elaborate; and if the authorities deprecate such an estimate of the value of domestic and industrial employment as appears to them to be undue and excessive, it is certainly not from any want of power to give instruction in both. I had lately an opportunity of examining a very large quantity of work produced in this institution, including not only the plainest sort, such as stockings, shoes, gloves and dresses, but even the most costly lace, and the most highly ornamental ecclesiastical vestments. I notice this fact, because it lends additional weight to the opinion expressed by the authorities, with which I cannot but concur, that the amount of attention to be given in industrial work may be safely left to their prudence and judgement, and that the skill acquired in it ought not to occupy a prominent place in the results of the annual examination.[54]

I think that the authorities of the training college at St Leonards looked back to the system which had already been established for the training of the sisters by the Society, and wished to preserve a measure of independence of government control of the curriculum to preserve their own characteristic approach. A glance at the Training School Journal shows the students not only performing plays like Macbeth, scenes from Homer, and farces like The Irish Tiger, but also making their own costumes. "The dresses were beautiful and suited to the different characters - being all cut out and made by the Sisters assisted by the Students".[55] This characteristic report of the students of the training college reveals the tradition of the Holy Child theatre, to use Cornelia's own phrase, as part of the life of the student teachers. A motive for the home made costumes would certainly be economy, as the Society was almost hopelessly in debt. But equally it was training. The excitement of preparing a play made all this a recreation, but at the same time very educational. The general picture of the training college students in the Journal shows them sharing a good deal of the normal recreations of the other schools, outings to Fairlight Glen, parties for St Patrick's feast day, celebrations of the feast days of some of the nuns. Certainly this close association with the sisters of the staff of the training college was one of the great strengths of the establishment.[56]

In his report for 1858 Marshall notices as the one solitary defect at St Leonards the "insufficient opportunity afforded for the practical study of school keeping, or, in other words, the unsatisfactory character of the practising school.[57] Marshall debates at some length whether this is a serious defect and notes that he cannot find it affecting any of the St Leonards teachers who are now in charge of schools. He concludes by leaving the question open. As a final thought he comments on the difference, now quite apparent, between the two colleges for women and the men's college at Hammersmith. His judgement on the lack of success of Hammersmith, and its cause is summarized in one sentence. "Our female training schools have the happiness to receive scholars who have had great care and attention bestowed on them during those all-important five years of their apprenticeship. Why is not Hammersmith in possession of the same privilege?"[58] The SHCJ in Preston actually had a dormitory full of pupil-teachers and gave them careful training, which provided good entrants. There seems to be no trace of any comparable provision ever made for boys, so that for the whole of the second half of the nineteenth century St Mary's college had great difficulty in finding suitable entrants. At one state, in desperation, the authorities had a preparatory school at St Mary's in an attempt to lift the candidates to an appropriate standard for entry.[59]

The early years at St Leonards training college had shown through the results three significant facts. It almost immediately produced excellent academic results, and the inspector Marshall and the CPSC were giving signs of great satisfaction. The results in drawing were quite exceptional. In November 1860 Cornelia was able to report to Bishop Grant that the inspector had said twice that it was the best female school he had examined in art.[60] And that not merely was the practice good, but so was the knowledge of the principles of drawing. Finally, and perhaps most significantly was the recognition by Marshall of the quality of moral formation which was given to the students in the training college, and the way in which this showed in their work whether they were gifted intellectually or not. The general picture here agrees with the aims of The Book of Studies, the writings of Cornelia Connelly and the general objectives of the Society it had developed in Derby and at St Leonards. What was happening in the training college was an extension of the general education of the Society rather than a separate and different project. This is an indication of the strength of the philosophy of education which the Society shared, and expressed in part in The Book of Studies.

The reports in the CPSC papers for 1859 again produced praise for St Leonards but there was a query about their results in the religious examination.

> St Leonards ... stands very high. Of ten second year students two obtain a first, four a second, and four a third class. Of eighteen first year students, 5 obtain a first class, nine a second and four a third. Every one of the 28 obtain a drawing certificate and five the higher memorandum of competency as a teacher of drawing. This college stands first of the forty-five in its drawing marks.[61]

But by contrast in the religious examination conducted by the diocesan authorities the Liverpool students had obtained seven firsts and sixteen seconds for their second year students as against three firsts, three seconds and four thirds at St Leonards. In their first year Liverpool had six firsts, twenty-one seconds and three thirds as against St Leonards with no firsts, seven seconds and eleven thirds.[62] This led to a flood of correspondence.

The chaplain, J. Bamber, wrote a number of letters to Bishop Grant giving his impressions as an interested party. He was responsible for giving the students instruction in Christian doctrine, based upon the catechism, and spent two hours a week on this. He added; "I have not thought it my business to enquire how the rest of the week was employed".[63] The first suggestion was that the St Leonards students were only getting four hours religious instruction in the week, compared with nine at Liverpool.[64] Later it was realised that this was incorrect, and that in fact there were five hours devoted to religious instruction when catechism, or doctrine, bible history and church history were all considered.[65] The chaplain cast envious eyes on the time allotted to drawing, though in the Society's philosophy this was part recreation, and he suggested that it should be given up entirely.[66] But at the time of writing he was aware that it was unknown whether the inspectors had found a weakness in any particular section of the papers, doctrine or sacred history.

The chaplain in his letter to the bishop then added;

> If then the Examiners' report on Sacred History is decidedly more favourable than their report on the Catechism and the lesson to a class, it would be a sign there is some fault in my teaching which - if I continue my lessons I should like to correct. I had time to cast a hasty glance over the Catechism papers before they left St Leonards, and I acknowledge I was very much disappointed with them. They were much worse than the papers which had been worked for me as exercises. I am convinced that the amount of time to be given to religious subjects is the main point to be attended to; but there were special circumstances this year which made the result worse than it would otherwise have been. After Mr Marshall's dismissal a notice was sent to Rev. M. which seemed to imply that Mr. M's report of his examination at Midsummer would not be received and as Mr Stokes fixed his visit for the week immediately preceding Mr Wenham's Examination, the children were at the same time pressed with the preparation of both, which no doubt made them write worse papers than they would otherwise have done. They were obliged to leave off their practice in giving lessons which they were doing in my presence and with great corrections and when the day of the examination came they were to a considerable extent without the immediate preparation which tells so much on an examination. I don't think any blame can be attached to the children. They were always attentive at my lessons and from all I have seen of them I have a very high opinion of their goodness and virtue.[67]

In spite of Bamber's references to children in his letter, he is referring to the senior students in the training college, and while he offers a number of theories as to what had gone wrong, he is confident of the goodness of the students. It will be noted that he himself was not satisfied with the papers which they had done. The examiners were Provost Cookson and Canon Wenham already mentioned. Clearly the whole question of the timing of the religious examination had again run into the sort of problem about which Cornelia had once written to Bishop Grant.[68] It was further complicated this year by the resignation of Marshall, who was virtually dismissed by the Council, and while his replacement Lynch was awaited, Stokes of the northern district was responsible for the secular examination.[69] But behind the immediate questions of the examination was a basic difference in philosophy between Mount Pleasant, Liverpool and St Leonards. Cornelia's system was very much that of trusting people, encouraging them to accept responsibility, and she saw this as the best form of moral training. In the training college, as a form of tertiary education, this included leaving the pupils to do their own homework and revision. The whole aim of her policy was not instruction but formation. To achieve this she was giving them more freedom than was usual in Victorian days. Certainly she regarded religious instruction and knowledge of Christian doctrine as very important, but she saw the moral formation of the teacher as a responsibility of the college, and as of equal importance. Marshall had already commented on the outstanding success which the college was achieving precisely in this sphere. And the final thought of the chaplain to Bishop Grant echoes this; "I have a very high opinion of their goodness and virtue".

Cornelia herself wrote to Bishop Grant on the 18th December to deal with a number of issues which he had raised. The health of the pupils was one; and she reminded the bishop that the children had five minutes recreation in the open at the end of every hour. The school work is not allowed to become a task, and she adds that "the pleasure they take in their occupations is the proof of their not being over taxed".[70] Finally in this letter Cornelia turned her attention to the matter of the time allotted to religious studies.

> With regard to the hours of the Religious Study I have only to say that it has not been limited. And I need not add that as we should miss the chief aim of our life, and the end of our vocation in a great

> measure, if we failed in making Religion the highest and dearest object we have in view, it is not likely that the children would be swayed in rather aiming at the Secular knowledge than in the Study of Religion! - I will enclose the hours and also those of Hammersmith and Lvpl if I can find them in the minutes. Their Meditations, H. Mass, - Ex Con. Rosary, Adoration & extra prayers, without any other study, would always prove how far we value Religious training and knowledge above every other Science.[71]

It will be noted that Cornelia places "religious training" first, which is how it ranked in her philosophy; knowledge was a part of the total religious formation, but the training included many things, and Cornelia lists some of the religious practices which contributed including the daily examination of conscience (Ex Con.) prayers and Mass. This letter was passed by Bishop Grant to Canon Wenham, with a query about the amount of time for religious studies. His comment in return was that "the only refutation of the latter charge (of which I have received patent proof) that the R Mother brings is that their whole object is to make the students devout and good. What has that to do with it?"[72] This would suggest that he was not considering the distinction between religious instruction and religious formation. Significantly, though Cornelia did not choose to make the point, the Jesuits in educating their pupils in the sixteenth and seventeenth centuries did not choose to spend long hours over the details of catechism questions, compared with the time spent on the study of the classics. The actual religious instruction was comparatively short, and their aim was to make the whole school a Christian society appropriate to growing boys. A great deal of the work of religious formation was done outside of the classroom, especially through the sodalities. Cornelia from her use of the Ratio studiorum would know something of this, and was certainly following the general system. She appreciated the great importance of the sodalities, and they were a part of her training. She had also developed her own philosophy of art and worked it into the school, but in part as a recreation. Both art and needlework were often done after school hours in a period of quiet recreation with one of the nuns reading a novel to the pupils. So Cornelia reminded Bishop Grant that drawing was "more of a rest and recreation".[73] The curriculum and the timetables of a number of the SHCJ schools show that this was an accurate description rather than an eloquent gloss. In the same sort of a way in the boarding schools the religious lessons were towards the end of the day, and instead of these seeming to the students as a final burden, they were regarded as something different, special and worth looking forward to.[74] It was an unusual approach, but if the memories of past students is valid, it worked.

To Grant Cornelia continued to defend both her students in the training college as well as her curriculum. "The students last year called themselves walking Bibles, and we all know that they studied very hard and thought they were thoroughly prepared for their Examination".[75] She then introduced a new dimension into the problem by adding that "if we have the same Examiner and the same circumstances this year we could not hope for any change of results".[76] The circumstances she refers to were the conflict between the secular and the religious examination. But what about the examiner? In a letter written probably four days earlier to the bishop Cornelia had argued that the results did not relate to the pupils, their work and their ability at all. It looked, according to Cornelia as if "the Examiners had rather cast lots upon the papers than examined them", with the result that some of the best students had been failed and some inferior girls given a first.[77] As the ecclesiastical examiners were not professional teachers it is possible that their decisions were erratic. It would seem from this letter of Cornelia's that Bishop Grant had suggested that she write to the superior at Mount Pleasant, Liverpool. She replied to Grant.

> I began to write to the Rev^d Mother at the Lp^l Training Col when my good angel whispered to me in thought, you had better let that alone at present and tell the Bishop that it is not worth while to mix up our arrangements with theirs, which might give another handle to M^r Stokes who is not our friend.[78]

The reference to Stokes, in view of what later transpired, is significant. It will be remembered that he had encouraged Emily Bowles in her attempt to found the first training college at Liverpool, a venture which ended in such financial disaster that it nearly bankrupted the Society. When Marshall resigned Stokes for a while took over his district too, and in his report on St Leonards, while he admitted the quality of the teaching, his is the first to offer a series of criticisms. He was identified there as someone who was unfriendly to them in contrast to Marshall who had been a great friend. Moreover in a few guarded letters in June 1857 Marshall himself had suggested some bias on the part of Stokes, and Allies from the CPSC in June 1861 wrote to Cornelia; "I don't think M^r Stokes means to be unfair; he can't help being so sometimes. M^r Lingen had certainly no notion there was any feeling in M^r Stokes' mind in favor (sic) of one Training School over another".[79]

There is in the Training School Journal an unfavourable account of the religious teaching at both Liverpool and St Leonards, which may be dated November 1861, and which might be the work of the chaplain who had replaced Mr Bamber, a Rev. Searle. He or an anonymous writer was very critical.

> I must candidly confess that after rising from the reading of them, and without any consideration but one - viz. that they are the religious examination

papers of Students who have finished their 1st Year in Training Schools - I am disappointed and surprised.

The questions are remarkably easy and such that you might justly expect any intelligent girl who has attended School with regularity and worked her way to the 1st form to answer well in writing - at least I am sure that if I had a Poor School under an intelligent and painstaking Mistress I should expect as much and I think I could secure it ...

I find that many of the Papers are apparently written without any care or thought and full of all sorts of errors; those that are better give me the impression of a mere writing off from memory of previously prepared lessons on Purgatory, Scandal, Extreme Unction and the Infallibility of the Church.

Some of the others contain mistakes so gross that you would request your mistress to penance any girl, rather advanced, who made them. And almost all the papers on the Infallibility of the Church impress one with the idea that the Pupils have been under the influence of Teachers who are thoroughly imbued with Gallican principles, whilst I notice that the few who take the question of Matrimony say quite coolly that the parties are the Ministers of the Sacrament; an opinion, which however true I have always taught should for very obvious reasons, be kept from the knowledge of the people.

I can only say then that in my opinion the actual results of the religious training of the 1st Year Students at Liverpool and St Leonards are poor, and most unsatisfactory, and show that we need indeed a revised code of rules to guide us in this matter. In addition to this, I do think that there is room to doubt whether a mere written Examen does fairly represent the actual knowledge of the Students. I think that to arrive at this you are bound to have a viva-voce one too. I think that many of the Students by judicious questions might be made to manifest a more real and accurate knowledge, some excel in writing, some in speaking, but a junction of the two would probably put you in possession of more reliable data for arriving at a just conclusion.

I do not know what you think, but I have quite a horror of teaching those who are to be the Teachers of our Poor Schools, Theological opinions in place of the sound and obvious doctrines in keeping with the spirit of the living Church and practically realized by the mass of the Faithful.[80]

The comments are especially interesting as covering both St Leonards and

Liverpool students, and in this context the writer does not choose to criticise one more than another. If it is Father Searle taking stock of the situation as he began his own work teaching in the training college, then he is in effect criticising Fr Bamber who had been previously responsible for the doctrinal instruction. Bamber was perfectly correct in his teaching about marriage, and who are the ministers of this sacrament. It would be remarkable if he had been teaching a somewhat Gallican attitude at St Leonards as the significance of the large work of Rohrbacher in twenty-nine volumes which the college had was that it was the first major ultramontain history produced in France.[81] The thought on oral examinations was one which Cornelia had considered. She had written to Grant in December 1857.

> We should prefer having only a written examination or if your Lordship advises or desires more that it might be simply in witnessing a lesson given by the Students on the articles of the Creed or on the Sacraments. This w.ll. embrace all that would be necessary for a certificate bearing on their future duty as Schoolmistresses.[82]

What is to be made of the dispute over the religious teaching at both St Leonards and even Liverpool? The public results of both colleges remained good. At St Leonards twelve second year students took six firsts and six seconds, while the fifteen first years took four firsts, ten seconds and one third.[83] This at least suggests the possibility that the ecclesiastical inspectors who lacked an English university education and the wide experience of examining throughout the country like the HMIs were not good examiners, and were perhaps unrealistic in their expectations. Possibly they were looking for the sort of papers which they had produced in seminary days. This would explain Cornelia's comment to Grant that the results looked as if the examiners "had cast lots on the papers" with indifferent students getting first in religion and bright students being failed.[84]

In a letter of acknowledgement to Canon Wenham who had sent certificates (which arrived) and a medal for J. Ryan (which had not yet appeared) Cornelia also raised other questions about the religious examination.

> With regard to the result of the Examination I am convinced that the inferiority is not because of any deficiency on the part of the Students or their course of study. If it is true that three of the Inspectors or Examiners belong to the Diocese of Liverpool and only one to this Diocese, it would not be surprising that Liverpool should carry the prizes - If it is also true that the questions are drawn up by the Liverpool Priests, who are in constant communication with the Students, and still more if the one who draws up the questions teaches or gives lectures to the children there could of course be few choices in favour of St Leonards, or even if the Liverpool Priest draws up the questions he more or less has communication with the School, and draws the questions to suit the lessons they have learned by heart - which no doubt would cause a great similarity in the writing (composition) (sic) a fact which would be sharply criticised, if not condemned, in an Examination held by the Council Office Examiners. I think that justice demands quite as strict a secrecy as to the questions in the one as in the other, and if a Liverpool priest draws up the questions for their School, one equally interested ought to do the same for the St Leonards School. The very fact that the Liverpool papers are so much alike would condemn them at the Council Office, even supposing there was not a possibility of their being particularly prepared for certain questions.
>
> You must not suppose that I intend to cast any imputation upon any one - I do not - but the facts certainly deserve investigation, and I trust they may have it, for the satisfactions of everyone, and for justice sake.
>
> With the felicitations of this holy season.[85]

Unfortunately Canon Wenham either did not reply or it has not been preserved. In the correspondence both the chaplain and Cornelia are loyal to their students. The question of a predominance of Liverpool clergy working as school religious inspectors, and also instructing in Mount

Pleasant, Liverpool does not admit of total resolution. It is difficult to identify all the religious inspectors and even more so to find out who drafted the examination papers. However it is known that the priests associated with the Liverpool training college during its early years included chaplains from the pro cathedral church of St Nicholas. Identifiable among these clergy is Provost Cookson who was both a diocesan inspector and a commissioner for the diocese on the Catholic Poor School Committee. When he left Liverpool for a parish at Fernyleigh, near Preston, he continued to visit the college regularly. Other cathedral priests were Canon Carr and Canon Wallwork and Dr Roskill. Both Dr Roskill and Canon Bennett of St Oswald's parish certainly helped in the teaching of religion in the college, while Monsignor Kershaw, a school manager, did readings from Shakespeare and Tennyson to help the students prepare for inspection.[86] It is not possible from the sources to place exact dates on all this interest, but the overall picture is one of real support by the local clergy for the training college; it was a form of support which the isolation of St Leonards made impossible in the south. There the clergy visits were mostly on the occasions of plays, concerts and prize givings. The Liverpool training college certainly benefited from being in the centre of one of the largest Catholic populations in the country. While the first and most obvious benefit was an abundance of schools to practise in, but also a more immediate supply of pupil teachers, and this support from the local clergy. Without suggesting that there was any deliberate collusion, it seems probable that the attitude of the examiners about questions could be known to the Liverpool students. It also seems that the educational philosophy in the training college was one of well drilling the students in the subjects with a lot of memory work. By Victorian standards Cornelia would be regarded as lax in this approach as she preferred a more intellectual formation with less stress on mere memory work.

The effect of this controversy upon the college was that at Bishop Grant's direction the time given to religious instruction was increased to nine hours a week, at the expense largely of the drawing programme. It is most unlikely that Grant understood to what an extent art was an integral part of Cornelia's philosophy of education; like most Victorians he would regard it as just an accomplishment. The training college in Liverpool had to fight to keep any drawing on the syllabus, an indication that the subject was not highly regarded by the diocesan inspectors either.[87] Also under the same episcopal pressure the method of teaching religion was changed somewhat towards more conventional lines of far more memory work. While Cornelia had not neglected this, her philosophy had always been to try to develop understanding and to avoid mere rote learning. A memorandum from the Training College Journal shows the revised method of instruction adopted reluctantly at the insistence of Bishop Grant. It dates from 1862.

> <u>Xtian Doctrine</u>
>
> 1st. Each Sister who teaches Doctrine is to hear the Students repeat 2 pages of the Abridgment Catechisms by rote before giving the lecture.
>
> 2. The Second Year Students are to go into the Practising School every Sunday at 11 (crossed out in pencil and amended to 2½) and one of them give a lesson on Doctrine at which all the other Students will be present, the Sisters who teach Doctrine and the Mistress of Method. The remaining half hour will be devoted to the criticism of the lesson.
>
> 3. On a Sunday for half an hour the Students will be questioned on the subject matter of all they have been taught during the week in Doctrine and Scripture History alternatively, and made to repeat what they have learnt by rote.

4. On the 1st Sunday of every month at 11½ the Students are to hold circles to catechise and interquestion each other on all they have learnt during the month, at which Reverend Mother, Mr Searle and the Sisters will be invited to be present.

5. In the afternoon of the same day they are to write papers on the same subject from 2½ to 5.

6. Every Sunday from 4 to 5 is to be devoted both years to the Life of Our Lord and the 2nd year on the Acts Ap. besides. The hours for Sunday are as follows.

9 Holy Mass
10½ Learn Gospel
11 Practising School
11½ Criticism of the Lesson
12 Repetition of the Doctrine learnt during the week
12½ Conference
2½ Drawing
4 Life of Our Lord
5 Reflection
7 Letter writing.[88]

The poor students under this pressure can hardly have seen Sundays as days of rest; perhaps Cornelia's claim that drawing was a recreation did prove to be true and bring some relief to them. The whole incident indicates the constraints under which the Society worked, and how vulnerable Cornelia's philosophy was to outside interference.

The final opinion of the new chaplain, Mr Searle, in two letters was to support St Leonards strongly. He too makes the point that the uniformity of answers in the Liverpool papers was a "mere mechanical one" and he described both Canon Wenham, the diocesan inspector and Stokes the HMI as both "inimical" to St Leonards on the grounds that it lacked a large school in which the students could practise.[89] Certainly this controversy served to highlight the lack of adequate places for practice, but it was certainly not the only factor involved. Stokes' interest and heart was in the Mount Pleasant college, and there he was known as a great friend, whose interest continued even after the college was no longer his responsibility in any way.[90] He seems to have had a bias against Cornelia Connelly since the affair of Emily Bowles and the first attempt at a training college in Liverpool, and this is a subject which must be considered shortly. But perhaps most basic to the dispute was Cornelia's own philosophy which placed more of a premium on intellectual and moral formation as against memory work; the controversy brings this aspect of her curriculum to the fore. She suffered from being in advance of her time, and her approach to education in this respect is more like that described so classically by Newman in his Idea of a University. The Victorian stress on memory work was something of a hangover from the monitorial method; that system might be declining by the mid century, but some of its assumptions as to how education was to be given still remained.

In March 1862 an "affair" came to light which was to threaten the existence of St Leonards. Lingen, as secretary to the Committee of Council on Education wrote to Allies, secretary to the CPSC, and claimed that at St Leonards Annie McCave, a student, had been presented to Stokes under a false name. Lingen concluded his letter; "My Lords (of the Privy Council) do not doubt that your Committee will agree with them in thinking that the Principal cannot under such circumstances, continue to hold any Office in the College at St Leonards".[91] The principal was Cornelia Connelly. The CPSC were not disposed to agree without investigating the allegation.[92] Lingen had made no investigation, and after the CPSC had made an enquiry they concluded that the allegation was false. The details of the Annie McCave affair produced a large correspondence which may be summarized.

McCave was a pupil teacher from Wolverhampton who had failed to gain a Queen's scholarship, and as her mother was a widow Cornelia had taken her into the college as a private student, paying her own way. She registered under her mother's maiden name, and Cornelia explained this as heing done "to avoid the reproach of other failures who had been refused entrance on the grounds of all failures being prejudicial, and I was induced to take Annie because her mother was a Widow and much grieved by having Annie on her hands".[93] McCave was at St Leonards when Stokes came for the examination in June 1861, but according to Cornelia was never presented for examination, and according to Sister Agnes Orr, the vice-principal, she was actually out in the fields, along with some other girls who were not taking the examination, and all were making point lace.[94] Stokes claimed to Lingen that she had been presented, but in a more detailed letter Cornelia gives a different account.

Before going to the training school, a separate building, and while still in the reception room of the convent, Stokes raised the question of Annie McCave being in the college under her mother's name. He was told that when she was eventually entered for any examination, "when sent in officially" her own name would be given.[95] Stokes, according to Cornelia questioned the propriety of this, but Cornelia maintained her right to take private students, and to register them under their mother's name if this was pastorally advisable. There was a witness present at this interview, Father J.G. Rowe, of the London Oratory, and at the time principal of the Hammersmith college. Armed with this information the CPSC checked on the list of those presented for reading in June 1861, found fourteen listed, all of whom took the examination, and no sign of either Annie McCave or A. Kavanagh, her other name.

Allies of the CPSC also checked with Sergeant Bellasis as to the legality of registering in a mother's maiden name, and with the legal opinion, and the documentary facts, he wrote to Lingen asking for any evidence that the principal at St Leonards had ever presented a candidate under a false name.[96] When no reply had been received after a month, he wrote again. Then in a reply of 23 April 1862 Lingen changed his ground; "The act imputed to the Principal consisted in designating Annie McCave by another name than her own to the Inspector in June 1861".[97] Previously it had been stated that the candidate was actually presented. With the evidence of the lists, which show no Annie McCave in the June lists, and her present under her own name for reading in November, examined by Morell, and signing the written papers correctly in the December, Allies concluded to Lingen; "This Committee trust that My Lords will coincide with the opinion which they have formed that the Principal is exculpated from the charge brought against her".[98]

The whole CPSC were supporting Cornelia Connelly and so in effect challenging the account given by Stokes. In the correspondence which the McCave affair created it eventually emerges that before coming to St Leonards Stokes knew of Anne McCave; she had been under his inspection as a pupil teacher at Wolverhampton; he knew she had failed her Queen's scholarship for Liverpool and that she had entered St Leonards as a private pupil. He gave a different account of what transpired in the convent reception room, claiming that he corrected the reading list and "positively refused to admit McCave to the reading examination by any other name than her own". He goes on to say that in December she was detected copying from another student.[99] This is a copy of Stokes' letter in the SHCJ archives with "false" written twice in the margin. The handwriting cannot be identified. By January 1862 Lingen had written again to Allies; "I am directed to inform you that the papers worked by Cornelia Lyns and

Annie McCave, who lately attended the above named Institution as Candidates for the Queen's Scholarships, afford indisputable evidence of copying".[100] Lingen, be it noted, argued from internal evidence, while Stokes claimed that McCave was detected at the time. Cornelia dealt with the allegation in a letter to Grant. "Her arithmetic papers (sic) (which I hear was examined by Mr Stokes) was copied by Cornelia Lyns, another Candidate, who acknowledged the fault".[101] But by this stage in some quarters Annie McCave was type cast as the guilty party. With regards to what actually happened in the convent reception room, the evidence of Allies suggests that Fr Rowe, who was present, supported Mother Connelly's version, and at first because of this Allies thought that the Privy Council would have to withdraw their allegations. "I cannot but think if they had any heavy shot to deliver, they would not have wasted ten days. Fr Rose, however, says, they will wait a month for the pleasure of tormenting people. Go on therefore with your prayers".[102] Much less optimistic was a memorandum from the chaplain Fr Searle who saw a government plot to reduce the number of training schools. He dismissed Lord Granville as "a weak official hack of no real ability, quite at the disposition of his subordinates", and thought Lord Palmerston "so exasperated with Catholics that he would willingly hail anything calculated even in a small way to annoy and put them down".[103] He was writing in the summer of 1862 when the changes in the grant system to training colleges were creating more pressure, with no grants at all for any candidate who had not had two years training. Allies reported general gloom among the heads of training colleges, and a move that they should all act together against the forthcoming minute.[104] The Catholic community, being particularly vulnerable, saw this as a sectarian attack upon them.

In the very considerable correspondence about the Annie McCave affair perhaps one of the wiser comments came from Bishop Grant. He suggested that Stokes, a busy inspector, mistaking a hypothetical instance for a real one, when referred to by the Committee of Council half a year after the event, failed in memory and made a statement which was objectively false.[105] Stokes was visiting half the country, and the incident only came to the attention of the Education Department when Lingen raised a query. So Stokes' evidence does not have the immediacy of a report made just after the event. Stokes would have none of this and wrote to Canon Wenham that "my serious remonstrance was the only reason for her being omitted from the nominal list" and claiming to be quite certain of this.[106] At this stage of the investigation the accusation was supported by Stokes and Lingen (who had failed to investigae it), while on the other side there was the contrary evidence of Cornelia, Sister Agnes Orr, and the support of Allies (now confident after his investigation), Bishop Grant and various representatives of the CPSC. Indeed a deputation from the Committee, consisting of the chairman, the Hon. Charles Langdale, Lord Petre and Sergeant Bellasis, as their legal adviser, sought to confront Lord Granville as President of the Privy Council on Education.[107] They were all convinced that the charge against Cornelia was ill-founded. But despite the deputation the Privy Council continue to press for the resignation of the principal.

Various opinions were expressed by those associating with the CPSC as to whether Cornelia should resign under this pressure. Allies regarded it as a point of honour that she should remain. Cornelia eventually proposed Mother Mary Theophila Laprimaudaye as principal provided that Stokes should not in future visit the college. She also thought it desirable to make the college free of dependence on government aid as soon as possible. Bishop Grant objected to a decision of the Privy Council taken without any investigation and refused to let Cornelia resign before he had made his own investigation. In one of the letters which resulted from this Stokes seems to have admitted that Annie McCave had never been submitted in writing as a candidate.[108] But by this time both Allies and Cornelia were convinced that the Privy Council desired to suppress St Leonards to reduce expenditure in the era of the Revised Code and payments by results, and thought that they were really concerned about the lack of an adequate number of practice schools, and used the incident of Annie McCave as a lever. As a final twist in a conference with Bishop Grant and Canon Wenham, Stokes pointed out that even if the training college was withdrawn, it would have to continue until the Christmas of 1864.

As he is a protagonist in this affair something more should be said about Stokes. After early education at St Paul's school he had studied at Trinity, Cambridge and obtained a BA with honours in 1844, and was later called to the Bar. It was probably in 1847 that he became a Catholic, and in response to the encouragement of Fr Faber of the Oratory he was appointed the first secretary of the CPSC. In an attempt to found a men's training college he was in correspondence with the Abbé J.M. Mennais, and was eventually involved in sending a number of young men to Ploërmel to study for the brotherhood. They settled in well, and one, John Kennedy, wrote an enthusiastic account of their life in the college to Stokes which was printed in <u>The Catholic School</u>.[109] But eventually it was proposed to bring them to England, and they settled in Brook Green House which at the time was also the offices of the CPSC. Frère Mélaine came as their superior, and when Stokes moved in with them there was trouble. The superior regarded himself as directly responsible to the Abbé La Mennais, and both he and Stokes wrote to Ploérmel complaining about each other. Frère Mélaine claimed that all the brothers were upset by Stokes "et par le mauvaise grâce que Mr Stokes a mise à me communiqués ce que vous lui disiez relativement à l'approbation de la congrégation".[110] The ultimate outcome here was that the Rev. John Glenie was appointed principal of St Mary's, Hammersmith, and once Stokes was out of the picture more tranquil days returned.

His work as an enthusiastic inspector has already been noted. He made important contacts both at home and abroad, and helped to found Mount Pleasant college in Liverpool. As early as 1857 there is some evidence of bias against St Leonards on his part in three letters of Marshall.[111] By 1861 Cornelia is writing to Grant that "Mr Stokes is not our friend".[112] Allies also noticed this, and commented on a correspondence between Stokes and another inspector, Morell, that "it seems to me an illustration of his bad spirit towards you". Stokes eventually denounced Morell to the Privy Council and forced his retirement. Although there may have been technical irregularities on Morell's part, the opinion of a recent study by Pamela Horn is that this was relatively trivial, and the whole affair is of interest to the historian as a part of the situation which led to the resignation of Lowe after the House of Commons had debated the issue of his mutilating the reports of the HMIs.[113] Significantly, after his dismissal in 1864 Morell secured an appointment as inspector of Catholic schools from the Royal Commission of the Patriotic Fund, with the approval of the Committee of Council.[114]

Stokes seems to have been a dangerous protagonist. Commenting on the letters between Stokes and Morell Mr Searle writing to Grant, commented on the "curious animus" of Stokes and thought it looked like a "pretty little conspiracy".[115]

The affair of St Leonards was discussed at the general meeting of the CPSC in June 1862, and the comments of Stokes were considered. In correspondence with Morell he had gone further than before. In a letter of 31 May he regrets to learn from Morell "that the practice of returning papers for correction of mistakes in spelling has been uniformly followed at St Leonards". Allies, for the Committee, protested that the attribution of such a statement to Morell's letter was a"pure invention of his own put in the mouth of a colleague". And he further protested that Stokes' remark that he will always "feel and show preference for honour over fraud and for sound institutions over corrupt ones" was an unjustifiable slur on St Leonards.[116] A letter of Cornelia's throws some light on the accusations seemingly, from this letter, made against both Morell and Lynch.

> There is no doubt that Mr Morell and Mr Lynch were most exact in keeping to the rules established by the P.C. which were read daily before the Exam. began; but Mr Morell and M.L. could best answer whether they admitted any return of papers that might in any individual case bring them under censure. I do not believe from all I have heard that Mr S (tokes) himself is one half as exact in keeping his rules, and one of our students says he left the school (liverpool) last year for more than an hour and ½ while the students were writing their papers & we c^{d} also prove that Mr Stokes had left the papers with the pupil teachers as Mr Morell did.[117]

When the Privy Council read the letters between Stokes and Morell according to Allies they reprimanded the latter gentleman.[118]

Clearly Stokes was a strong character, and a rough person in a dispute. One significant fact which he lets slip in the correspondence is that he knew about Annie McCave before ever he visited St Leonards.

Because of this I consider that Bishop Grant's hypothesis is the correct one. Stokes had "mistaken a hypothetical instance for a real one" and in the half year between the incident and the query of the Privy Council he got mixed up. Cornelia in a letter notes that McCave was in correspondence with some of the Liverpool students and she adds "In fact I heard that he joked over it with the Students at Liverpl to catch something against us".[119] Stokes' animosity towards Cornelia Connelly need not obscure the good work he did in other spheres, but his character appears as something worthy of Strachey's Eminent Victorians. The projects he approved of he supported with enthusiasm. Sister Mary of St Philip of Mount Pleasant said of him in 1870 that "he had watched over the College with such unflagging interest, his guidance had been so helpful, his counsels so judicious, that to lose him now was like parting with a pilot just as we were launched on an unknown sea".[120] Liverpool was definitely his college. He served as a member of the Royal Commission on primary education in Ireland from 1868-70, and was a frequent writer on educational subjects especially in The Tablet, The Rambler and The Catholic School.[121]

The moment at which Cornelia handed over to her successor as principal of St Leonards training college is a suitable time to consider the college which she had established and her general attitude to teacher training. Like the whole structure of The Book of Studies the college benefited from Cornelia's wide experience and her eclectic approach. All the teaching orders were aware of developments on the Continent. For the likes of Kay Shuttleworth, Dorothea Beale and Matthew Arnold visits abroad were voyages of exploration in foreign lands in quest of inspiration to help to deal with the educational problems at home. For many of the teaching orders it had rather the appeal of returning home.

The Sacred Heart nuns could look to their enormous expansion in France and elsewhere, and the solid tradition which they had so quickly established. Home for the Notre Dame nuns of Liverpool was Namur, and they too had a tradition and had already acquired skill in dealing with governments, accepting grants and preserving a measure of independence.[122] Echoes of the traditions of the teaching orders are to be found in The Catholic School, which not only described some of the orders but also commented upon Jacolot, Père Girard, Pestalozzi and Stow.[123] Cornelia had considerable knowledge especially of the Jesuits and the Sacred Heart nuns, and was quick to add to this with help from the opportunities offered. So in 1856 she wrote to Marshall; "Will you bring your beautiful lecture with you that I may copy it out for the use of our Sisters?"[124] She also had in the Jones' library the life of Bernard Overberg who had founded an important normal school at Münster before becoming rector of a seminary. Significantly his biographer says of him that "there is not the slightest reason to accuse him of leaving the heart untouched".[125] He was not concerned merely with intellectual instruction. It is not clear to what extent Cornelia's concern for moral training was based upon her own instinct, or The Spiritual Exercises or authors like Crabbe and the other manuals which she collected. What is certain is that she was seeking to develop moral responsibility through giving more freedom than was usual in her day to the students. It was a bold philosophy in Victorian days.

In view of Michael Berry's comment that there is a "peculiar lack of published material" about the institutions responsible for the training of teachers in the nineteenth century some further account of the St Leonards college is called for. The course was from Christmas to Christmas, and not the ordinary academic year. Entry into the college normally followed five years as a pupil-teacher and the successful completion of an examination to gain a Queen's scholarship. This would meet the basic cost of the training. A number of nuns took the examination to qualify as teachers without having studied in the college. Initially the Committee of Council offered a range of subjects in which students might qualify, and other certificates could be obtained. Since 1856 the Department of Science and Art in Kensington had been combined with the Committee of Council to form the Education Department. But there were still special inspectors in art, and Bishop Grant was concerned at non-Catholic inspectors coming into St Leonards, and asked Cornelia about them on more than one occasion.[126] He saw this as breaching the agreement about Catholic inspectors for Catholic schools. Individual training colleges had at first the opportunity of developing something of their own approach, and for Cornelia this clearly involved the development of art, which was eventually attacked. Many of the inspectors were interested in the curriculum in the training colleges, and of them all Henry Moseley did most to shape it. Attempts were made to establish science as an important option, under the three headings of natural philosophy, botany, and agricultural chemistry, and in this respect Moseley was able to report with enthusiasm of some of the work in the colleges, as in his comments on Chester in 1845. But in 1857 the Education Department began to restrict this. A letter of Lingen to the principals of the colleges reduced science to a fringe subject, against Moseley's efforts to make it a core subject.[127] It was only between 1870 and 1880 that science really came back in response to a series of text books originating from the Education Department and firms like Macmillan, Collins, Longmans Green who all produced works which met the requirements of the old South Kensington syllabus.

The training college students could offer specialized subjects such as Latin, Euclid, algebra, mechanics, book keeping, domestic economy. From the wide range of possibilities Cornelia chose at St Leonards to present courses in the principles of teaching, which she lectured herself, English grammar, Latin, English literature, geography, history, maps, the elements of algebra, general science, arithmetic, French, Christian doctrine, bible history, ecclesiastical history, music and drawing.[128] This range was covered by seven nuns and the chaplain, initially John Butt, then Mr Bamber and later Mr Searle. A later list of the courses drops both French and Latin but adds needlework.[129] A request in June 1861 from the Education Department asked for a time table made out under the subjects of instruction and showing precisely the hours per day and per week devoted to the subject, and also the number of teachers employed.[130] A summary of such a schedule from about 1857 gives for a day; lectures, study and composition, 8 hours; French and music, 1; drawing, 1; household work and meals, 1; recreation, 3½. On a weekly basis this produced 8 hours of composition; 3 of bible history; 4 of English history; 4½ on geography and maps; literature and grammar were given 3; doctrine, 2; algebra and arithmetic 4; drawing, 8; Latin, 2; music and French, 7; and finally teaching method and practising school, 3.[131]

The long hours were a common feature of the training colleges. Behind the actual quantity of information was the larger question of culture. Matthew Arnold reporting in 1852 on teacher training wrote that he was;

> much struck with the utter disproportion between the great amount of positive information and the low degree of mental culture and intelligence which they exhibit. Young men, whose knowledge of grammar, of the minutest details of geographical and historical facts, and above all of mathematics ... often cannot paraphrase a plain

> passage of prose or poetry without totally misapprehending it, or without falling into the gross blunders of taste and expression.[132]

It was a universal problem in the training colleges; there was a general lack of culture among those who were to teach in the poor schools. It was at this level especially that both Liverpool and St Leonards were highly successful in transmitting not just knowledge of facts in various subjects to gain a certificate, but a whole culture. It was achieved not so much by formal instruction, though this was important, but by a shared life. The religious life of the convent, shared recreation with the nuns, the school theatre, the liturgy in the chapel, needlework while a sister read a novel, outings and retreats, sodalities and games all built up into something which was far greater than five, six or even seven subjects mastered for a certificate. It was achieved at St Leonards because the seven nuns of the staff were themselves ladies of some culture and broad experience, and of course because of the considerable personality of Cornelia Connelly herself. Marshall had noted in 1857 that many of the candidates came from a class "hardly susceptible of polish and refinement" but their life, perhaps first as pupil teachers living in a SHCJ convent in London or Preston began a process which St Leonards was able to continue with marked success. Their moral formation, which both inspectors and chaplains commented upon, came from the same source, contact and association with the nuns.

There is in the Training College Journal a transcript in Cornelia's hand of a report by Marshall in 1856. He begins by noting that the facilities for men are small compared with those of the other dissenting bodies, naming English Wesleyans and two sects of Scotch Presbyterians. But by contrast the facilities for women are almost equal to all three of these. He calculates that seventy students will complete their apprenticeship annually, and that the two colleges of Liverpool and St Leonards can accommodate a hundred or so a year.[133] He notes that the persons "primarily invited to enter" are the pupil teachers who have successfully completed their five years' apprenticeship, but that other "well recommended young women" can also be trained. The contrast in development of the two female colleges and Hammersmith is marked. The men's college struggled to survive. Britton in his study of St Mary's regards the supply of pupil teachers as the most vital factor which was constantly working against the college.[134] Hammersmith tried the experiment of a full preparatory year in an attempt to make up the leeway, but in 1866 Stokes was reporting to Manning;

> The one institution in Great Britain which trains masters for R.C. schools under Your Lordship's Minutes, a college with ample accommodation for 70 students, provided with a competent staff of teachers, liberally maintained as to diet and service, with a beautiful chapel and abundant religious advantages, which admits students absolutely free of charge, and even defrays their travelling expenses, cannot after thirteen years of increasing effort, fill so much as a fourth of its rooms with candidates for the office of schoolmasters.[135]

Marshall when he underlined the superiority of Liverpool and St Leonards to the Newcastle Commission offered another factor in creating this difference; "Our female schools are taught by a class so immeasurably superior to those who teach the males, that the final result is that they are a totally distinct class of persons altogether".[136] Marshall was talking generally and referred to both the poor schools and the training colleges. The Christian Brothers who were doing pioneering work in the Catholic community for boys had adopted a policy of refusing grant and inspection, because of their experience in Ireland.[137] This left their schools gravely overcrowded and greatly dependent on a monitorial system which was out of date.[138] There seems to be no sign of any work towards developing pupil-teachers on their part. And as they were not receiving grant, they lacked the financial incentive. This was a serious failure in the Catholic system.

The career of school mastering in Catholic circles was far from lucrative. It is suggested that Mr Kelly of the Wapping District Charity School (1801-1816) was the worst paid schoolmaster on record with a yearly stipend of £31.10s. against a more normal rate of between sixty to eighty pounds.[139] The salaries for Catholic masters remained the lowest in England throughout the nineteenth century, and an attempt to introduce a pension scheme for them in 1877 failed because they were not earning enough to be able to pay into it. The Rambler in 1862 was suggesting that it was not just the low salary, but also the status in the community, irksome relations with the managers, lack of career prospects which all combined to contribute to the failure to attract Catholic boys into the profession.[140] The average salary for a master in 1861 was £94, often including lodging, but a few years later this had sunk to £88. But for the Catholic master the average was £60 sinking to £55.[141] Generally throughout the country female teachers attracted lower wages. Among the SHCJ archives is a letter from Father Butland of Great Haywood, Rugeley, with details of his little school, and asking for a good mistress "capable of enlivening the children with a few songs" all for thirty pounds a year.[142] There was a concerted effort by both Marshall and Stokes in The Catholic School to inform public opinion through their reports. So Stokes looked at certificated men in charge of thirty-seven schools in his northern district and found that their average salary for 1856-57 was £67.17s, which he argued was thirty pounds lower than the average received by Anglican schoolmasters in Lancashire, and forty pounds lower than the average which the dissenting schoolmasters were receiving. And he noted that they fared less well in the matter of rent free houses.[143] The same picture was true of the female teachers, but probably not to the same extent, and they did not face the problem of trying to support a family on this salary. But the growth in the number of Catholic female teachers was achieved without the attractions of a well financed career.

There was another aspect of teaching in the poverty of the Catholic community which was not stressed. It was unhealthy. Working conditions for teachers were not good. Giving evidence to the Cross Commission in 1888 Dr Graham made the point.

> 69 out of 600 certificated teachers that have passed through Hammersmith have died often at a comparatively early age ... generally of consumption, arising, I have no doubt, from the unfavourable conditions in which they live and the surroundings of the schoolrooms, and so forth ... our schoolrooms are very poor.[144]

Although Graham was only speaking for the men's college, the same is true of the conditions in which many of the female teachers spent their days. A concomitant of the poverty of the Catholic body was both poor wages for the teachers and bad teaching conditions. Many of the SHCJ nuns died comparatively young, and on one occasion when Bishop Grant was expressing concern about the Society having a sufficient endowment to support the sisters in their old age, Cornelia was quick to reply that they were more likely to die young from overwork. Indeed the inspectors saw this as a general problem, and raised the issue in the Newcastle Report.

> We have expressed our fears that the hours of work are too many; that the time given to outdoor exercise is too short, and that the attendance of

> the students in the practising schools tends to confirm any bad habits which they may have acquired as pupil teachers.[145]

If this was true of the training colleges, many of which were purpose built, it was far more true of the schools which were often badly sited and not designed for education. While this was a general problem of the age, it was at its worst in the poorest section of the community. And reporting on poverty Marshall had noted that the Irish were in a class of their own. It was also, from the nature of things, the poorest section who were most likely to suffer from the effects of the Revised Code in 1862. A great deal was written about the Code at the time, and there have been some recent studies. It may have had some beneficial results, but it certainly placed the greatest strain on those most subject to extreme poverty, and it applied additional burdens to the training colleges. Some indication of the actual problems of financing St Leonards may be found in an appendix which gives the account for 1861. The college represented an investment by the Society of over three and a half thousand pounds, and in addition to all running costs the nuns had to meet capital repayment. The income from tuition fees in 1861 was £390.5s. Into this precarious situation came the further provisions of the Revised Code. Grants for students were not to be paid until they had graduated, and furthermore secured two favourable reports in the schools in which they taught, with a year between each report.[146] In addition the students' personal allowance was to be discontinued, and the college authorities must in future find one fourth of the maintenance of the students.[147] Since 1857 the CPSC had been giving an annual grant of £125 towards the salaries of the sisters lecturing in the training college, and a further capitation grant of £2 per student.[148] But it too was in financial problems and at the CPSC meeting in April 1863 Canon

Walmsley proposed;

> that notice be given to the female training schools of Liverpool and St Leonards that owing to the want of funds in their hands the Committee may be reluctantly compelled to withdraw or reduce after the year 1864 the grants hitherto made to them.[149]

This was seconded by Sir P. Mostyn, and after considerable discussion the motion was withdrawn. But a further indication had been given of the precarious state of the finances of the Catholic body. Both a knowledge of the shortage of funds and the demands of the Revised Code made the sisters SHCJ seriously consider the position of St Leonards as a training college.

Something of the problems of a principal of a training college may be gleaned from the miscellanea of documents in Cornelia's Training School Journal. There are time tables, lists of students, of prize winners, some accounts, lists of text books, documents from the Committee of Council on Education, notifications about examinations, lists of the drawing examinations, an early outline of the course of religious instruction from Mr Cookson and Canon Wenham, a general syllabus, some early descriptions of the college, HMIs' reports, some detailed work on parts of the course, such as history, the hours of teaching done by the staff. Cornelia found the educational minutes "a teaze" and added the thought that "Blackstone is light reading compared to them".[150] And Allies forwarding a reply from Lingen in civil service jargon added a hope that "this answer will be clear to you; the more so because it is not to me".[151] The amount of time the staff were actually teaching ranged from nine hours by Cornelia, especially on method and no doubt helping with the art, to seventeen by Miss Buckle. There is a detailed comparison of the time allocated to the various subjects by the three

Catholic colleges. Other than the nine hours of religious studies in Liverpool, the largest item is St Leonards eight hours devoted to art; but the time table does show that this was at 6.45 in the evening, giving some colour to Cornelia's claim that it was part recreation. It was followed by supper and free time. The copies of the returns describing the site reveal a local problem. In response to the question about sewerage Cornelia has written: "The Commissioners of Sewers and drains ought to drain the place, but they do not. The main drain runs into the Cliff upon the Town, not to our detriment, but certainly to the ill health of the Town, if not remedied".[152] An early paper from the Committee of Council asks about which subjects the promoters intend to offer, and lists a possible thirteen. Seven get a straight affirmative; religious instruction, English grammar & composition, writing, arithmetic & book keeping, English history, geography and algebra. But on three the college will only be teaching the rudiments; these are geometry, mechanics and the elements of physical science. Reading, as "part of Elocution" is qualified in the return by "Yes as far as desirable for female teachers". Industrial instruction is described by Cornelia as "needlework, Domestic Economy, gardening". Also agreed as part of the syllabus was "the organization, discipline and management of Elementary Schools". This list did not include drawing as that subject came under the direction of the Department of Science and Art.[153]

Cornelia directed the teaching as she did in the other schools. Mistresses made monthly reports in the training college. Typical are;

> Arithmetic. Miscellaneous Exercises in Fractions, (Decimals and Compound Proportion. (signed) Sr. Teresa. (Then in Cornelia's hand) Rules Explained?
> Geography. Learnt from Cornwell for repetition the 4 first pages of the physical geography of the British Isles - Read one chapter from Guyot. S.L. Ignatia.[154]

In addition to covering the work done, there were also reports on the students. Comments like "attention excellent and conduct v. good" are frequent, but there are also notes that individual students are "vulgar, obstinate" and so on. Of one the note "head smells". Of M.A. Collins "very eccentric" and of Cath. Long, bracketed with Collins the note "making love in the chapel, very vulgar".[155]

Some lists give an indication of the place of origin of the students, with a clear majority coming from the north of England, and a few from Wales and the south of England. A group of the students who graduated in 1859 were placed in schools in Broadway, Peckham, London, Ramsgate, Abergavenny and St Leonards. London eventually becomes the commonest placing of former pupils.[156] A return requested by the Education Department in 1860 asked about the hours which the students were spending in teaching practice. The return in June showed two students with only twenty hours, one with forty, another with sixty, four with seventy and one with eighty hours.[157] Even the time and subject of practice lessons given before an inspector are listed, with some challenging abbreviations.

Subject of lessons given before the inspector

Multiplication of fractions	35 min	2nd Group	
History of literature	50	1. Tron	
Hist. of B. Constitution	40	2. Complex S.	
Climate	40	3. H. of Commerce	30 min
Forms of Profs.	45		
Hist. of E. Language	45	1. Numerals of C.	
Hist. of Woolan Manufact.	30	2. Division of Fract.	
Analysis of Sentences	40	3. Distribution of Pits	25 min
Mountains	30		
Rivers their sources	35	1. Ep. of a Sent.	
		2. Multiplication	
		3. Pronoun	20 min
		1. N. Conquest	
		2. Words	
		3. Flora of O.N. World	30 min

1. Prime and C. No - Dictation S. Sentence	20 min
Adverb Formentation W noun (?)	25 min
noun Ph. gen of E. Wool.	25 min
Predicate Climate Multipli (er)	20 min
Ocean Currents Rivers of E. etc.	25 min.[158]

The long columns in the Training School Journal suggest something of the ordeals through which the students passed on their way to a certificate. The good results of both Liverpool and St Leonards have already been noted. Some subjects in other colleges were notorious for the high level of failures. The inspectors' reports for 1851-52 show some remarkable statistics. At Warrington 95% failed in drawing from models; at Salisbury 80% failed biographical memoirs, which some of the women's colleges took as being more lady-like a subject than history; at Whiteland 97% failed in Welsh and 72% in the history of language and etymology; at Chelsea 86% failed popular astronomy and about 90% failed Latin. Cheltenham had a 71% failure in bookkeeping, while 87% failed French, 40% vocal music, 28% penmanship and 21% natural history.[159] While matters were not always as bad as this, the figures do put into perspective the considerable success of the two Catholic female colleges.

During the years since the mid fifties there had been considerable changes in the staff of the training college. In a return of the Annual Grant Form in 1856 the college staff are listed as "Mrs Connelly, principal;

Miss Buckle, head teacher, Miss Orr, Assistant Teacher, Miss Cussack, Drawing Mistress, Miss Hunt, Mistress of Method, Miss Green, Mistress of Music, Miss Noble, Second assistant, and the Rev. John Butt, chaplain." Also identified are the subjects which the seven teachers were covering. In January 1862 Cornelia again lists the staff. Her vice-principal was now Miss Orr; there were four new sisters on the staff, Newsham, Atkinson, Mullen and Clack. Miss Hunt was still mainly concerned with method and practice teaching, and Miss Green with the music, and also needlework. Miss Newsham had geography, physical science and drawing. Miss Atkinson with arithmetic and drawing; Miss Mullen with geography, history and grammar, and Miss Clack with Euclid and algebra. Two other long serving members of staff Miss Orr is merely designated as vice-principal, and Miss Buckle was dealing with literature and history.[160] In an additional reply to Stokes she gives the hours which the staff were actually teaching; Miss Orr 4/am & 5/pm; Miss Buckle, 17; Miss Hunt, 8; Miss Newsham, 14: Miss Green, 11; Miss Atkinson, 14½; Miss Mullen, 11¾ and Miss Clack, 17.[161]

Quite another picture of the training college is given in a note for August 1863. The nuns are on retreat and the students are preparing for an ecclesiastical examination, making up their lessons in method and school management; both church history and doctrine are now being learnt by heart because of the controversy about the previous religious results. Part of the exercise consisted in students questioning each other. There were in addition the inevitable compositions to be done.[162] This stress on memory work was against Cornelia's better judgement, but she had little option under the pressure from her bishop. She had in January 1858 outlined her approach to education in the training college in a letter to Marshall, and it was clearly the general line of <u>The Book</u>

of Studies applied to the training of teachers.

> In the lectures generally we have worked upon the primary point rather than in diffuse matter. Method & the means to carry out the end to be attained, cause & effect, the cultivation of the understanding & the judgement rather than the memory, have been the pivot upon which the Instructions have turned during the past two years. I do not mean to say that the memory has not been cultivated, but simply that it has held a subservient position to the understanding & the judgement.
>
> We hope with the advantage of two years experience to improve in the Methods & Means of practical School Management, & also in the Reading and writing of our Students.
>
> This last year we were disappointed in finding that the Syllabus set forth for the Male students, was not followed in the papers sent to the females, which we expected at least on those subjects belonging to females. Our Students had prepared Shakespeare's Lear, instead of which they had a passage from Cowper whose writings are offensive to truth & therefore discarded by us. We earnestly beg to know whether the Syllabus sent to us this year for the Male Students is to be followed for the females, or whether we may expect a similar guide for them.
>
> We are convinced that it is a great mistake to suppose we may aim at more than can be accomplished (without injury). The more definite the course to be prescribed, however largely extended, the more certain must be the result.[163]

While her philosophy was clear outside forces were tending to destroy it.

Sometime in the autumn of 1863 Cornelia resigned as principal of the training college, to be succeeded by Mother Mary Theophila Laprimaudaye; the exact date is not recorded. This step had been opposed by both Bishop Grant and Allies of the CPSC. Allies was for taking the matter to Parliament, though he regarded that body as a "packed jury" perhaps thinking of Newdegate and the continuous agitation for the inspection of convents by a few MPs. Fortunately Walter Arnstein's sympathetic biography of Newdegate illustrates something of the depth of suspicion against which the nuns had to struggle for a quarter of a century.[164] The majority of those who were concerned about the allegation levelled at Cornelia in the Annie McCave affair saw it as a grave injustice against her. With the two further factors of the increased difficulty of financing the college under the provisions of the Revised Code, and the lack of a sufficiently large practising school the nuns eventually decided to withdraw the college from government grant. The author of the Annals SHCJ for 1863 wrote;

> Before the end of the year it was decided to give up the Training School. The want of a sufficiently large Practising School was a great drawback to success, and an Inspector had made it difficult to continue working under Government. The Sisters engaged in the work saw it, however, given up with regret, on account of the advantage it had been to the Society. During the eight years of its existence, many of our most valuable Religious had come from among the Students, and the methods of teaching in our Schools had been systematised and much improved.[165]

With admirable restraint the author does not name Stokes, but briefly lists the main factors in the decision. In its eight years the college had trained almost exactly one hundred teachers, and a significant number had joined the Society. This is an indication of the extent to which the life in the college was not just one of instruction for the students, but the sharing of the whole culture of the nuns.

The first thought was to run the college privately as a training centre, free of the government restrictions, but it was soon realized that this was not feasible. Once the resident students had completed their two year course, with a further inspection even from Mr Stokes, the college was immediately transformed into a Middle School. The highly stratified nature of the Victorian society resulted in even the middle class being well and truly subdivided; the upper middle class required a "more select school for young ladies" and the convent boarding school at St Leonards met this need, as did also the main school at Mayfield. The Taunton Commission considered three different middle class schools, and by its definition this top class catered for young ladies up to the age of eighteen who came from families of the clergy, gentlefolk, lawyers, the military. In general these schools offered a patrician education. The daughters of well to do tradesmen, farmers and the like in another group were offered education usually to sixteen. The lower middle class usually left school at fourteen and were the offspring of artisans. Of these three groups only the first would be regarded as gentlefolk, but in Victorian days the two other categories were increasing in many countries, and tended to require different schools.[166] Wiseman had been very conscious of the need for schools for the upper middle class, and had pressed Cornelia to make this her work. Sensing her reluctance to neglect all the other children, he sent Sergeant Bellasis to explain to her how important these differences in society were.[167] Cornelia's reaction was to meet Wiseman's wish by providing schools for the upper middle class, and in every case also poor schools. With the closing of the training college, she now developed in the premises a school for the middle middle class. In the SHCJ documents the upper school is usually referred to as the convent school and this as the middle school. It offered exactly the same education as the upper school, but it was less expensive, and girls were trained for a number of professions, such as to be governesses in the homes or teachers in poor schools, if they chose to go on to a training college. It thus provided another avenue of preparation for the training college, which was fortunate as eventually the whole valuable system of pupil teachers was subject to government cuts.

The training college had cost the Society over three and a half thousand pounds and somehow the property had to be used efficiently. Bishop Grant raised a legal query as to whether the trust deed covering the training college would allow this change of course.[168] Once this problem was solved the middle school very quickly built up into a thriving establishment, and it did not run into the sort of difficulties which had marred the undoubted success of the training college. Moreover the confidence of the Catholic community in the SHCJ remained and even increased, and within seven years Cornelia was approached to open a training college in London. In the event this did not materialize, but later in the century the Society moved back into teacher training in England, and also in America.

The superabundance of material which the two controversies about religious education and the Annie McCave affair created could easily lead to an unbalanced vision of the eight years of the St Leonards Training College. By national standards it was high success, winning many glowing reports and training a hundred pupils who were afterwards noted as good teachers. For Cornelia Connelly it was the final period when her philosophy of education came to full maturity. As college principal she had a great deal of administration, but she also at times taught method and drawing, took part in the students' teaching practice and provided general supervision of both the whole curriculum and the work which the individual mistresses were doing. She had for a decade been doing method with her novices, all of whom had ratio notebooks, and the vast majority of whom were preparing to actually teach, though some were given administrative work. The novices' notebooks show the same philosophy in embryo as that of the training college. So among the rules for second year novices on teaching methods there are six on questioning pupils, which include the instruction not to allow the children to guess "but let them use their reason and judgement".[169] Other characteristic insights of Cornelia's about the need for the young to frequently change position, that the manner of the teacher must be sympathetic, that the whole mind must be engaged and that the character of the individual child must be considered are all to be found here. The phrase "whole mind" in this context will certainly be a stress on the use of the intellect and not just the memory.

The period of the training college in the history of the development of the method of the Holy Child nuns, and its publication in The Book of Studies, is also significant in that it brought Cornelia Connelly into further contact with the general world of education in England. The requirements of the Committee of Council on Education extended the range of text books, and Cornelia as principal was forced to read some of the current authors to be able to assist the students in their knowledge of method, and to prepare them for the examiners. The sisters in 1848 had already been speaking of "our method" but it is clear that by 1860 this had developed considerably. The basic structure and approach remain consistent throughout. The state of Cornelia's educational papers do not admit of exact dates being placed on the development, but the twelve years saw the growth of the method of the SHCJ to full maturity and to the stage at which the Society was confident enough to publish its Book of Studies as a general plan for all its schools from the training college and convent boarding schools down to the poor schools.

Cornelia regarded the training college as an apostolic work. It had been in her mind from the start, while the community was still in its earliest days at Derby. The closure of the training college must have been a great blow to her. But in the midst of all these troubles she is to be found corresponding with the Duchess of Leeds about a possible training college in America, and assuring Bishop Grant that "where there are many contradictions, there much fruit is to be hoped for".[170] Clearly fortitude was part of her philosophy; it was not a form of stoicism, but a Christian belief in the Redemption which enabled her to face so many trials. If those students who trained at St Leonards for the teaching profession gained a share in this outlook it was a great endowment with which to face the problems of the poor schools in the industrial slums of Victorian England.

CHAPTER 10

CORNELIA CONNELLY'S PHILOSOPHY OF EDUCATION

Much of Cornelia Connelly's thinking began from a religious level. This is especially true of her approach to education. Her attitude to children, her ideas on girls' curriculum and on an appropriate school society all came from her understanding of the mysteries of the Incarnation and Redemption. Given the theological climate of the nineteenth century this is remarkable. In this chapter her thought is followed from its roots to its full flowering in an education philosophy.

In theology the great movements of the day were basic. Shleiermacher and Hegel had raised fundamental questions about the possibility of religion, echoed in England by Coleridge who saw Christianity as primarily ethical.[1] It was especially Strauss who introduced the second stage of fundamental studies which concentrated on the possibility of christology, with major writers like Feuerbach and Kierkegaard causing reactions among English Protestant writers.[2] The Oxford Movement, while it produced many works on the nature of the church did not immediately concern itself with christology, though the influential work of H.P. Liddon as a late contribution is not to be overlooked.[3] Certainly the nineteenth century was a fertile era for Protestant theology, but the basic questions which were being discussed did not seem to provide an ideal base for the construction of a theology of education. By contrast Catholic studies took a line of their own. Denied the use of the historical and critical methodologies, the theologians eventually turned to a revival of the thirteenth century scholasticism especially associated with Thomas Aquinas. The early writers in this movement were Matteo Liberatore and Joseph Kleutgen, and although there were other writers with different approaches like de Maistre, Bonald and de Lamennais in France, and Möhler at Tübingen, scholasticism eventually became dominant. Between 1855 and 1866 when Cornelia was at the height of her constructive work, there were many interventions by Rome to condemn a variety of theological ideas, traditionalism, ontologism, Gürther's dualism and Frohschammer's rationalism. The restoration of Thomism was in part made possible in Catholic circles by the crushing of other systems of theology.[4] While this destructive process was taking place there was little in the theology of the day to encourage a nun seeking a deep religious basis for a vocation in education. The one figure in England who bridged the religious divide was Newman, and his theology was not based upon any single tradition but on a deep and extensive reading of the Fathers of the Church.

There is no suggestion that Cornelia was in any way a patristic scholar. But she had benefited greatly from the work of Ventura, and did know something of the Fathers. Her knowledge of scripture was wide and had been realized and activated through prayer; her spirituality was based upon the great classical writers, and this gave her a christology which was quite independent of any of the contemporary controversies. All this has been detailed in the second chapter, and is further illustrated by the catalogue of the authors which she used in an appendix. Equally important was the actual point of departure for her thinking. Many Christians had approached education from a religious position. Often the starting point was the doctrine of original sin, which was in part responsible for the strain of deep pessimism in Victorian literature, evidenced in the works of Matthew Arnold, George Eliot and Thomas Hardy which followed either a loss of faith or a joyless outlook on Christianity.

In contemporary literature the figure of the child very often occurred in situations associated with discussion of the fall of man and the brevity of life.[5] All this was a tradition which smacked of the Calvinism of the sixteenth century, and had often given rise to an oppressive form of education. Rousseau had reacted against this to the wildly simplistic view that "everything is good as it comes from the hands of the Maker of things; everything degenerates in the hands of man". He transferred original sin from the child to society. Any theory of education starting immediately from the child was likely to be torn between the optimism of Rousseau and the Calvinism of many writers. Rousseau's Émile was widely influential, but would not easily be reconciled with the classical teaching on either the Incarnation or the Redemption. In France the tradition of Rousseau was carried into public education by Condorcet and Jules Ferry. In a speech 19 April 1870 Ferry committed his life to this belief in the perfectability of mankind. He said that we shall be truly emancipated:-

> when humanity appears to us, no longer a fallen race stricken with Original Sin ... but as an endless procession striding on towards the light; then we feel ourselves part of the great Being which cannot perish, Humanity, continually redeemed, developing, improving; then we have won our liberty, for we are free from the fear of death.[6]

It was not an outlook which the Fathers of the Church would have recognised as Christian, and it is doubtful whether it had a lot to offer to education.

The point of departure for Cornelia Connelly was not original sin, but was expressed in the title of her society, the Christ child. This provided a beginning which was basically very optimistic, and yet in view of the doctrine of the Redemption one which did not take an unrealistic view of life. It began first with Christ the object of religious worship, and the motivation of the teachers was to serve him specifically by working for his children. So the pupil was seen first and foremost as a child of God and through the saving grace of Christ an heir to the kingdom of heaven. The vision of Christ also provided the answer to the question of human existence, and so to the ultimate purpose of education. This outlook did not deny the fact of sin and the possibilities of evil inclinations in the pupils, as well as within society at large, but it did provide a first basis which was full of hope and promise. It provided a deep motive for the respect for the individual which characterized the teaching of the Society HCJ, and also for the policy of working to develop the talents of each person rather than of implementing some abstract curriculum. One of Cornelia Connelly's dicta was; "Be yourself, but make that self just what our Lord wants it to be".[7] On one occasion she sent a water colour to the novitiate with instructions for it to be copied by everyone. Some of the novices had never held a paint-brush, and there were protests. Her reply was "We must seek for hidden talent".[9] A part of her education philosophy was that God had given talents to the pupils; the teachers had to find them; an encouraging outlook. According to Sister Berchmans, who died in 1904, her three mottoes were CCC, Courage, Confidence and Cheerfulness, and she acted on the principle of encouraging any talent she could find.[10] This attitude sprang from her devotion to Christ as the Holy Child, and a respect for others as children of God.

As the point of departure for Cornelia was the Christ child, her philosophy is basically a child-centred one, but differs from Froebel and Pestalozzi. There was no suggestion that the child would determine the content of the curriculum, but because of respect for the individual the curriculum in The Book of Studies is open to wider development, and as the examples of students' work has shown there was no question of restriction; her philosophy was that all things were possible. Her emphasis on activity methods as shown in her approach to the learning of reading was based upon her own experience as a mother, rather than on a theological or philosophical premise, but in a general sense it was a recognition of the needs of the individual, and so child-centred. Unlike Rousseau she did not propose to restrict reading to a stage when sense activities had all been developed, but she integrated the learning of reading and writing, and with considerable use of activities to assist in sustaining interest for the young. But the most basic conclusion which she drew from her starting point was that of the respect due to the child, and by children to each other. This determined the ethos of the schools.

Teacher attitudes were founded upon this before all else. From the start the novices were trained in this outlook which in terms of spirituality was especially characteristic of St Francis de Sales, and although there is no direct reference to him, the Salesian influence is certainly to be found in both The Rule and The Book of Studies. Characteristic injunctions are:-

> The Mistresses shall at all times strive to gain the hearts of their pupils to the love and imitation of the Holy Child Jesus by the practice of humility, sweetness, gentleness and love.
>
> Let them generally lead their pupils by love rather than fear. The pupils must be watched over and spoken to with great sweetness and charity, the

> Mistresses thus fulfilling the office of guardian angels. In dealing with offences against the rules of the school, the Prefect is advised to do what she has to do in the spirit of lenity and charity.[11]

Cornelia wrote to a sister suffering from discouragement in 1877 on this theme.

> If I have never seen them, it is always the same. That they may learn the joy of loving the God who died for us and of being happy in the Convent where He dwells in His most loving form of Holy Childhood. Stiffness and rigour will not bring forth love, and these are not the spirit of the Holy Child. But pains-taking for the eagerness of love will always bring forth delicious fruit.[12]

The devotion to the Holy Child was the basis in the Society for Christian optimism, and for attitudes to the pupils. It was a first guide as to how pupils should be treated, and even of what subjects were appropriate for the curriculum.

The curriculum for middle class girls in Victorian England lacked all guidelines. The findings of the Schools Inquiry of 1864-67 revealed the sad state of chaos which passed for girls' education, and showed the lack of direction and of competent teachers. Miss Buss and Miss Beale met the situation by attempting to do anything which the boys' schools were teaching. This did not imply a solid philosophy of the curriculum, but only raised basic questions about the coherence of the work done in boys' schools and colleges. As late as 1867 Charles Kingsley was commenting; "British lads, on an average, are far too ill-taught still, in spite of all recent improvements, for me to wish that British girls should be taught in the same way".[13] To bring subjects into a curriculum on these grounds might be a bid for female equality, but it was certainly no way to construct a curriculum.

By contrast Cornelia Connelly had a philosophy of the curriculum. The prime concern was the development of the individual. She saw this as essentially moral and intellectual together; one without the other was a distortion. Intellectual development required the growth of the powers both of understanding and of expression, and again to develop one and not the other was false. She thus established a general arts programme in which reading and writing, learnt simultaneously (which was not always the case at the time) developed naturally into literature, elocution, drama and music. According to her philosophy there was another mode of expression, even more international than reading and writing, to be found in the wide field of art. So she insisted on this as an integral part of the curriculum as it demanded both careful observation and understanding as well as skills of expression. In her thinking art was so important that it included geometry, map making, and geology, and associated with the school drama in the making of scenery. It was regarded both as an integral part of education, and also as a relaxation so that it often came at the end of a day's work.

As the aim was personal development there was considerable variety in the range of subjects which some pupils studied. Some of the more gifted eventually studied classics in both Latin and Greek, and one or two the gospel of St John in Greek; for sixth formers there were considerable courses in architecture, the history of art and of music, some philosophy of history and a little logic. The literary studies included classics from these and some European languages at least in translation, so that a pupil who had completed a full course at St Leonards would have an outline knowledge of classical literature and some acquaintance with the literature of France and Italy; while English literature ranged from Chaucer to Macaulay. The accumulated experience of the school theatre would also have included plays in both French and Italian with a wide variety of English drama.

Music too was seen in terms of personal development, but this subject had a special place because of its part in the liturgy and in the devotional life of the school, which was on a daily basis and not just a matter of Sunday worship. It was encouraged both in school choirs for recreation, school concerts and liturgy. Instrumental music, mostly piano at first, was an extra, and was supported by a succession of music masters, mostly foreigners. It was prized for the contribution which it made to the happiness of the school. In Cornelia's philosophy a happy school was necessary for good learning. In 1869 she wrote to Mother Xavier Noble at Sharon in America to give an account of the visit of Father Carter who was helping the development of the SHCJ there. At the end of a long seven page letter she concluded; "After we had had a long talk, I said it was of great consequence to make people happy and that they would always succeed the better for being happy".[14] The underlining was characteristic; so too was the philosophy. It was for this reason that she was prepared to run the risk both of ecclesiastical censure and Victorian disapproval by allowing card playing, dancing and sea bathing in her schools.

The curriculum also included mathematics, needlework, some domestic science, and, while science in general might seem absent from The Book of Studies, there was actually more done than it would suggest. The reason for this was the way in which the art programme had developed. In The Book of Studies it is inaccurately described as drawing, while in actual fact it was a very full scale study of art in various forms which included painting, both water colour and oils, tapestry work, principles of perspective and illumination. It was perhaps the question of perspective which led Cornelia to include geometry with art and to allow the two to develop a study of architecture. In a similar fashion maps were regarded as an art form so that the geography in the school became closely involved with art. The final development was to include some natural history, astronomy and geology. There are sufficient surviving examples of pupils' work in these fields to demonstrate that The Book of Studies is only an outline, and that some pupils did achieve impressive standards. The inspector Marshall, a Catholic convert, was delighted to find geology studied at St Leonards, and commented upon the fact.[15] Bishops might have been less encouraging, but seemingly never noticed its place in the school curriculum. The strength of this art programme is highly unusual if not unique at this time. One of the great formative influences upon Cornelia's own development had been The Spiritual Exercises, which have been considered in the second chapter. These eschewed abstractions and started from graphic gospel scenes of which the retreatant was directed to make a "composition of place". Others might meditate on truth, justice and Divine beauty; those who followed the paths of Ignation spirituality looked into the cave at Bethlehem, watched the Master call his apostles, wept at Calvary and pictured for themselves the last judgement. This graphic and visual approach appealed to Cornelia, became a part of her spirituality and inspired her approach to art which was seen as having a deeply religious nature. Her application of Ignatian spirituality to education in this field would seem to have gone further than the traditions of the Jesuit schools had taken it, and is probably an original contribution made by Cornelia. One of the many effects was to establish a link between religious studies and art and create another centripetal force within the curriculum.

The programme of basic religious studies began with the basic diocesan catechism, but even here Cornelia showed independence in using a number of texts written by non-Catholics for the youngest children. If noticed this was very likely to attract ecclesiastical censure, but because of her insistence on texts suitable to the child Cornelia was willing to take the risk. So there was in use David Blair's First or Mother's catechisms and Mortimer's The Peep of Day. The dryness of the diocesan catechisms was relieved by considerable use of pictures. Once the girls reached middle juniors there was a start made in both bible and ecclesiastical history. Later the English catechisms were replaced by some of the larger French catechisms as the pupils had progressed enough to be able to handle these texts usefully in French. Ecclesiastical history was a major part of the religious studies, and Cornelia stressed that the bad example of Judas was as important a lesson as the good work done by the saints, and that the pupils were to know of both. Although religious studies obviously had a very important place in the curriculum, it was never considered that good teaching of religion was enough in itself. Dorothea Beale contrasted the approaches of Froebel and Rosmini. "Froebel's religious teaching is very beautiful, but he brings out less clearly than Rosmini the priority of the personal; if Nature speaks to a child of the All-Father, it is because he knows that all has come to him through persons".[16] Although Cornelia's copy of Rosmini remained with the pages uncut, she certainly agreed with this principle, and concluded that not only did true religious teaching involve knowledge of persons, but it also demanded a personal response if it was to be genuine. So the curriculum here was not concerned so much with religious knowledge but with formation. Again it was the outlook of The Spiritual Exercises. This called for a response on the part of the pupils to the mysteries of the Incarnation and Redemption.

For Froebel everything has an outer and an inner aspect, and is a symbol of a hidden spirit; all things share a single inner unity because they manifest the single spirit of God. True knowledge is to be found by seeing through to this unity of spirit, and the natural sciences and mathematics greatly assist in this vision. Cornelia is probably closer in her educational philosophy to Froebel than to Rousseau or Pestalozzi, but she is far more christocentric than any of them. The vision of reality was Christ, who revealed God in human form, and because of his Redemption the whole of reality was sacramental. This meant that all was seen in relation to the saving work of Christ; created nature not only spoke of God but related to Christ. And true education was to be based upon this vision, and followed the principle of using the concrete to reveal the spirit. This gave Cornelia a very confident and open attitude to teaching. In the archives SHCJ are notes given by an old sister in 1916 who could look back to the earliest days of the Society and to Cornelia's leadership, with sufficient distance to begin to assess her qualities.

> Rev. Mother Foundress was not only up to date in the Catholic World, but in advance of date. Higher studies, best books, needlework, machines, even sculpturing statues - "We never know what we can do till we try" - "Perseverance gains the crown". Her bright encouraging spirit - every little effort (counts) etc. The energy of the sisters over work was most striking, and had to be checked.[17]

The quotations from Cornelia suggest the quality of her leadership, but it is only the conjunction of her spirituality and her educational philosophy which reveals its source.

The curriculum was based upon a recognition of what was worthy of the children of God, a basic outlook which gave her teaching a strongly intellectual slant against the prevailing stress of the day upon memory work. So in 1858 she wrote to Marshall;

> Cultivating the understanding and the judgement rather than the memory has been the first point upon which instructions have turned during the past two years. I do not mean that the memory has not been cultivated, but simply it has held a subservient position to the understanding and the judgement.[18]

Cornelia was writing of policy and theory in the training college at St Leonards, but she was also expressing her own philosophy which governed the method in The Book of Studies. She saw this as true to the nature of the human person and appropriate to the dignity of the pupil as a child of God. It was in the light of her theology stemming from the contemplation of Christ Child that she saw it as a duty of the teacher to make children happy. It was not just that happy children work better but rather that love was creative, and all was to be seen in the light of Christ, who was the love of God made visible. He provided the pattern for the person, the school and society at large. So in school the shared recreation of pupils and teacher which could have been a matter of strict surveillance was in the recollections of past pupils a matter of delight. One of the alumnae of the first SHCJ American school at Towanda gave an account of the various studies and concluded; "Our daily recreations were joyful and exhilarating events sponsored by one of the sisters".[19] Others, it will be recalled, remembered Cornelia dancing round a room with a pupil to a waltz tune. All the evidence points to remarkably happy schools, notably free from the blight of the Victorian Sunday, and stern injunctions that children were to be seen and not heard. It was a society designed for children.

There is an obvious danger of a children's society degenerating into sentimentality and softness. The corrective here was the realistic vision of a mother, and Cornelia's theology of the Redemption. Both intellectual and moral effort was required of the pupil. Cornelia is remembered as saying; "Do not make milksops of your children; labour strengthens the body and study the mind".[20] A very early entry in one of her notebooks, about 1843, reveals her mind in respect of the response required by God.

> True liberty is that of the children of God: it consists in commanding the inclinations of the heart, in raising itself above all human fear and in walking with agility in accordance with the precepts of God.[21]

The purpose of the Incarnation was to restore union between man and God, and through God's mercy that restoration was made by the mystery of our Redemption. The vocation of the sisters in the Society HCJ was to share in the merciful work of God, in the redeeming office of teaching in the church. This idea of vocation was strongly fostered in The Spiritual Exercises where the retreatant is asked to make a choice between the following of Christ and other paths in life, and after this "election" to seek through prayer to find a precise vocation within the divine plan. This would mean giving a priority to following the leadings of grace and often involved considerable renunciation of natural desires. In a Puritan or Jansenistic sense this could lead to a joyless outlook, but from her own experience Cornelia was able to write of "this jubilee of heart ... not bargained for in this life of accepted suffering". A part of the school life consisted in initiating the pupils into this mystery of the Cross, and so in encouraging them to gain some experience of the truths by which the nuns lived. This was a far more subtle matter than mere instruction, and it raised the questions of the conditions in which real moral education could best take place.

Rousseau considered that all a child needed was protection from the corrupting influence of society; Cornelia was both mother and Christian enough to believe in sin, and her outlook was more realistic. The comments in the school reports show that the pupils were a very normal mixture with some who were lazy, others bad tempered, rude or disobedient. This was a situation which called for redemption. In Cornelia's theology the sisters were called to mediate God's grace in the particular circumstances of the school. It would involve suffering and sacrifice, but this was not only the cost of following Christ in this vocation, but also a part of the process of gracing the pupils. Within the Christian tradition various reactions had followed a consideration of the needs of the young. Luther concluded that since the young did not possess conscience they required discipline.[22] And many a school master had turned quickly to the biblical injunction "Spare the rod and spoil the child" without looking for any further suggestions from Holy Scripture. From the start Cornelia was strongly against corporal punishment, and this was eventually written into The Book of Studies. The transfer of moral values was to be achieved in a very different way.

The school society was to set values and uplift the pupil. Many things were to contribute to moral formation, an attitude of trust by the teachers, a shared religious life, the confraternities, the school theatre and the religious life: all contributed. Cornelia's basic philosophy here was constructive, and by the standards of the time she did not produce many school rules. One of the sisters writing her life in French summarized her attitude.

> She did not seek to subdue but to direct, not to
> break but to develop, and to the youth overflowing

> with life, who surrounded her she did not urge living less but living more.[23]

"Be yourself, but make yourself all that God wants you to be" was her challenging saying which suggested the channelling of energies to a divine purpose. This was the psychology of The Spiritual Exercises with a stress on the positive, which might call for mortification and sacrifice in the achievement, but which was fundamentally a very positive outlook and therefore more capable of attracting the heart. To communicate it in school was an overall responsibility of staff. It was something which school spirit and life might achieve when a lesson might not. Cornelia gave unusual freedom to the pupils, who were not spied upon but were themselves responsible for their own observance of school rules. This was very unusual, and commented upon by some French girls at St Leonards. It was also a part of the criticism which Stokes had levelled at the training college; the students were not closely supervised. Despite the criticism Cornelia strove to maintain this approach to moral training based upon self motivation. Towards the end of her life she spoke of "pains-taking for the eagerness of love" in the service of God. This was the vision she sought to give her pupils, and because of the very unusual circumstances of her own life she could speak with great conviction.

It has been suggested that moral education is impossible without the habitual vision of greatness.[24] The vision offered to the pupils was above all that of Christ, a vision which was to be seen reflected in the lives of the saints. This was both part of the religious instruction in class and also part of the devotional life of the school in chapel. The vision was reinforced by the lives of the nuns. Sister Christina, Coventry Patmore's daughter, is an example which has been quoted already.

The power of the example is illustrated by the steady supply of vocations which the Society received from its schools, indicating that the nuns were both liked and admired. In a closely shared life pupil and teacher knew each other well, and there was ample opportunity for the young to see how genuine the sisters were in their vocation. From watching Mother Connelly in church many pupils concluded that she was a saint, and former pupils spoke of the help she was able to give.

> When I was at school at St Leonards at the age of 12, I had a big sorrow. I lost a small sister of three that I loved very dearly. I fretted a good deal, till one day I met Mother Connelly in the garden. She called me and asked me about my little sister, and I soon found myself chatting freely to her about the child's beauty and charming little ways. Then Mother Connelly told me in a gentle loving way that our Lord loved her far more than I did, and that He had taken her away to make quite sure that she would be with Him in Heaven for all eternity, and that He did not want her to be hurt or spoiled by any of the ugly stains of the world. Then she drew a lovely picture of how happy she was with our Lord. I was quite comforted and never forgot her words.[25]

There is a suggestion here of Cornelia combining her moral vision with an outlook of beauty, speaking of some of the ugliness of the world and the lovely picture of heaven.

The role of the school theatre in moral training has already been treated in the appropriate chapter, together with the reply of Cornelia to the sisters who thought that the plays were disturbing the girls and causing them to have airs and graces. Cornelia argued that the theatre presented a useful forum for moral training, and various accounts from the pupils themselves support the validity of this judgement. The plays also often served to present high ideals and noble sentiments which could easily be lost in a classroom situation. The Jesuits had been the first to use the theatre as an instrument of education, and there is considerable evidence that even in the sixteenth century they were beginning to appreciate the different contributions a theatre could make to the life of a school.[26] Certainly the Holy Child theatre, though not treated in The Book of Studies, became an integral part of the system of Cornelia Connelly, and its value for moral training was recognised.

Another major factor in religious formation was the role which the various sodalities played in the life of the schools. It is hard to overestimate their influence. The school confraternities, begun by the Jesuits in the sixteenth century, represented the most significant attempt of a religious community to share its spiritual life with others. It provided a valuable forum, other than the classroom for an exchange of ideals and for the practice of common religious exercises. Works of charity were done together, and there was the stimulus of a shared experience. They provided a channel through which the lives of the saints could be popularized, so reinforcing the vision of greatness necessary for spiritual development. Some of the lives were of people who in the past had belonged to the same confraternity, and this tended to create something of an esprit de corps. The celebrations of saints' days then became something of a family occasion. It is evidence of the importance of the sodalities in the eyes of the pupils that alumnae often continued to sign themselves E. de M., enfant de Marie, and still regarded themselves as members of the Children of Mary sodality. It was obviously appropriate that in a Catholic school the leading society should be a strongly religious one, and in Victorian days, and for many years afterwards, the sodalities certainly fulfilled this role. They provided considerable backing and support for Cornelia's policy of trusting the pupils, placing them on their honour and leaving them with no close supervision. The resulting self discipline was perhaps the most valuable training which a school could give.

Because of the presence and acceptance of religious ideas and ideals it was possible to do things with pupils which in other circumstances might have been dangerous to them, emotionally upsetting or unacceptable to their parents. One year just before the summer holidays it became clear that Sister Mary Agnes was dying. Some of the pupils wished to see her, and then had second thoughts feeling that the request would be regarded as madness. But Cornelia knew of their affection for the sister, and unexpectedly sent a message that if the senior Children of Mary wished, they might be taken to say goodbye to Sister Mary Agnes. An eye witness wrote of the occasion later.

> I was one of the privileged four, and recall, after over fifty years, every detail of those five minutes which have ever been remembered among the most impressive of my life! It was past 9 o'clock. Mother (Cornelia) met us outside the Infirmary door, and said that Sister was pleased and wished to see us, but we must go to her separately and only stay a minute or two; that it was a great grace to see one who would so soon be with God, and that we should ask her to pray in Heaven for us that we might always remain God's good children, and do God's holy will. It was all so mysterious, and yet so real - it was something I had never come in contact with before - death! - and without any attractive surroundings, it was beautiful, and there was a peace unfelt before, as kneeling by her bed, her hand rested on my head. I forget now what I said to her, but she said in a low whisper to me, "I think the Holy Child will have you for Himself". She seemed so calm and happy, asked me to pray for her, and then made me a sign to go and kneel at the window opposite her bed, which looked down into the Chapel and faced the Altar. There was not a sound to be heard. All the lights were out, save the Sanctuary Lamp, and one lighted at the feet of a lovely ivory crucifix which stood on an Altar prepared for our Lord's visit to her in Holy Communion, the following morning. In the presence of the Blessed Sacrament a faithful soul awaited the Heavenly Bridegroom.[27]

The two Christian mysteries of the Incarnation and Redemption provided the basic structure for Cornelia Connelly's educational thinking. From these she drew an understanding of what was appropriate for the curriculum for girls, with its strong stress upon art. They were children of God, to be treated with reverence, and lovingly educated. To do so was an act of divine mercy, and a vocation which shared in the redeeming work of Christ. The optimistic and happy outlook derived from the primacy given to Christ and signified in the title of the Society of the Holy Child Jesus. Reverence as a primary attitude to children had been stressed by some of the Renaissance humanists and was characteristic of Erasmus's philosophy.[28] But Erasmus insisted that a student's mind should be treated with respect as a God-created thing. Cornelia had a christological basis which provided for an even deeper philosophy as it takes the thought into the heart of the Christian mystery. By contemplating the love of God incarnate in Christ the sisters were to find the source of the love which they were to expend upon the pupils. And like Christ's love to death on a cross, the vocation of the nuns was sacrificial, and was to mediate the mercy of God no matter what the cost to themselves. In a letter to the nuns in Blackpool, perhaps in 1857, she offered points for meditation during Lent.

> 2ndly Let us as a continuance of the points ... encourage ourselves with the remembrance of our high calling, which Our Lord has so particularly blessed that He promises, that we shall shine as stars. Let us ask ourselves whether we trample upon all inferior motives in fulfilling our duty to our children. Have we endeavoured to form them according to our Divine Model. Have we represented Him in our conduct to them? Have we led them to that union of prayer which must secure their virtuous and pious resolutions? Such as we are such will be our children.
>
> 3rdly ... The more we love God the more perfectly we shall be in the joy and liberty of His children ... forgetting ourselves and rejoicing in Him. We must take the joyful song of the lark soaring high in the heavens as a resemblance of our recreation joy, and his

> descent into the hollow of the grass to build his nest, as a picture of our silent humility out of recreation. That is of what we wish and aim at.[29]

The phrase from Daniel "The learned will shine as brightly as the vaults of heaven, and those who have instructed many in virtue, as bright as stars for all eternity" was one which Cornelia had entered into her note-book early in life, and which was a favourite among teachers.[30] But the mediation is not centred upon the reward but the model for education which Cornelia finds in Christ.

As a final insight into Cornelia's philosophy of education, it is possible to consider the recollection of one of the early pupils at St Leonards, Catherine Harper, who afterwards became a Sister of Charity. Looking back later in life she was able to identify some of the elements which made the school so outstanding, and the significant leadership of Cornelia.

> She had great sympathy for children and did not try to force upon them wisdom beyond their years. We all loved her and thought her very holy, and would consider ourselves honoured by a smile and a few words from her. Often I came in for rebukes for bad behaviour, and at these times she could be very stern. But the general atmosphere of St Leonards was one of joy and contentment. There was no spying on the part of the nuns, but we were greatly trusted, and trained to a high sense of honour ... a method that completely achieved its end. There was a sense of freedom and broadmindedness about the school that was delightful. Our lives were made happy by numerous little treats and customs on different occasions, to which we looked forward eagerly. On Holy Innocents' Day we dressed up as nuns ... the best part of this was that we were allowed to go all over the convent and mix with the nuns. On another Feast Day, we had to hunt for our breakfast, which was hidden somewhere in the grounds. At other times, we had long walks or picnics, which were pure joy.
>
> With all this gaiety and fun, there was mingled a most attractive spirit of piety. Our dear Lord and His Mother, our Guardian Angels and the Saints were mixed up with our daily life in a happy and loving spirit, which

> never made devotion tedious or distasteful. We were supplied with motives which raised our obedience to the school regulations on to a high plane. I have never forgotten how we were taught to keep silence as we went two by two to the chapel, so that we might be asking our Angel Guardians to prepare our hearts to appear before Our Lord. Again, we were taught to rise promptly in the morning by being reminded that our good Angel was waiting for this first act that he might present it as a morning gift to Our Lord.
>
> Reverend Mother loved the liturgy of the Church, and had the gift of spreading this love among us. We were taught to sing Vespers, and every Saturday we all assembled with our Missal and Vesper book to find and mark the place for the next day, the elder girls helping the younger ones.
>
> As I grew older, and began to reflect upon all that I saw, I was struck with the religious spirit among the nuns. They were so unworldly although their duties brought them much into contact with the world, and after more than sixty years they still stand out in my mind as examples of simplicity, generosity, and kindness. Reverend Mother had a very masterful character and a wonderful love of God and great power over others. I thought she showed great good sense in educational matters. She seemed able to imbue all the nuns with her own zeal and large-mindedness. Her voice was rather stern and very determined, though her manner was gentle and winning and her face beautiful. We used to go down to the hall on Feast-days to wish her a happy Feast, and she would speak a few holy, motherly words to us, telling us how we should draw practical help for our own lives from the mystery we were celebrating. She would generally end up playfully, and tell us to run away and enjoy ourselves.[31]

The invisible basis for the structure which Catherine Harper observed and benefited from was the related doctrines of the Incarnation and Redemption; and for Cornelia these two were combined in the Holy Eucharist. This was the reason for her love of the liturgy. The Eucharist was the centre of her life, and she was always very unsatisfied with a new foundation when it proved difficult or impossible to provide daily mass for the community, as at St Ann's Albany. The importance of the mass is revealed in a letter written to the nuns for the Lent of 1857; she proposes that during the season:

> we shall particularly unite ourselves to the Passion of our Lord during Holy Mass, placing ourselves on Mount Calvary, remembering that the past, the present and the future are equally present to our Lord, and that the Sacrifice of the Mass is to us the same as that on Mount Calvary - Oh my dear Sisters how is it that we see so few souls truly united to the Passion of our Lord? - So few who are willing to be crucified with Him? - Because of failure in recollection and mortification - Because of forgetfulness of the sufferings of our Model of love - Let us no longer fail but now try our very best saying "I will now begin" yes my Jesus! I will in Spirit follow Thee to Calvary and feel the stripes they laid on Thee; with David in his blest vision of Thee be wounded with Thee and in Thee, that on the Cross I may die with Thee, in all my daily obedience and little sacrifices be one with Thee, and never seek myself in blame or praise, in contempt or honour but in Thee Sweet Victim of Charity.[32]

Cornelia's experience of The Spiritual Exercises had led her into the mysteries of the Incarnation and Redemption, and also to the degree of humility of wishing to suffer and be rejected for the sake of Christ. The same deep experience also provided her the foundation for the whole of her educational thought. Education is aimless without a model. Such a model should represent all that is best in human nature, and so be at once an ideal and a guide. Cornelia found this in Christ. This was all that people should be. The task of education is one both of growth and of change, and the development involved can be painful. This task calls for motivation of the highest order and for assistance and the experience of the value of suffering. The work of Christ, and especially the work of his Redemption was the source of power here. So Christ was found to be both model, motive and giver of grace. This was a Pauline vision very much after the concept of the hymn in Colossians.

> He is the image of the unseen God,
> and the first-born of all creation.
> ...
> He holds all things in unity
> ...
> As he is the Beginning,

he was first to be born from the dead,
so that he should be first in every way;
because God wanted all perfection
to be found in him,
and all things to be reconciled through him and for him,
everything in heaven and everything on earth,
when he made peace
by his death on the cross.[33]

CHAPTER 11

ACHIEVEMENT

The work of Cornelia Connelly is to be measured in both the schools which she founded, and likewise in the Society of the Holy Child Jesus. Some of the schools are still in existence, and the SHCJ continued to spread after the Foundress's death, and still works in education. Different yardsticks apply to schools and religious orders, so in considering her achievement they will be dealt with separately. As an American Cornelia Connelly might have been expected to return to her own country to work in education, and there is evidence that this was her original intention. When she entered the convent of the Trinità in Rome in April 1844 she was considering joining the Sacred Heart Order, but for the time being she did not enter as a postulant because of her children. She was assured by the Roman authorities that they were her first duty, and that, although she was expected to become a nun, that should not be until they were old enough to be left. Thus in 1844 Cornelia was led to think that no final decision would be expected of her for quite a while. She was encouraged to look to her own country as her field of work by Father Grassi, who had once been rector of the College of Nobles at Polotsk under Russian rule, teacher of astronomy and physics at Stonyhurst and then president and second founder of Georgetown College for which he obtained official sanction for it to grant academic degrees. In Rome he was assistant to the Jesuit General, and for a while spiritual director to Cornelia. He had left his heart in America and encouraged her to return there to follow her vocation.

All this changed. A threatened schism in the Society of the Sacred Heart probably contributed to Cornelia wondering if her vocation really lay in that order. But a tradition in the SHCJ was that her attention was actually directed to England by the Pope. So Mother Buckle in her unpublished manuscript wrote; "She had come from Rome in 1846 with the full approbation of Pope Gregory XVI to begin the Society in England, where - and not in Rome or America - she was recommended to found the Mother House".[1] With regard to her interest in her own country the tradition was that the Pope had added "From England let your efforts in the cause of education reach America". Why England? Cornelia in 1844 was known to the Earl of Shrewsbury, Bishop Wiseman and other English notables in Rome. According to Bellasis, her first biographer, they singled her out for special work in England, where there was a grave shortage of educational facilities for middle class girls. There were some enclosed orders of nuns with restricted facilities, and a number of societies which had either returned from exile or were new foreign orders coming into England. They were doing much good work, but none quite met the need of the new developing Catholic middle class. Buckle suggests that Cardinal Fransoni was aware that there was "an almost complete absence of prominent laywomen" among the English Catholics.[2] And in her biography Bellasis refers to all this in general terms.

> So it was that whilst Sister Cornelia (as she was now being called in the Society) was praying fervently to the Holy Spirit to guide her steps, she was not forgotten by the outer world, and there were those who were discussing and planning among themselves her possible future, and divining that she was destined by God to be the Foundress of a new Religious Order.[3]

Bellasis then attributed to Gregory XVI the decisive intervention, and describes the Pope as declaring that Cornelia was not called to join any existing order, but that she was "called to do a great work in God's Church". These words of the Pope "changed her whole outlook".[4] Pierce in an account in the American Catholic Herald (17 December, 1846) seemed to suggest that the Pope's wishes had been conveyed through Cardinal Fransoni.[5] Certainly Cornelia came to England convinced that she had the highest authority to found a teaching order, and that a major part of its work related to the education of middle class girls. As this was her understanding of the mission entrusted to her, any assessment of her work must include this dimension.

Very soon after she had arrived in England the definition of her task was repeated by Bishop Wiseman, at the time her ordinary. He wrote to welcome her and her two companions to Derby, and after remarking upon the wonderful providence which had provided them with a ready built convent, he considered the scope of their future apostolate.

> The field which you have chosen for the exercise of spiritual mercies is indeed vast and almost boundless, but it presents the richest soil, and the promise of the most abundant return. The middle classes till now almost neglected in England, from the mass and staple of our society, are the "higher class" of our great congregations out of the capital, have to provide us with our priesthood, our confraternities, and our working religious. To train the future mothers of this class is to sanctify entire families and sow the seeds of piety in whole congregations: it is to make friends for the poor of Jesus Christ, nurses for the sick and dying, catechists for the little ones, most useful auxiliaries in every good work.[6]

Wiseman saw the role of the middle class lady as either in a religious order or as the mother of a family. Cornelia, because of the stress upon schooling, sought to develop a religious society which was

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Wiseman saw the role of the middle class lady as either in a religious order or as the mother of a family. Cornelia, because of the stress upon schooling, sought to develop a religious society which was international, and not based upon just one particular diocese, and from the first she had her sights set upon America.

But first, before her achievement in founding and establishing the SHCJ, the schools may be considered. During her lifetime seventeen foundations promoted a wide variety of schools, often several upon one site, in England, America and France. Not all survived but the continued growth of the Society in the field of education was the first tribute to its success. She had been given the middle class as her particular target, and the higher and middle schools at St Leonards, Mayfield, Blackpool and Philadelphia all flourished, with a finishing school in France to give a final gloss to accent and culture for some of the pupils. These schools won and maintained an enviable reputation for real education. It will be remembered that Cornelia was a decade or so ahead of Miss Buss and Miss Beale in developing her curriculum, so that this growth also represented pioneering work in English education. Wiseman was so concerned about the plight of middle class girls that he once sent Sergeant Bellasis to explain to Cornelia that in English society it was quite impossible to mix the classes; Cornelia's response was to open different schools on the same campus. So at St Leonards after the closure of the training college in 1864 the building was almost immediately used for a middle school in which an identical education was given to one class of girls while the convent building housed the upper class school, and on the corner of the site there was the parish poor school, also staffed by the sisters. Because of her theology Cornelia could not envisage restricting the work of her society to the middle and the upper class girls, and the statistics which have already been quoted indicate that the vast majority of the pupils were poor.[7]

The range of the schools was from infants' departments, orphanages, poor schools through to the training college and finishing school in France. Although the training college in England had a short career, the Society returned to this work in London later with the help of Sir Joshua Fitch after the death of Cornelia. From the start a training college had been envisaged in America too. The final outcome there was Rosemont College, Pennsylvania, which received its charter as a liberal arts college in 1922. This was a final stage in the development of the SHCJ convent school, which in 1866 had been given authority by the State Legislature "to confer such literary degrees and academic honours as are usually granted by colleges upon such pupils as have completed in a satisfactory manner the prescribed course of studies".[8] These were not degrees in the modern sense, such as Rosemont college can grant, but the approval did show the quick appreciation of the work of the SHCJ in America by the civil authority.

In contrast to the range of schools stands the one educational philosophy which was found to be generally relevant. The Book of Studies was the nuns' handbook whether they were in a poor school, orphanage, training college or dealing with aristocratic young ladies. The range of studies varied; the basic philosophy remained constant. The same outlook of respect for pupils was asked of all teachers; there was the same attempt to create a freer and happy society for children. Teaching techniques were fundamentally the same with the constant stress upon the importance of the visual and the Christian role of art in the programme. More or less the same plays were performed in both England and America.[9] As early as 1850 Cornelia had been writing of "our method" and by the end of her life this method was in use in three countries, and the training of the sisters throughout the Society was done by reference to The Book of Studies. Had the Society dissolved into a number of diocesan congregations this unity in educational expertise could never have been achieved.

In difficult circumstances in England the SHCJ became pioneers and leaders in the Catholic community. In the face of continuous poverty they established what could be achieved, they defined possibilities and at the same time raised standards. Their poor schools figure prominently in the inspectors' reports of the fifties and the sixties, and these reports were spread in Catholic circles both by the annual reports of the CPSC and The Catholic School. Their reputation as teachers was known, occasionally was the subject of gossip, but was eventually commended by a growing band of satisfied families. The Society was very much a part of Newman's "Second Spring" and significantly the nuns included those who came from the old Catholic recusant stock, from the Oxford Movement converts and from Ireland.[10] The blending of these three streams caused Wiseman and Manning considerable difficulties. Manning in the 1850s commented that "it is well that the Protestant world does not know how our work is hindered by domestic strife".[11] Many of Wiseman's dreams ended in disappointment because of the divisions of opinion within the different sections of the Catholic community.[12] But within the SHCJ there were no splits arising from these different groups.

Newman in his famous sermon had spoken of the resurrection of Catholicism. "The English Church was, and the English Church was not and the English Church is once again. This is a portent worthy of a cry; a second temple rises on the ruins of the old".[13] Mother Buckle in her recollections quoted this, and then took up the theme as applied to the SHCJ.

> This momentous era had now come, and therefore was it necessary that religious bodies of various habits and different aims should come to England and help restore the glories of the past by fulfilling their mission of devotedness and love. It was not enough that foreign religious should come to our aid. A Congregation was to be founded in our own beloved land full of the peculiar spirit of the English nation and to carry its best features to the different lands where it would by the grace of God be established.[14]

It is a significant feature of the SHCJ that it is an English Society, with its roots very much in this country. Cornelia had wide experience and was anything but insular. But once she arrived at Derby she began to stress the importance of reading the lives of English saints. Mother Buckle states that Cornelia "always mentioned it as one of the great mercies of God to our Society that although its Foundress was American the religious body was essentially English in its origin and traditions".[15] This was true of the ethos of the schools. In a reply to Bishop Grant in 1861 Cornelia deals with an objection from a mother that there were no organized visits to chapel in school in the afternoon.

> Regarding the Visit to the Blessed Sacrament the children are allowed to go down at 5¼ every day besides going after supper when the litanies are said, but they are not obliged to go. We generally find much more real piety - when we do not exact practices that are not of obligation.[16]

It was typical of her to incline towards liberty, and while it may not have been true of most of the schools in Victorian times, it is probably a more truly English attitude. One of the results here was that the schools did not develop the precious attitudes characterized in Frost in May.[17] They were free from any system of spying and were notable, or in some eyes notorious, for their freedom. The final result of the decisions which Cornelia took is not to be found in The Book of Studies, and is a spirit rather than a method. I would entirely agree with the author of a French study of Cornelia who wrote in 1931 of her system of education;

> It remained more a spirit than a system because it was the education desired by a mother and a very intelligent woman, who considered that education must not be a collection of rules, nor even the search for certain qualities, but a living preparation for life, and that it must go hand in hand with a contemporary social life.[18]

There was one restriction of the Catholic society from which Cornelia could not escape. By a policy of the English hierarchy pupils were not to attend Oxford or Cambridge. The ecclesiastical legislation was directed at boys, as it was still presumed in the mid-century that girls would not attempt anything so preposterous as to try to attend a university. Newman's university in Dublin floundered, and Manning later tried to establish one in Kensington (1875-82) which has been described as a "fiasco which had something of the virtue of an Ultimate Deterrent".[19] For girls in the Catholic community the only real entrée into tertiary education was to be found in a teacher training college, or in the finishing school of the SHCJ in France. The system of the SHCJ certainly developed under the stimulus of the training college at St Leonards, but thereafter it remained static until Catholic girls eventually began to take up the challenge of public examination. Significantly as soon as papal permission was granted for students to attend Oxford and Cambridge the SHCJ opened a hostel at Cherwell Edge for students who included some of their past pupils and some of their young religious.

It was really Cardinal Vaughan in 1897 who opened the way for Catholic girls to move into the area of competitive examinations, and so to university training.[20] The challenge was met by Cornelia's successors.

If there were definite restrictions upon education from within the Catholic community, this was only a reflection of Victorian society's attitude to women. It was not ladylike to earn a living, and middle class education lacked the spur of a profession, and the whole movement so well represented by Miss Buss and Miss Beale was not just concerned with the education of girls but with the wider question of the role of women in society. The nuns in the Catholic community were making one significant statement about this, namely that even ladies could nurse and teach, at least if they were religious. By the 1850s the number of gentlewomen who needed to earn their living was increasing, and at first the only scope for them lay in needlework and some forms of teaching, often as a badly paid governess, or subsistence as a companion.[21] Female independence was precarious, and it was only in 1882 that married women gained equal property rights.[22] Victorian society still assumed that a woman's place lay in the home, and many concluded from this that they had little need of education. The first restriction upon the education of middle class girls was public opinion. The inspectors commented upon this fact. But under various pressures public opinion was slowly changing. These pressures ranged from political reforms, the influence of the French Revolution, economic factors through to spiritual movements, of which the SHCJ were a part. It has been suggested that the Oxford Movement helped to bring back some mediaeval ideas of womanhood such as those exemplified by Hilda of Whitby, Catherine of Siena, and Teresa of Avila.[23] Significantly all these saints were part of the spiritual reading of the SHCJ nuns together with Gertrude, Jane de Chantal, Margaret Mary and Margaret Mary dei Pazzi and the Blessed Virgin

Mary. The library at St Leonards and in the other schools offered an alternative vision of the role of women.[24] So while society had a rigid Victorian mould the spirituality of the nuns was suggesting other possibilities to their pupils, and perhaps this enabled the schools to achieve the notably freer atmosphere than most schools of the time. Many of the women who worked to change Victorian society's notion of a woman's role came from an Evangelical background like Elizabeth Garrett Anderson, Emily Davies, Sophia Jex-Blake and Constance Maynard, but there was a lot of undiscovered common ground between them and the nuns in some of the Catholic orders. Unfortunately the structure of society was such that these different streams did not meet. Ideally the SHCJ should have been giving evidence to the Schools' Commission, and joining the School-mistresses' Association when it finally started in 1867. But Victorian ideas about nuns did not provide an opening in this direction. But if this did not happen in society at large, there is ample evidence that the schools were successful in exercising considerable pressure upon the parents, and broadening their ideas on education for middle class girls.[25] The schools were highly successful within the Catholic community, they had a well thought out curriculum, a liberal regime and a widening influence. Cardinal Wiseman's heart hardened against the nuns when Cornelia blocked his "marine residence" at St Leonards at the time of the case of Connelly v Connelly. But at the end of his days he visited St Leonards and found himself surrounded by the daughters of the old Catholic families, the Petres, Cliffords, Arundels, Talbots, Mostyns, Beddingfelds, Welds, de Traffords and others, and then said "Reverend Mother you have realised the desire of my heart".[26]

Cornelia Connelly was the foundress of not a school but something more like an education authority with its own range of schools. This in itself was a major achievement; the foundation of a religious order was an accomplishment in a different dimension. With religious orders stretching back in the history of the Church for some seventeen or eighteen centuries, and a great deal written about their history, attention has recently turned to study the factors involved in the development of such societies.[27] The initial study made by Raymond Hostie, SJ is restricted to male orders from the fourth century onwards, and as it is a psycho-sociological study it is only very tentatively that its findings can be applied to female orders in the Church, given that male and female psychology are by no means identical. Hostie is hardly to blame for restricting his work. Some years ago the president of the Union of Superiors General in Rome made a statement on behalf of 221 male and over 2,000 female heads of orders.[28] While this is some indication of existing orders, a survey obviously has to consider those which have flourished, declined and ceased to exist. There are many of these too. The hypothesis which Hostie offers from his survey is of a life cycle of birth, growth and decline, but on a much larger than human scale.

> Religious institutions have a hard life. Ten to twenty years is a normal gestation period for them. Consolidation takes almost twice as long. Expansion, if not delayed by the incubation period, takes about 100 years. Stabilization goes on for an equally long period. Then, suddenly, a period of decline sets in which in its turn may last from fifty to a hundred years. After this stage, depending on the circumstances, extinction is duly recorded but very much later. The full life cycle of religious institutions lasts usually somewhere between 250 and 350 years.[29]

Hostie makes due allowance for orders like the Benedictines which have managed to renew themselves and are still active after fifteen hundred years. His picture of the birth of an order is of early followers gathering round a leader, and eventually a rule being written to try to express both the ideals and the discipline of the emerging society. As the written word cannot adequately meet this demand, the life of the founder, posthumously, becomes another expression of the spirit of the order. If this model be accepted, it supports the thesis that for the SHCJ schools it is necessary to combine The Book of Studies with the practice in the schools and the life of Cornelia Connelly. In the history of the Society it underlines the grave difficulty which she faced in that her Rule was never approved by Rome during her lifetime. Soon after the foundation in Derby she had diocesan approval from Wiseman, but although she sought Roman approval, and went twice to Rome to work on revisions of the Rule with consultors, drafted and redrafted it, papal approval was never forthcoming. In retrospect it is easy to see that Rome was acting cautiously because of the apostacy of Pierce, and his presence in Florence. When approval was finally given after Cornelia's death, it was to the original Rule which she had written, without any substantial alterations, so that it is clear that there was nothing intrinsic to the Rule to prevent its approval. However lack of this seal by Rome did hamper the work of the Society and made Cornelia's position difficult. A number of bishops clearly preferred to have everything on a diocesan basis; the bishops of Philadelphia and Liverpool both made bids to curb the freedom of the Society, and Ullathorne expressed an attitude which was probably common to many Victorian bishops.[30]

> The troubles of the French Congregations of which you speak have all arisen from their adoption of the democratic method of election. Democratic government is bad enough for men, but it is absurd for women. As a rule sentiment is their motive power; and sentiment in them is like india rubber, at once tough and elastic, yielding on pressure, but reasserting its old

> tenacity, until you can put light and principle in the place of sense and sentimentality. But it is hard to get these into some minds and some Communities.[31]

There was some conflict of interest in what Cornelia understood to be her papal directive in founding the Society, and the desires of some diocesan bishops, and she had, unfortunately, to face these difficulties without the support of final papal approval. It was a trial which she shared with other nineteenth century foundresses, some of whom found themselves excommunicated by irate bishops.[32]

The size and rate of growth of the SHCJ was not spectacular by comparison with some of the nineteenth century orders such as the Mercy nuns, the Society of the Sacred Heart or the Daughters of Our Lady Help of Christians.[33] Between the years 1846 and 1879 the SHCJ had professed a total of 244 nuns of whom 55 were in the United States.[34] Fourteen of these sisters subsequently left the Society, Emily Bowles being the most obvious one mentioned in this study. After the death of Cornelia the Society continued to grow, and expanded into missionary work in Nigeria; there is an unpublished study of their contribution to education there.[35] This growth from nothing to nearly two hundred and fifty in thirty-three years is impressive, and in terms of educational recruitment in England was an important contribution. Not all of the sisters taught, but they did contribute one way or another to the running of the schools and formed a team which included cooks, infirmarians, secretaries, novice mistresses as well as teachers. The achievement of Cornelia lay in the creation of the whole team under very difficult circumstances.

The economics of the growth have been mentioned, and it is remembered here merely that the development was made in the face of both continued poverty, and also bigotry against nuns in Victorian society. A subtler problem was that of the divisions within the Catholic community between the old recusant stock, the new converts and the Irish. These divisions did not appear either among the pupils or the nuns although there were representatives from all three sections. Annie Laprimaudaye's father had been Manning's curate in Anglican days, and after conversion she was educated at St Leonards, joined the Society and played a prominent role.[36] The names of Bellasis, Marshall, Allies, George Matthew Arnold, Garside, Cavendish and Harper are but some of those associated both with the Oxford Movement and St Leonards. Some of the old Catholic names have already been listed.[37] Lady Castlerosse, who had been one of Cornelia's first pupils, later advised Mrs Ryan of Temple Mungret, Limerick to send her daughters to St Leonards, and two sisters, Eugénie and Bertha both became SHCJ nuns, and have been the subjects of a biographical study which illustrates something of the Irish tradition among the pupils as well as the spirit of the school.[38] The general scene is one of a creative blend of the three sections of the Catholic community which was not to be found in the country at large. A list of former students of St Leonards from 1850 to 1879 shows that of 462 pupils (listed with the date of their entry to the school) some 82 are known to have become religious in a wide variety of societies, but often including the SHCJ, and 142 to have married. Among these there were nineteen titled ladies.[39] The list for a shorter period at Mayfield, 1872-79 reveals that of fifty pupils, thirteen had become nuns and eleven were known to have married. Obviously the lists are incomplete, and after Cornelia's death someone has continued to add RIP after many names, suggesting that families thought it important to let the schools know of the death of a past pupil. Though incomplete the lists do tell a lot of the influence of the schools, the composition of the pupils and the effectiveness of the work of the SHCJ, especially when it is remembered that the schools for the middle and upper class pupils were a small minority.

The SHCJ also attempted to influence Catholic society by providing facilities for further religious development for ladies. In 1860 in the convent in Harley Street about one hundred ladies joined in making The Spiritual Exercises preached by Fr Eyre SJ. Lady Fielding and Lady Mostyn slept in the convent and Lady Clifford and Mrs Bellasis came each day.[40] It was the largest retreat organised for secular women at that time in England, and it became a tradition of the Society to involve their past pupils both in retreats and bazaars.[41] There were some functions of a more strictly educational nature for the past pupils of the training college. The impression gained is that while the SHCJ was cut off from the general society of girls' schools and staffs in Victorian England, it was in close contact with the Catholic community, and by 1860 had something of a leading role in girls' education. Cardinal Fransoni had been aware of the absence of prominent laywomen in the English Catholic community in 1846, but in a number of ways this gap was being filled by those in contact with the SHCJ.[42] Both Mary Allies and Agnes Lambert did a certain amount of writing,[43] Euphrasis Barbier became the foundress of the Congregation of Notre Dame des Missions,[44] and when the sisters were making their French foundation at Neuilly in 1876 they took temporary accommodation at Grenelle, Paris, in a house which had just been left vacant by a former pupil, Berthe Mercier, who with a few friends had been running an orphanage there.[45] Many of the girls were marrying into the upper class of society and nineteen of them were titled ladies by 1879.[46] Given that the Victorian Catholic upper class was not vast, a notable proportion of it was influenced by the work of the SHCJ.

The growing Society of the HCJ had suffered from a number of threatened splits with the trouble caused by Emily Bowles, and later a group of nuns known as the Preston cabal. A threat to the unity of any extending order would seem to be a normal sign of growth, and arguing from the history of other orders it is by no means certain that this would not have occurred even if The Rule had been given Roman approval. The indications are that between foundation and growth to mature establishment this is a crisis which religious orders, like many other societies, have to meet and conquer. Mother Buckle was critical of some aspects of Cornelia's government.

> I was always sorry that Mother Foundress did not put herself intirely (sic) with intire (sic) confidence in the hands of the Cardinal (i.e. Wiseman) and let him act as he pleased. He would have been a great Protector of our Order and perhaps done as much for us spiritually and temporally as Bishop Ullathorne did for the Dominicans and Mother Margaret at Stone - I could not help thinking as a Jesuit Father said - There was a great deal of natural and human mixed up with the Spiritual work of our Foundation - In most cases of a new Foundation or a new Congregation we see a Saint or holy soul place herself like St Jane Frances of Chantal under the Direction of a holy Bishop or Priest who takes the whole responsibility and the spiritual life of the Congregation is as flourishing as the temporal progress of the Community - I always thought too that from being a Convert and an American convert there were protestant ideas mingled with her Catholic convictions and a certain independence and want of those Catholic traditions which the Holy Father has since condemned under the name of "Americanism".[47]

Americanism was not so much a heresy of the New World as a recurrent nightmare which came from the French Revolution and haunted the Holy Office in Rome, taking a long time to work through the curial system.[48] Mother Buckle's outlook is typically Victorian and would have deprived the Society HCJ of all originality. It could never have produced The Book of Studies or the ethos of the schools of the Society. Victorian male prejudice would have triumphed and girls' education suffered. This would in all probability have been a more serious threat to the Society than bigotry from without. That caused unpleasantness, so that in London the sisters could not walk the streets in their religious habits in safety but it probably did not really impede their work or change the nature of the Society. The campaign of Newdegate and others in Parliament for the inspection of convents was a threat over the nuns for most of the century, but Gladstone noted that in the whole of his many years of campaigning Newdegate never produced one clear example of the abuse which he constantly alleged.[49] But the threats did not deter the sisters, and did not alter their style in the way in which immediate direction from the Catholic hierarchy might well have done. Cornelia's independence of spirit was a gift to the Society.

Much contemporary work on the role of women in nineteenth century England takes the form of a study of feminism which has still to complete its purpose of winning complete equality.[50] The story of Cornelia Connelly is a part of this history. A feminist such as Simone de Beauvoir has written on the harmful aspects of religion, so that it is astonishing to find her also recognising that women can achieve transcendence through it. She recognises that mystical fervour can be united with a life of activity and independence,[51] and certainly both these qualities are found in Cornelia. Her contemporaries did not always regard them as virtues. De Beauvoir, because of the limitations of her atheistic existentialism, is inclined to regard mysticism as merely subliminated eroticism, but at the same time she is clearly captivated by the personality of St Teresa and writes of her with enthusiasm and eloquence.

> There is hardly any woman other than St Teresa who in total abandonment has herself lived out the situation of humanity; we have seen why. Taking her stand beyond earthly hierarchies, she felt, like St John of the Cross, no reassuring ceiling over her head. There were for both the same darkness, the same flashes of light, in the self the same nothingness, in God the same plenitude. When at last it will be possible for every human being thus to set his pride beyond the sexual differentiation, in the laborious glory of free existence, then only will woman be able to identify her personal history, her problems, her doubts, her hopes, with those of humanity; then only will she be able to seek in her life and her work to reveal the whole of reality and not merely her personal self. As long as she still has to struggle to become a human being, she cannot become a creator.[52]

In a rather clinical work this is a surprisingly lyrical passage. De Beauvoir does not offer any explanation as to why the phenomenon of mysticism should occur often in the Catholic Church; she is merely fascinated with the spiritual freedom of Teresa of Avila. A similar freedom is to be seen in the life of Cornelia Connelly, and from this spirituality stemmed her creativity in girls' education. It was achieved in the face of great difficulties, and clearly based upon her understanding of the mysteries of the Incarnation and Redemption. From the general tenor of her life one would suspect that the depth of this insight grew from mystical graces, but the evidence here is restricted.[53] But even without this she is a clear example of theological understanding resulting in creativity in education, and this is perhaps the final significance of her achievement. Many of the ladies in the nineteenth century such as Florence Nightingale and Dorothea Beale were working from a deeply religious background, and teaching especially was seen as a religious ministry. Matthew Arnold, addressing teachers, told them that "no parochial ministry can be more properly a cure of souls than yours".[54] The secularism of the twentieth century would doubt whether theological insights and educational practices could meet in a fruitful union. Cornelia Connelly is witness to the contrary.

Pope Gregory XVI seemed to have asked Cornelia to found a teaching order, and Cardinal Wiseman was very insistent on the needs of middle class girls. Cornelia achieved both of these aims, and also contributed considerably to the needs of the poor. T.W. Allies giving evidence to the Newcastle Commission of 1860 dwelt on the poverty trap, and the fact the government money was not reaching those most in need; "Catholics, as I have stated above, are in too many places simply in the condition of Lazarus, and not even a dog from the Privy Council office comes to lick their sores".[55] It was the charity of the religious that reached those most in need, and in many parts of London and the whole of Preston it was the Holy Child nuns. The quality of the education given to the poor was of the highest; what Marshall as inspector said of St Leonards in 1853 was eventually echoed elsewhere; "I have never seen and never expect to see a more admirable school".[56]