THE DEVELOPMENT OF METHODS FOR THE STUDY OF PROPERTIES AND PERFORMANCE IN FABRIC FOR INDUSTRIAL AND ENGINEERING END-USES

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by

DAVID G. NEILLY

being an account of work carried out
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Department of Textile Industries,
The University of Leeds,
LEEDS, LS2 9JT.

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"I admire from a distance those who contain themselves till they worked to the bottom of their results, but as I am not in the very least sensitive to having made mistakes I rush out with all sorts of crude notions in hope that they may set others thinking and lead to some advances"

Professor G.F.Fitzgerald (1889)

ABSTRACT

This work examines the history of industrial fabrics and investigates how certain of these fabrics have developed to meet the changing demands of their end-uses. It also examines how woven textile fabrics are increasingly competing with the traditional engineering materials as new fibres and filaments allow an ever increasing range of properties; improved fabric engineering techniques are also ensuring that industrial fabrics are more suited to their end-uses.

To aid fabric engineering a greater knowledge is required of fabric structure and mechanics, so developments in this field are examined.

To help improve fabric research of this type, realistic physical testing methods are required both to test the usefulness of mathematical models, and to simulate conditions experienced in use. Due to certain restrictions of this type of testing, a suitable selective fabric extension measuring device is required so that problem areas such as clamping effects can be avoided. The lack of a suitable device to help overcome problems such as this has been a long standing difficulty, so the development of a new fabric extension gauge was one of the main objects of this work.

Before such a device could be developed research first involved a survey of many of the previous extension measuring devices, however, as expected nothing suitable emerged. After considering many ideas for possible new devices, it was decided to try and develop a gauge using the relatively new material PVDF piezo polymer film. This is a thin, low modulus film which develops an electrical charge proportional to a CHANGE in mechanical stress, and which can be easily cut to any desired dimensions. Initial attempts to develop a suitable extension measuring device were not completely successful, but when suitable following circuitry was found, and a proper mounting procedure determined, the new gauge appeared very promising.

When it was considered that a suitable extension measuring device was available, the next task involved the design of a biaxial tensile and shear testing machine for the new Clothworkers' Textile Mechanics and Structures Laboratory. It was considered that the availability of a suitable selective extension measuring device was of paramount importance before the design of the new tester could be considered. This apparatus was based essentially on the proven principles of Yendell's and Bassett's testers, but a number of unique features were to be added, such as independently controlled clamps, and the ability to cycle in shear. The principles involved in the design of the mechanical hardware are described, as also are certain original recommendations which have been suggested for the second stage of the project in which the sophisticated control, measurement and analysis techniques will be developed.

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CHAPTER 1

THE HISTORY AND DEVELOPMENT OF INDUSTRIAL AND ENGINEERING FABRICS

Introduction

Today there are many uses for industrial and engineering fabrics and these include air inflated structures, personal load carrying equipment and carrying bags, tarpaulins, protective clothing, conveyer-belting, sailcloth, and geotextiles. In the manufacture of the majority of these fabrics man-made and synthetic polymer fibres are used, but for thousands of years before these fibres became predominant, the natural fibres, especially cotton, were the main fibres used in the manufacture of this type of product. It was not until the mid-twentieth century that the man-made fibres began to gain a strong foothold.

Initially these new fibres were developed and introduced to supplement the natural fibres. They were not really intended to be imitations, and each had its own individual characteristics. All fibres have their own particular advantageous properties suitable for specific end-uses, and the future of the textile industry to a large extent depends on the use and development of all fibres to provide the widest possible range of fabrics for the growing number of potential end-uses.

In the past a relatively narrow range of properties were available from the natural fibres, compared to what is available today, and although a particular construction may be essential for a given purpose, it is often the choice of the fibre that determines whether the textile will withstand the agents and environmental conditions to which it is exposed. These agents may include extremes of temperature, severe weather, chemicals, atmospheric pollutants, and micro-organisms. Other requirements are mechanical, these may include resistance to high stress, abrasion, fatigue and shock loads. In part it was the narrow range of properties which limited the use of textile fabrics in industrial, constructional and engineering applications (1). Despite this there were a number of industrial applications and some of these date back thousands of years, these included the use as tent fabrics, sacking, funerary fabrics, sailcloth and awnings.

1.1 The Earliest Fibres Used in Industrial Fabrics

The most ancient use of fibres was probably for cords and ropes. The making of which by plaiting and twisting fibres, hair and strips of hide probably began in Palaeolithic times; cave-paintings in eastern Spain of Late Palaeolithic or Mesolithic date depict a person using what appear to be ropes to climb down the face of a cliff, in order to collect wild honey (2). The earliest definite evidence of weaving comes from the Neolithic cultures of c.5000 B.C. (3) However, knowledge of how men lived before this date gives some idea of yet more primitive techniques from which weaving derived. These early techniques may well have been woven mats or baskets made from strips of papyrus or plaited rushes (4) In the manufacture of the first industrial fabrics, such as mentioned above, fibres such as flax, wool, ramie, cotton, animal hair and asbestos were amongst the first recorded.

The use of natural fibres for textile materials began before recorded history, and the oldest indication of their use in Europe is probably the discovery of linen fabrics at excavation sites of the Swiss lake dwellers c.2500 B.C. (3). The spinning and weaving of linen was being carried on in Egypt by 3400 B.C., and this indicates that flax was cultivated sometime before this date. Reports of the spinning of cotton in India date back to 3000 B.C.. Hemp, which is considered to be the oldest cultivated fibre plant, originated in S.E. Asia, then spread to China where reports of cultivation date to 4500 B.C.. The use of natural fibres for spinning and weaving considerably predates the establishment of these civilizations (5).

Cotton is the world's most important non-food agricultural commodity, and it is found as hairs which are attached to the seeds of certain plants of the genus Gossypium. It is the only species of this genus which is commercially cultivated.

The concept of producing textile fibres from seed-hairs was known to the early Indian peoples and materials have been found in tombs which date as far back as c.3000 B.C.. Cotton was probably cultivated in Egypt by about 600-700 A.D., it was also produced by the early Chinese.

During Roman times cotton was produced in the Mediterranean basin, and was grown on the Greek mainland from the 8th century A.D.. Arab traders introduced cotton to the rest of the African continent. In the 12th century Venice became a major cotton manufacturing city, processing cotton from the Mediterranean area into cloth for sale in Europe (5)

The fibre obtained from the flax plant, from which linen is manufactured, is one of the most ancient of the fibres known to man, and some think second only to wool. To-day flax fibres come from the annual, Linum Usitatissimum and can be grown in many temperate and subtropical regions. This annual flax is known to have been cultivated for at least four thousand or five thousand years in Mesopotamia, Assyria, and Egypt and was, and still is found wild in the districts included between the Persian Gulf, the Caspian Sea, and the Black Sea.

In excavations in the 1860's it was discovered that the lake-dwellers of Eastern Switzerland, at a time when they only used stone implements, and did not know the use of hemp, cultivated and wove a flax which is not our common annual flax, but the perennial flax called Linum Angustifolium, which is wild south of the Alps. This flax is usually perennial, rarely biennial or annual and is found wild, especially on the hills throughout the region of which the Mediterranean forms the centre; that is in the Canaries and Madeira, in Morocco, Algeria and as far as the Cyrenac, from the south of Europe as far as England, the Alps and the Balkan Mts.; and lastly in Asia from the south of the Caucasus to Lebanon and Palestine. The cultivation of this flax is very ancient and was replaced by the annual flax (6).

It has been suggested by one author (6) that this annual flax appears to have been introduced into the north of Europe by the Finns (of Turanian race), afterwards into the rest of Europe by the western Aryans, and perhaps here and there by the Phoenicians, lastly into Hindustan by the eastern Aryans, after their separation from the European Aryans.

Others (7), however, simply say the use of linen spread from Egypt throughout the Mediterranean and was carried to northwest Europe by the Romans.

As already mentioned the cultivation and preparation of flax is one of the most ancient of all textile industries, very distinct traces of its existance during the stone age being preserved to the present day. Keller (8) said of the lake-dwellers of Switzerland:-

> "Flax was the material for making lines and nets for fishing and catching wild animals, cords for carrying earthenware vessels and other heavy objects; in fact, one can hardily imagine how navigation could be carried on, or the lake-dwellings themselves be erected, without the use of ropes and cords; and the erection of memorial stones (menhirs,dolmens), at whichever era, and to whatever people these monuments may belong, would be altogether impracticable without the use of strong ropes"

As mentioned previously, hemp (cannabis sativa), is possibly the oldest cultivated plant, it originated in Central Asia and spread to China where it is reputed to have been cultivated for more than 6000 years. However in many cases this plant was not cultivated for its fibre, but for the drug which could be produced from it.

Animal skins and furs were the clothing of primitive man, but he soon realized that the hair and wool could be removed from the animals and spun into yarns, which could be woven into fabric. Wool was probably the first fibre that man made into a fabric and this may date back to the earliest Stone Age 1,750,000 years ago. Wool fabrics have been found in the ruins of the Swiss lake dwellings. In Iraq, archaeologists have found seals indicating trade in wool as early as 4200 B.C.. It was evidently from Central Asia that sheep and wool were introduced into other areas of the world (9). The first domestic sheep in Europe were brought from the Near East by neolithic settlers, who finally reached Britain around 3000 B.C.. There were wild sheep in Britain before this, but they were deer-like creatures with very little wool.

Asbestos is a mineral fibre and it was apparently used by the Greeks from ancient times. However, the first recorded account of its use was not until the 1st century A.D. by Pliny the Elder (c.23-79 A.D.). He wrote a National History dealing with astronomy, geography, zoology, and mineralogy, and was unfortunately killed during the eruption of Vesuvius. The Romans used it for lampwicks and cremation cloths, but it was apparently forgotten in medieval Europe. In the 13th century Marco Polo brought back news from China of cloths that did not burn when thrown in the fire (10).

Apart from these fibres others were used quite extensively in the production of early industrial fabrics, these included jute, ramie and silk, but they will be mentioned later.

The first mechanical use of fibres was probably in the form of ropes and cords, but it is the investigation of industrial and engineering fabrics with which we are now concerned. As mentioned the first fabrics were probably plaited rushes which formed mats. Evidence of nets has been found from very ancient times and these may loosely be described as the first industrial fabrics. The first true industrial fabrics, however, were probably funerary fabrics and sacking or also possibly tent fabrics, awnings or sailcloth. In later times the industrial uses, of natural fibres, increased and included such uses as linen webs used in saddle manufacture, flags and ensigns, kites, balloons, windmill sails, dirigibles, aeroplane fabrics, tyre fabrics, and military applications such as belts for machine-gun cartridges and torpedo screens.

1.2 Early Industrial Fabrics

Funerary fabrics were probably one of the first of all industrial fabrics, they were used for mummy wrappings. A mummy is a dead body, as preserved by the ancient Egyptian method of embalming. The preservative climate of Upper Egypt and the belief of the Egyptians in life after death led them to take unusual care when preserving the bodies of their dead. In prehistoric times in Egypt the dead were laid in the graves on mats in the crouching position common in the burial of primitive peoples, and were supplied with jars of food, flint instruments and other objects which might be required in the after-life (11). In Egypt examples of both fine and coarse linen cloth has been found in burial chambers which date from 3400 B.C.. Some mummies have been wrapped in as much as 900 m of very fine linen. Cotton fabrics have been found in tombs in India dating from 3000 B.C., however, not all these fabrics have been used as funerary fabrics, many were furnishings for use in the after-life. Funerary fabrics may have been one of the earliest industrial fabrics, but they did not really require any complicated engineering for their end-use, so added no new technology to the early industrial textiles industry.

Sailcloth could also have been one of the earliest industrial fabrics. Sails started to evolve from the moment man first realized that a palm frond, a bush, or a bulky cargo helped to propel a boat if the wind was astern; it was then a short step to making a sail specially for the task . The oldest evidence of a sailing boat may be a clay model of c.3500 B.C., found in a grave at Eridu, southern Mesopotamia. A small cylinderical socket in the bottom slightly forward of amidships, and a hole in either gunwale a little abaft this, may represent a mast step and the means of securing rigging (12). Generally it is assumed that this model represents a skin-covered coracle; and although the features described could be sail fittings it is not certain.

Definite evidence, and the earliest known picture of a sail craft appears on a small vase from southern Egypt, now in the British Museum in London. This vase is considered to date from c.3000 B.C.. Other possible representations of sailing craft are to be found on pottery dated 3200 B.C., but interpretation is difficult. In the present state of knowledge, all that can be said with certainty is that in craft of skin and reed, rudimentary sail was used in Mesopotamia and Egypt during the 4th millennium B.C., and that it was in these areas of the Fertile Crescent, and not in the Far East, that sail was first hoisted (12).

The earliest proper sails were square and were used mainly in the eastern Mediterranean and on the rivers of Egypt from about 2500 B.C. onwards, but it took over 3000 more years to develop the lateen fore-and-aft sail in the Middle East, thus opening the way towards progress into the wind (12).

It is not certain what the first sailcloth was made from, but the Egyptians are believed to have used woven strips of papyrus as early as 3000 B.C.. The Roman bulk grain carriers, such as the one in which St. Paul was wrecked on the island of Malta, used tanned ox hides, as did St. Brendan for his legendary voyage from Ireland to America (13). The earliest actual record of a textile sail fabric is of the Phoenicians of Tyre obtaining their linen sailcloth from Egypt in about 500 B.C. (14):-

> "of fine embroidered linen from Egypt, was your sail, serving as your ensign; blue and purple from the coasts of Elishah was your awning"

Flax was in general use for commercial and naval ships up to the end of the sailing ship era, and in fact is still woven for some of the world's sail training ships, and for the few remaining spritsail barges (13). Hemp and ramie were occasionally used, but flax and cotton were the chief fibres employed at the end of the 19th century. The very best sailcloth was made from long flax, as this fibre possesses flexibility, lightness and strength combined. Egyptian cotton was used for yacht sails and for the lighter commercial sails, and American cotton was used as well as flax by American square riggers and schooners.

The fact that an open, limp membrane surface is stressed under wind loading, thereby changing its form, and that defined forces occur at its edge is one of the early technical experiences of mankind. As the sails required to drive a craft to windward function on an aerodynamic basis, the material from which they are made assumes considerable importance, and no matter how much care goes into making a particular sail, it will never be satisfactory if it is constructed from an inferior textile fabric. Hamburger (15) states that, "historically products were manufactured to 'serve the purpose' rather than to serve a specific purpose". Sailcloth must have been one of the first fabrics which were engineered to meet a specific purpose. As the craft grew in size and as the rig developed and the requirements for windward performance became more demanding, so also would the demands on the cloth itself. Sailmakers wish to build into a sail a certain aerodynamic shape and they want the sail to retain this shape, the difficulty is the sailcloth itself.

In the past the shape which has been built into a sail has been mainly dependent on the skill and experience of the sailmaker, but to-day they are learning to use computers to aid in the design of their sails. To do this they must, among other things, be able to consider that the cloth is of a certain standard and specification and that these are achieved consistently. However, often this was and in fact still is a problem as there can be much variation in each batch of fabric, even across the width of the cloth with problems such as uneven tension in the selvedges. These variations in the cloth make it unpredictable under stress and therefore logical or analytical sail design is practically impossible. This problem was recognised many years ago, and as Sadler (16) pointed out in 1892 :-

> "If more attention were given to the manufacture of canvas, and to the displacement caused in the threads when in their relative position in the sail by strains, and if a correct allowance were made for such displacement, the greater part of the yacht-sailmaking trade of the world would not be confined to a single firm as is now the case".

It was not until quite recently that research was carried out to try and deal with these problems objectively (17) (18). However, research (19) (20) (21) had been carried out previous to this, before World War 1, which dealt with many similar problems in fabric which was to be used on closed membrane structures, such as dirigibles. This will be looked at later in Chapter 1.3 .

The word ´awnings´ has a wider use to-day than its original nautical use. An awning was a roof like covering of canvas or similar material, used as a shelter from the sun or rain above the deck of a vessel. One of the earliest records (22) show that the Phoenicians from Tyre obtained their awnings from the coasts of Elisha, probably about 500 B.C.. This fabric would not have required the same level of technology during its manufacture as that of sailcloth.

Tent cloth was another very early industrial fabric. The tent has been defined as a portable habitation or place of shelter, consisting in its simplest form of a covering of some textile substance stretched over a framework of cords or poles or of wooden rods, and fastened tightly to the ground by pegs (22). The tent is not man's earliest dwelling, because it is difficult to make a fully portable dwelling; but the simplest we know of, the windscreen and the hut, are very close to being tents.

One of the first proper tents, was the nomads black-tent. This was the tent of the bible, Jews and Arabs, and early records appear describing it (23). Faegre (24) states that the black-tent probably first appeared somewhere near Mesopotamia. Its origin was most likely tied to the domestication of goats and sheep, the animals that provided the material for the tent cloth and permitted the early nomads to begin their break from settled agriculture. The black-tent moved from its homeland and spread from the Atlantic to the eastern borders of Tibet. As it spread it was adapted to fit each particular environment it entered. Black-tents are still in use to-day and there dwellers are weavers. They weave not only the roofs, walls and floors of their homes, but many of the furnishings as well.

The preferred fibre for all black-tents is goat-hair, only this fibre has the requisite strength and length. It is the particular tensile qualities of goat-hair that give the black-tent its distinctive form. Many tents are made of pure goat-hair, but often sheep or camel wool or a plant fibre is added. Pure sheep wool stretches too much under tension, while camel hair is short and weak, thus a certain percentage of goat-hair is always needed. The true black-tent obtains its "blackness" from the natural jet black colour of the goats hair, however many "black-tents" are not black at all but dyed other colours.

The horizontal ground loom is used to weave a variety of different types of cloth. Roof and tension band cloth is made with a tight weave to shed water while walls are a looser weave.

The primary purpose of the tent is to provide shade, protection from the cold, wind, sand, and dust, and to provide privacy. The black colour is functional in that it gives more shade, and while black absorbs heat, the loose weave lets heat disperse so that the inside is 10-15 degrees Centigrade cooler than outside.

The tent cloth is a thick heavy blanket and although the weave is loose it gives a fair rain protection, when wet the yarns swell closing the holes and the natural oils on the hair shed the rain for a while. The tent will leak in prolonged rain and the greatest problem with a wet tent is that it can become so heavy that the pack animals cannot carry it.

Wool and hair material insulate from cold, the Tibetan black-tent made from Yak hair is used in extremely cold country. The black-tent walls do not protect from the wind, so the dweller must put up reed, stone or brush for additional protection in wind.

The life of the tent cloth is five to six years and in order to keep the material from rotting the lower edges are pitched so they don't touch the ground. The tent cloth is stretched by stays made from wool, hair or hemp (the latter is strongest). The desert tribes use very long stays to absorb the shock of high winds. The tents of the eastern zone have stays attached directly to loops sewn to the edge of the tent cloth. The western zone are more complicated. The stay is attached to a stay fastener which is itself fastened to a tension band. This method spreads the stress created by the stay over a wider area of the tent cloth.

There are many different type of black-tent and these include Kurd, Lur, Tibetan, and Bedouin.

The black-tent, which is still used today, although in many cases modern fabrics are used, was by no means the only tent used in ancient times, but it is an example of one of the first tents which it appears evolved so well to suit its application in its initial years that it has lasted for thousands of years.

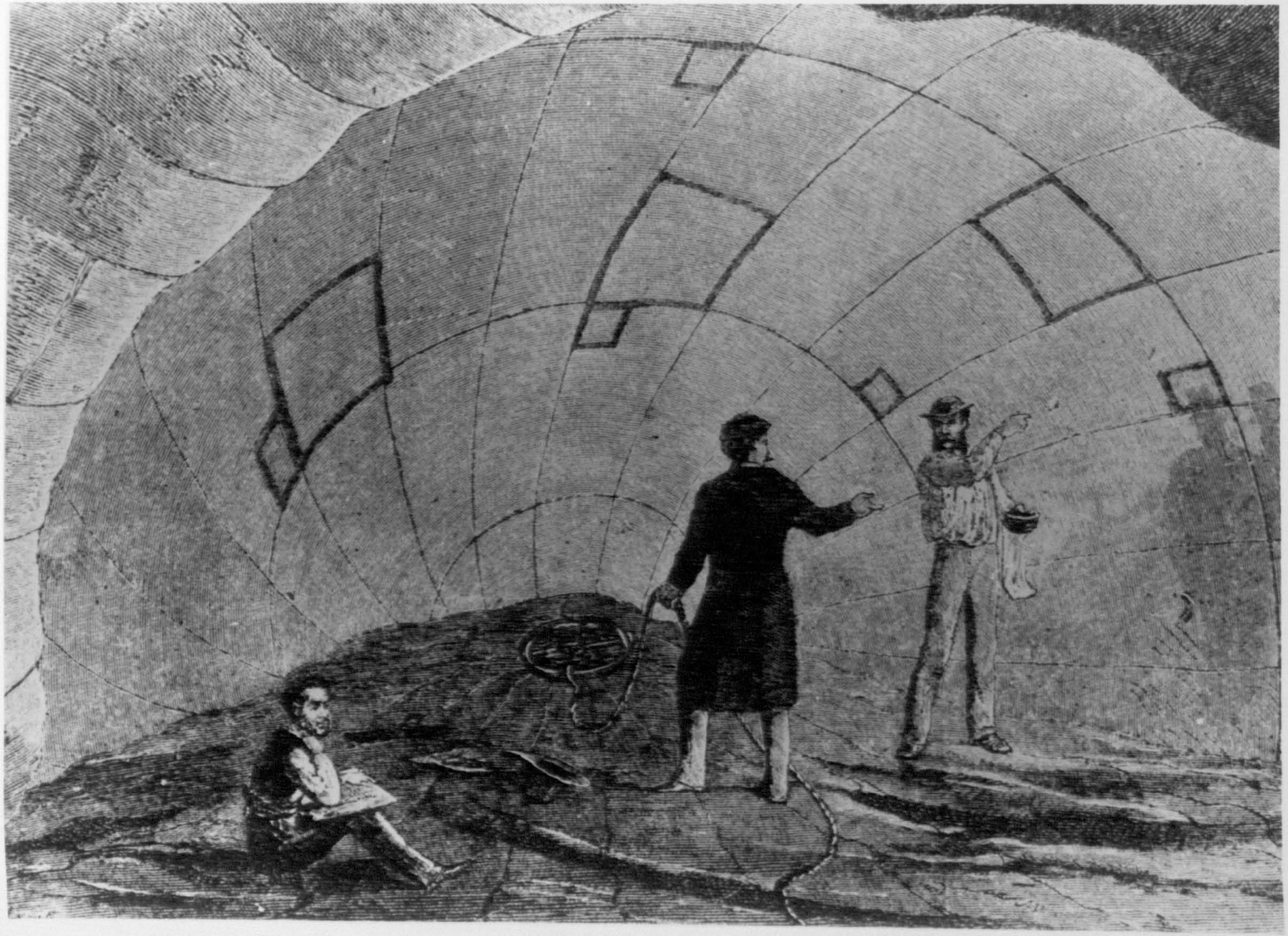

Plate 1 - John Wise working on the interior of a balloon inflated with air (c.1835). Was this type of structure the inspiration for the first air houses?

So as can be seen ever since pre-historic times hand made tents of various materials and design have been the all seasons home of nomads, but also the campaign shelters for armies. In the old Orient, and in medieval and Renaisance Europe, ostentatious and richly furnished tents were even the status symbols of princes and nobles.

Nowadays extensive use is made of tents by trade fairs and exhibitions, circuses, exploration teams and highly mobile troops in the field. New designs are being developed for even larger and more stable frame-and-fabric structures. In 1971, Price and Newby (25) carried out a survey of air-structures, this included one of latest type of temporary habitable structures which are known as "air-houses". However, if a tent is defined as a framework covered with a fabric skin, such "blow-up" structures are not really tents (26) (see Plate 1). Nevertheless it is to a great extent new fabric applications such as these which are stimulating the need for new research into the mechanical properties of woven fabrics.

Sacking was a very early use for industrial fabrics and there are many ancient references to sackcloth. A sack (27) is a large bag of coarse cloth material which can be used for holding grain, flour, coal, vegetables and many other commodities. In the past sacking has been a heavy closely woven fabric, originally flax, but by the early 20th century it was almost exclusively made from jute or hemp. Sackcloth was formerly worn in mourning or penance and there are numerous biblical references, eg. (28).

Another quite early use for fabrics, although the use was probably not extensive, was in the manufacture of kites. Sail and box kites are still used as toys to-day, and the latter was discovered by L.Hargrave as recently as 1896. Sail kites however, have been known for centuries and their basic form is known to most. The membrane is made of cloth, parchment or paper.

In the times of the Dacians, Scythians, Parthians and Persians, as well as the Romans since Constantine, mobile kites were used as banners. Christian Armies carried them in the early Middle Ages and they were also known in India at that time (29).

Dacians are depicted on the frieze of Trajan's Column in Rome with their field kites. These kites consisted of open metal caps and membrane tubes fixed to them; these were inflated by air to look like the bodies of animals. On some occasions lighted torches were put in their mouths, and at night this gave the impression of beasts spewing forth fire and smoke and moving through the air under their own power. In 1241 a "Christian Army" is said to have been put to flight by such banners carried by the Mongols.

Complete animal bodies with clawed feet and stabilizing wings on either side were constructed in the 15th century. In an armoury book from Frankfurt on Main, dated 1490, there is a dragon kite which is inflated by hot air and moves forward by means of a rocket in the hind part of the body and is held by a long string (29). These closed membranes can be considered as forerunners of the later hot air balloons.

Kites were used for scientific purposes by Wildon in 1749 for the measurement of atmospheric temperature and in 1752 by Franklin for the proof of thunderstorm electricity. Kites were also important as research apparatus in metrology.

1.3 The Development of Modern Industrial Fabrics

The fabrics which have been mentioned so far are examples of uses which are in some cases well over a thousand years old. However, in the past few hundred years there have been increasing uses for industrial fabrics. One of these was in the construction of free and captive balloons. These are generally regarded as the forerunners of present day pneumatic structures, but as we have seen, pneumatic forms have existed very much longer. Indeed apart from the kite structures, inflatable mattresses made from skins and fitted with bellows were depicted in a 1537 edition of a book on warfare compiled by Flavius Vegetius Renatus in the late 4th century A.D. (26). Despite this balloons have remained by far the most important prototype for pneumatic structures to date.

A balloon by definition is a globular bag of varnished silk or other material impermeable to air, which, when inflated with gas lighter than air, can be used in aeronautics, or according to its size, for any purpose for which its ability to rise and float in the atmosphere adapts such a mechanism. "Balloon" in this sense was first used in 1783 in connection with the invention of the Montgolfier brothers, but the word was in earlier use (derived from Italian ballone, a large ball) as meaning an actual ball or ball game (30).

Cyrano de Bergerac (1619-1655) in his novel "Les Etats et Empires du Soleil", describes a smoke-filled balloon that, with the aid of a sail, carries a cabin in space. A copperplate engraving of this fantasy appeared in 1657. At about the same time the Jesuit, L.Lauras, also developed the idea of a warm air balloon. On 8th August 1709 in Lisbon the Brazilian, Bartholomew Lourence de Gusmao, ascended to 200 feet (60.96m) in a hot air balloon. Also in a Russian manuscript it is recorded that in the year 1731 in Asen an official of the province of Nerechtes Krjakutnoi made an ascent in a hot air balloon in which he was almost killed when thrown against a bell tower, but he saved himself by grabbing the ropes used to ring the bells (29).

To most people it is the hot air balloon constructed by the brothers Joseph Michel and Jacques Etienne

Montgolfier that is considered the first structure of this kind. The balloon first ascended on the 5th June 1783, at first unoccupied, later with animals, then on the 15th October 1783 the first human being ascended. This was Francois Pilatre de Rozier in a captive balloon. On the 21st November 1783 Pilatre de Rozier and Marquis Francois Laurent d'Arlandes were the first men to ascend in a free balloon in the Bois de Boulogne.

On the 1st December 1783 Charles then ascended from Paris using a hydrogen balloon. Modern balloons descended from this type of balloon and it was more significant for the future of balloon travel. The envelope was spherical and was airtight and tear resistant. It was made of silk and this was strengthened and the air holding capacity improved by a coating on the inside of liquid rubber. There was a gas valve on top of the balloon which could be released from the basket using a cord. In this way gas could be released to prevent an undesired ascent, just as an undesired descent could be prevented by throwing out ballast. The inflation tube was kept open and air pressure forced the gas into the balloon. In the air this open tube prevented the balloon bursting because the excess gas could escape when the air pressure lowered during ascent. When descending this had to be compensated for by throwing out ballast. In the Charles balloon a net was used to fasten the basket to the balloon. This distributed the load uniformly (29).

During the 19th century the use of balloons increased and there were fears that Napoleon's army might invade London using this new contrivance. Balloons were used for military observation, sport, map-making, and scientific purposes and there are many accounts (31) (32) (33) (34) in the 19th and early 20th century literature of balloonists and their exploits.

In 1931-32 the Swiss physicist, August Piccard (1884-1962) made record ascents in his stratosphere balloon to 16,000m. This was the largest balloon in the world at the time and it resulted in important discoveries concerning such stratospheric phenomena as cosmic rays. This balloon was only partially inflated on the ground and by means of gradual expansion of the hydrogen it only obtained its spherical shape at its highest altitude.

In the 1950's research sponsored by the joint military services of the U.S. resulted in the development of the modern zero-pressure balloon. These were tear-drop shaped and constructed from polyethylene film and were used extensively in scientific work.

Even today new uses are being found for balloons. Piasecki (35), an American aeronautical designer describes the "Heli-Stat". This invention proposes to combine a balloon and helicopters to form a new type of vehicle. Piasecki (35) recognised that some 40-50% of a standard helicopter's lift force is used to support the helicopter itself. Subtracting that, the lift power of even the largest commercial helicopters is usually not much more than 15 tonnes. He proposes to overcome this limitation by combining the technological advantages of the modern helium balloon to those of the helicopter.Two Sikorski SH34 helicopters are to be joined to a 1 million cubic foot helium balloon and therefore all the helicopters lift can be used to carry load. The load could amount to 100,000 pounds (45,360kg) and the "Heli-stat" will carry it economically for up to 50 miles (80.47km). Potential uses include large-scale agricultural spraying, heavy container transport and the lifting of heavy pipeline sections to remote areas. The design is also to be adapted to carry the U.S. Army's new Main Battle Tanks which weigh 53 tonnes each. Although details of this machine have been available since 1961 it will not be test-flown for the first time until sometime in 1985.

From the first day that a man ascended in a balloon, it did not take long for him to realise that an ordinary balloon is, in fact nothing more than a lifting machine, no more capable of sailing the sky, in the proper sense of the word, than a cork floating in the water is capable of sailing the sea. Experiments were carried out in which sails were attached to balloons in an attempt to make progress against the wind, none of these attempts however, were very successful. One of the earliest successful attempts was by the Frenchman, Giffard (1825-85). He built a long cigar shaped balloon, or non-rigid airship as they became known. This was 104 feet (31.7m) long and 39 feet (11.9m) in diameter and was powered by a heavy steam engine. This was first flown near Paris in September 1852, but its success was limited.

What the first designers were after was a balloon which could be steered. To achieve this ,long streamlined, cigar shaped balloons were developed and these became known as airships. In fact airships became known also as dirigibles, a word which came from the French diriger, "to steer". For 50 years after Giffards attempt progress was slow and in 1909 Thayer (36) was able to say :-

> "First, with regard to the balloon or air-ship, it may be said that it is only within comparatively recent years that any successful attempts have been made to direct its motion of translation through space, irrespective of the direction of the drift of the wind. And it is only within the last twenty years that the so-called dirigible balloons have been successfully constructed, all of them working, however, on the same principle or method of propulsion......screw-propellers"

In these early days both the French and British systems of construction produced a rigidity in the envelope by means of the enclosed gas which was under greater pressure than the outside air. In the German construction of General Count von Zeppelin the rigidity of the envelope, of the ship proper, was materially assisted by longitudinal ribs of aluminium, braced, more or less transversly, and held in place by circular ribs of the same metal attached to the longitudinal pieces at regular intervals. The skin of the envelope was supported on the frame and lifting power was supplied by a number of gas-bags held internally. These Zeppelin designed airships first appeared about 1900, but other quite well known German airships were designed by Major von Parseval. The principal characteristic of the Parseval ship was that it had its design based on engineering tests. The torpedo-shaped form of the envelope was the result of tests at a research laboratory set up at the University of Gottingen, to obtain a shape giving the least head resistance for a given volume. The arrangement of fins and rudders for stability of route and control was also studied by the use of small models in the Gottingen wind tunnel. The strength of the envelope fabric required was determined from the known pressure distribution about the hull in motion, as found by wind-tunnel tests at Gottingen, together with the known physical properties of the fabric as given by a testing machine (37).

In the first twenty years of the 20th century the airship and indeed early aircraft research could be likened to the present day space programme. To early aeronauts and aeronautical engineers it seemed obvious to use textile fabrics, of the woven type, in the construction of their balloons, airships and aeroplanes, because of its lightness. However, this was not fabrics only asset. It had tear strength and could recover from loads and also had the ability to absorb repeated flexing along with the ability to redistribute local overloads. It was also easy to form and work with and it was readily available. Many of these properties were still found an advantage in the late 1950's and early 1960's when work was being carried out for the U.S. space programme. Fabrics were investigated as the construction material for such structures as inflatable re-entry vehicles. Topping (38) and Leonard et al (39) describe some work which was initiated for applications such as this.

The early aeronautical engineers did however have problems in finding the correct fabrics. There could be many variations in the properties of the fabrics and it was their problem to link the most advantageous mechanical properties to lightness of weight as well as the ability to withstand ultra-violet light. In the early years of the 20th century much work was carried out on the investigation and testing of fabrics to ensure they met certain specifications and much of this involved the design of new testing apparatus, as little, if any, previous work had been carried out. This work was very much accelerated due to threats of war, as there were many obvious military applications. Research (19) (20) (21) (40) (41) (42) as would be expected, was concentrated in countries such as U.K., U.S.A., France and Germany, and one of the most outstanding pieces of work of this time was carried out in Germany by Haas and Dietzius (19). In their report they state that in the envelope of semirigid and non-rigid balloons :-

> "Every applied force causes a deformation. So long as the deformation does not impede the operation of the ship, it may be ignored. This is usually possible when the ratio of length to breadth (of the envelope) is small. As the ratio increases, the bending and shearing forces, partly resulting from the load, partly appearing only when the ship is in motion, increase; the shearing forces appearing especially when the airship is moving rapidly. The limit beyond which the deformation is no longer tolerable is then easily reached and passed. This was the case with the trial airship of the Siemans-Schuckert Works. It became apparent in the early weeks after the filling, and later on during voyages, how advantageous, and indeed how necessary, it would be to have an exact knowledge of the properties of the fabric, in order to plan the shape of the envelope"

In the U.K. in May 1909, it was decided that aeronautical research must be co-ordinated in some way. Therefore Asquith, at the suggestion of Lord Haldane, the War Minister, appointed the Advisory Committee for Aeronautics for the Superintendance of the investigations at the National Physical Laboratory, and for general advice on the scientific problems arising in connection with the work of the Admiralty and War Office in Aerial Navigation (43). It was the responsibility of the committee to bring some cohesion to the work being carried out, but it had no executive functions and could not initiate research. Its role was purely advisory, and it could study, with a view to proposing practical solutions to only those problems which had arisen from outside research and which were referred to it (44).

In addition to investigations conducted at the National Physical Laboratory on its behalf, the committee was also concerned with the work on aeronautics undertaken at the Royal Aircraft Establishment and in the Universities and firms. The researches emanating from these sources were embodied, along with much else including administrative material in the committees "T" (45) and plain number series of reports. Some of the reports were intended for committee circulation only, but many were published under the committee's auspices in the Reports and Memoranda series (20).

As a result of this expansion in research in the field of aeronautics, Hunsaker (37) stated in 1914 :-

> "There has thus evolved a new technician, the aeronautical engineer. The aircraft of 1913 are principally to be distinguished by the evidence of engineering skill in their design and construction"

As can be seen an airship is essentially a power-driven balloon, which can to a certain extend be steered against the wind, the lift derived from the gas is known as the static lift. In addition to this static lift airships have a dynamic lift due to their movement through the air. All airships have streamline envelopes or hulls, which contain the inflation gas. In the early 20th century this gas was generally hydrogen, later helium was used.

There were three main types of airship: the non-rigid, semi-rigid, and rigid. The rigid type was pioneered by one of the best known airship manufacturers; the Zeppelin Co.. However, the British and American designers did play an important part. The rigid airship with its internal framework removed many of the tensile stresses from the fabric envelope, and as the name suggests added rigidity to the structure which the fabric of that period could often not hope to match in the non-rigid airships. The first British rigid airship to fly was the R9, on the 27th November, 1916. This was followed by the R23,27 and 31 classes during the First World War, and R36 and 80, R100 and R101 after. The R101 was destroyed by fire, and after the disaster the building of airships virtually ceased.

Although the large scale use of airships ceased fifty years ago a new interest has arisen. A British company based at R.A.F. Cardington, the virtual home of the British airship where the legendary R100 and R101 were based, has developed a new airship. The company, Airship Industries, has learned from the errors of the past and the first design to be commercially produced was the 12 seater, Skyship 500 with a top speed of 60 knots (111.0 km.p.h).The 500 applied up-to-date technology to the age old problem of getting the maximum payload off the ground as efficiently as possible. The 500 is only a fraction of the size of the Hindenburg, but it is non-rigid and requires no complex metal framework, gas pressure keeps the envelope in shape; helium which is inert is now used.

All serious airship designing stopped in the mid-1920's, and since then we have flown Concorde and landed on the Moon. Much of the modern technology; aerotextiles,propulsion,avionics and aerocomposites have been applied to an entirely new generation of airships, not the least of these being the British design of vector thrust, which helps with take-off and landing. Another great plus point is the use of advanced materials; the gondola is made of Kevlar reinforced plastic, which is very light and strong. The gas envelope itself is constructed from polyester, which again is light and very strong, and as sailmakers have discovered, increases shapeholding capabilities. Larger versions of this airship are planned.

In the early years of the aeroplane the airship had many advantages over it, but it took a relatively short time for the aeroplane to improve, and by 1920 Hunsaker (46) stated :-

> "The latest German rigid airships have a maximum speed of about 70 land m.p.h. and the NC-4 flying boat has a top speed of about 90 m.p.h. To cope with gales of general extent the airship is clearly at a disadvantage. It is possible that following the present trend of design the airship speed will not be pushed much, if any above 80 m.p.h., while a speed of 115 m.p.h. for the flying boat is already in use"

Today aeroplanes have overtaken airships in virtually every area. However the uses of aircraft are so extensive and varied that a market for airships can probably be recognised in such military applications as airborne early warning for surface fleets; an airship could be used to see over the horizon and would be difficult to pick up itself, because it is made from plastic and has a low radar signature. It could also be used in sub-marine warfare, because it is quiet and could tow a sonar buoy. On the civilian side the applications could be in scientific work, ariel advertising, television broadcasting and sight seeing.

When the development of the aeroplane caught up with that of the airship, the airships military capabilities began to appear very limited and they were gradually displaced. Also because airships were filled with hydrogen, the opinion of many was that they were too dangerous for civil use. Therefore after the first quarter of the century all aeronautical research was confined to the aeroplane. Despite the reduction in the use of the airship, fabric research did not stop as many of the aeroplanes used woven textile fabric as wing and fuselage coverings. Before the large reduction in airships, it had been discovered that a number of light fabrics of cotton, each made up of many fine yarns per unit width, vulcanized together with a thin ply of first-grade rubber between them formed the best airship fabric. In order to enhance resistance to tearing and improve dimensional stability, the two fabrics were placed with their yarns at a relative angle to one another. This also formed a fabric which was very impervious to the leakage of gas (47).

Gliders, pioneered by men such as Cayley, Lilienthal, Chanute and Montgomery, were probably the first heavier-than-air craft to fly prior to the Wrights first powered, controlled flight in a heavier-than-air machine, at Kitty Hawk, N.C., on 17 December 1903. With the advent of powered flight in aeroplanes, new requirements were made of the textile fabric. Haven (47) wrote :-

> "First of course, great strength must be present, since the total sustaining area in such crafts is relatively small and when manoeuvring in the air the wings may be subjected to severe impulses. In order to facilitate the navigation of the air, the wings of such machines must present a smooth surface rather than a series of more or less deeply depressed pockets. The fabric must be easy of application to the wings, must be very light in weight, and must lend itself readily to quick and easy repair. With reference to weathering, it must exhibit the same properties as balloon fabric, with the exception that possibly impermeability is not of so great importance"

Fabrics were ideal for wing coverings as they were flexible and easily bent to conform to the wing curves. One of the first fibres tried was silk, but despite its strength this was very expensive and not easy to work with. Next aircraft engineers tried linen, because of its great strength and fineness. However the areas in which the ideal flax could be grown were limited to the British Isles, the Belgian area, and parts of Russia. The supply of these fabrics was therefore not sufficient and during W.W.1 the supply practically exhausted. It was therefore necessary that aeroplane engineers, especially in the U.S.A., should look for an alternative material which possessed somewhat similar properties to linen, but which was cheaper and more easily procured. Cotton was the obvious choice and fabric specialists (48) set about manufacturing a cloth which did not exceed 3.5 to 4.0 ounces per yard in weight, to be made of first grade, long staple cotton, and lastly be highly absorptive of the various dopes and cloth varnishes employed in tightening and repairing wings of aeroplanes. In later years these wing fabrics give way to rigid metal sheets which apart from any other reasons were required due to increasing speeds and altitudes.

In more recent years woven fabrics have had a new use in the aircraft industry. Manufacturers such as McDonnell Douglas (49) have realised for sometime that the lighter an airplane is, the farther it can go or the more it can carry. The problem has always been reducing weight, while maintaining strength. The solution has been to use lightweight, high-strength carbon fibres. Sheets of woven, carbon fibre cloth are cut to the precise shape required. They are then built up layer by layer, to give them strength. Soft and pliant, these stacks of composite cloth are easily shaped to aerodynamic forms, then cured under pressure at high temperatures. The result is wings and other parts that are lighter and more resistant to corrosion and have longer life than comparable metal parts.

Due to the use of carbon-epoxy composites for more than 25% of all their Harrier II structure, U.S. Marines have a plane that can land or take off vertically, and go twice as far or carry twice as much as earlier models.

Another important textile fabric which partly owes its development to the aircraft, is tyre fabric. The tyre is a rubber hoop which fits round the wheel rims of not only aeroplanes, but also bicycles, motor cars and other road vehicles. The first pneumatic rubber tyre was patented by R.W.Thompson in 1845, but it was John Boyd Dunlop of Belfast who independently re-invented the pneumatic tyre for use with bicycles (1888-1889).

Up until the last war cotton was by far the main fibre used for tyre fabrics, but in the 1940's and 50's rayon made huge inroads. In pre-war days the basis of the strength in all pneumatic tyres was a heavy, accurately woven cotton cord fabric. When made of a high-grade cotton, woven with precision and vulcanized into the tread many plies in thickness, such fabric gave to the tyre a flexibility, strength and durability which would be very difficult to obtain otherwise. By the 1930's the motor car tyre fabric had been essentially standardized after a number of decades of use, so there was little departure from conventional specifications in regard to fibre, weight, character of the yarn, and fabric strength. Of course tyres for aeroplane use had to be much lighter than those used in the motor car. One of the main requirements for a good car tyre was that it would give good mileage, but as the aeroplane tyre was in contact with the ground for only short periods, dependability and strength were more important than durability.

It was important in a tyre that an external load applied at any point on the fabric would be equally resisted by both sets of yarns. It was therefore important to take great care in weaving, and by rigid inspection and frequent tests ensure that this was secured. One important factor in the manufacture of tyres is explained by Illingsworth (50) :-

> "It is not generally recognised that textiles are much more liable to fatigue-failure when under axial compression than when under tension and it is the practice, when designing composite rubber products, to avoid, as far as possible, compression of the textile. Thus, in the case of transmission belting, the fabric should be on or outside the neutral axis - difficult often to avoid in tyre casings, therefore every step should be made to ensure the fatigue life of tyre cord is as high as possible.
>
> In the early days cords were designed for the maximum strength, but it was found when high twist was put in that although it lowered the strength it greatly increased the fatigue resistance and the mileage increased. This was one of the most important steps in modern car tyre design."

Another relatively new, but rapidly growing application for textile fabrics is geotextiles. These not only include woven fabrics, but non-wovens and also knitted fabrics, and they are usually manufactured from polyamides, polypropylene or polyesters.

The word "geotextile" was first coined by J.B.Giroud at an international conference held in Paris in 1977, and this word has been liberally translated to include the more specific headings of geofabrics, geomembranes, geogrids, and geotextiles (51). Giroud (52) has defined geotextiles as:-

> "the textiles or fabrics (woven or non woven) used in geotechnics for hydraulic purposes such as filtration and drainage, and mechanical purposes such as reinforcement and sparation"

He has also defined geomembranes:-

> "as waterproof membranes used for lining ponds, canals, dams, tunnels, and other geotechnical applications"

Previous to the use of geotextiles natural materials such as woven-reeds had been used for centuries, and there are many examples in historical literature of civil-engineers using tree branches or other such natural materials to help stabilize the ground for roads or railways which had been built over swamps and marshes. The earliest references are probably those found in Exodus (53), ie., reinforced earth: "straw to make bricks". One of the earliest modern references to this type of textile fabric application appears to have been by Beckham and Mills (54). They discussed the use of cotton fabrics for reinforcing roads.

It was in the Netherlands in the early 1960's that engineers seriously began to investigate the possibility of using woven fabrics as a separation/filter medium. This was a result of the damage caused by the storms of 1952-53; the Dutch had used traditional reed woven mats for scour protection and these had been destroyed by woodworm. At the same time engineers in North America were investigating the possibility of using woven textile cloths as a substitute for granular filters. In France, also, they were looking at the use of non-woven textiles in earthworks.

Today textiles still have many obstacles to overcome before they gain wide acceptance in the more traditional engineering fields. Their low elastic modulus relative to metals, their elasto-plastic behaviour and strain rate dependency have not helped their acceptance amongst engineers in heavy engineering situations where load bearing properties are required. However, they have now accepted geotextiles to the extent that there is a growing appreciation of the methods of their application for stabilization, reinforcement of soils, roads and loaded areas. There is, however, still much debate as to the best design methods and guidelines to be followed to ensure the most economic and long term performance of such materials (51).

The previous accounts attempt to show the development of certain fabrics in some of their important industrial end-uses, and how they have been adapted over the years as the requirements changed with advances in the end-uses, these advances in many cases being due to improvements in the properties of the fabric itself. The majority of uses mentioned needed specially engineered fabrics to meet the requirements; however, up to less than one hundred years ago the production of these fabrics tended to be more of an art which developed through trial and error. It is only quite recently that those who manufacture the fabrics have attempted a scientific approach, and that textile technologists have come into being who attempt to gain a knowledge of fibre structure and fabric properties, as well as understand the limits of endurance of their materials in particular severe environments.

1.4 Man-Made Fibres Used in Industrial Fabrics

Prior to W.W.2 cotton was the only fibre used to any great extent for industrial purposes. Just after the war rayon made great inroads and by the end of 1951 over 60% of the total industrial consumption was rayon, and if further supplies had been available this may have been greater. Nylon also found uses in the tyre cordage industry, but polyester was still very limited in use.

In the 17th century the physicist Robert Hooke had suggested the possibility of extruding artificial silk by a mechanical imitation of a silkworm (55). Then in the 19th century Louis Schwabe successfully produced filaments from molten glass by forcing the liquid through nozzles ending in fine holes. This first man-made fibre, however, was not suitable for textiles. At this time experiments were undertaken with the object of dissolving wood cellulose and then separating the resulting liquid from its impurities, and then extruding and hardening the liquid to form fibres. The fist man-made fibre, which had an industrial use, was probably produced in 1883 when Sir Joseph Wilson Swan, working on the problem of producing a filament for an electric light, patented a process for squeezing a nitrocellulose solution through holes to form filaments, then treating the filaments with chemicals to change the flammable nitrocellulose back into cellulose. Swan exhibited articles made from his filaments, but did not develop its textile potential (55) (56).

In 1889 Chardonnet exhibited materials woven from a fibre, he called artificial silk, at the Paris Exposition. In the 1890's the process for this fibres large scale production was developed by other chemists and by 1905 commercial production began; viscose as it became known began to develop as a major man-made textile.

After W.W.1 other man-made fibres were developed, these included cellulose acetate in 1921, nylon in 1935, polyester in 1941 and numerous others after W.W.2.

Man-made fibres were little used for industrial fabrics before W.W.2. Rayon tyre fabrics were made experimentally in 1924, but not until 1936, after the discovery of a suitable adhesive and the development of a high tenacity rayon was a really satisfactory tyre made. At this stage rayon was more expensive than cotton, but considered worthwhile in certain cases. W.W.2 helped its development as rubber was scarce and regular rayon fibres and their high tenacity allowed less rubber to be used in tyres. Regular fibres made finer yarns and allowed thinner plies. Thinner plies allowed tyres to run at lower temperatures and this was important when synthetic rubber was introduced. In the early 1950's the rubber industry used 80% of the total quantity of textiles used for industrial purposes, and at this time rayon was the most common man-made fibre used. Nylon, however, became quite common in the manufacture of heavy duty tyres. Before W.W.2 rayon was also the first man-made fibre to be used in a yacht sail. The genoa on board "Ranger" in 1937 was made from this fibre, but it stretched too much for head sails and was too porous for spinnaker use. Nylon was tried after W.W.2 and initially it gave rise to great expectations, because of its high tensile strength, but it stretched too much and was soon limited to spinnakers. Other materials used included Acrilan, which was also found to have too much stretch. It was in 1952 that the first British boat carried a polyester sail. It was the genoa on the 8m CR class "Sonda". The first big success of polyester was in

1954 in the Star World Championships in Portugal. The Cuban helmsman, Cardenas had the only polyester (Dacron) sails in the fleet, and he won easily. Polyester is still the main fibre used in sailcloth.

In most industrial applications man-made fibres were found which took over from the natural fibres, such as cotton. In 1948 Bendigo (57) wrote :-

> "Synthetics are admirably suited for industrial uses, especially where definite specifications can be laid down for the textiles needed. Producers can spin fibres and filaments with particular properties wanted, in most cases, if the type of fibre is not already in production. In their development work, the fibre producers are looking far ahead, many uses have already been developed even though not enough fibre is available to fill them.
>
> Many textile mills welcome the production of yarns and fabrics for industrial uses since, as one mill man puts it, 'industrial customers are not so fickle'. The fabrics are not so subject to fashion or whim, and yardages needed can be scheduled more accurately. In fact, some whole mills and sections of other mills have been set up to run constantly on one type of industrial fabric.
>
> Production of industrial fabrics usually entails meeting the user more than half way. It is necessary for the textile mill to understand the users problem and to work out for him the particular textile product he needs. In some cases regular products can be used, but in many instances a special type is needed."

There were many other opinions expressed at the same time due to the boom of man-made fibres for industrial fabric manufacture. As Pollitt (58) stated :-

> "It has been fashionable to say fibres can be 'tailor-made' by which it is meant that they can be produced with any desired combination of properties. In its original context the term implies making to the measurement of a particular consumer, but with

regard to fibres there is little evidence of bespoke production for particular purposes. Rather it appears that fibres are made with new combinations of properties and are taken 'off the peg' and tried whenever there appears to be reasonable use. In the present state of knowledge concerning the properties required in fabrics for particular purposes, it is inevitable that the choice of the most suitable fibre for a fabric for a particular use should be largely determined by the results of trials of existing fibres. It may at some later date be possible to analyze the conditions and mechanical actions to which fabric is subjected when used in a particular way, and so from a background of previous experience deduce the specification to which a fibre is to be 'tailor-made'. At present there exists only a small part of the knowledge required for this procedure."

This ideal situation has still not been achieved but it is hoped this present work will help bring us a little closer, by producing new tools which will aid in the analysis of the mechanical actions to which a fabric is subjected when used in particular ways.

Man-made fibres are produced almost entirely from organic polymers, constructed from various carbon derivatives. Cellulose is the basic material from which most of the commercially important natural polymer fibres are produced, and although supplies of cellulose are readily available, conversion to a form suitable for fibre production presents certain problems. The raw materials of synthetic polymer fibres, however, are simple organic chemicals that come from stores of available carbon compounds. Initially the industry relied on coal for these materials, but now petroleum has largely taken-over. The rapid development of the synthetic fibre industry has put a heavy demand on the petrochemical industry (59).

As world population expands, the demand for textiles can be expected to increase. As well as this a need for greater versatility in textile materials is probable. The man-made fibre industry is expected to supply an increasingly large share of the total world fibre output, and it is expected that a certain proportion of these will consist of specialized types. These specialized fibres can be used in the production of many of the industrial fabrics which are in demand at present, and if new fibre forming polymers are discovered which are more suited to specific industrial applications they may lead to improvements and increased demand in the particular end-use in which they are being applied. It is expected, however, by certain sources (59) that the greatest production will be in the "bread-and-butter" fibres, such as polypropylene, that can be produced cheaply to provide the kind of textiles that have long been produced from cotton.

So as can be seen the use of industrial fabrics is to a great extent dependant on the fibre used as well as the fabric structure. This present work, however, will be dealing mainly with the fabric structure. The fibres and filaments mentioned so far were not developed specifically for use in industrial fabrics, but were found most suitable for uses in certain fields. Kevlar was the first fibre forming polymer to be developed and marketed specifically for industrial applications (60). It was, however, not developed for a specific industrial end-use, this may still have to come in the future. Every particular application could use its own specific fibre which has been designed specially for it. At present the fibre is selected which is best suited for the particular application, and the mechanical properties of the yarn and fabric can then be engineered as required.

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CHAPTER 2

THE STRUCTURE OF WOVEN FABRICS

Introduction

In the past few decades there has been an increasing number of uses for textiles. Apart from the traditional uses, new applications have been found, and many of these are in the fast growing aerospace industry, as well as architectural uses, geotextiles, auto-fabrics, and many others. There are undoubtably many reasons for the expansion of textiles into areas such as those mentioned, and these may be economic, aesthetic or just a desire for change. From the scientific view-point it appears that this expansion has been, and is due to the evergrowing number of new materials, which give a wider and more varied range of physical and mechanical properties, thus allowing textiles to compete with many of the more conventional materials. As well as this, textile technology has rapidly evolved from being craft based, to being science based. Technologists are using the findings from much recent research to "engineer" fabrics for specific purposes, and certain researchers such as Moghe (61) claim that mathematical models allow the behaviour of these fabrics to be predictable. This relatively new outlook and approach generally makes fabrics more acceptable to manufacturers and consumers as an engineering or structural material, as fabrics are now often more suited to their specific end-use.

2.1 Background

Although the basic principles of weaving have remained the same since ancient times, it was not until the late 19th century that weavers began to take an interest in the fabrics structural properties. Even after researchers such as Ashenhurst (62), Armitage (63), and Law (64) had derived formulae for calculating the maximum threads per inch in their simple cloth-setting theories, weaving still basically remained an art until Peirces's (65) classical paper was published in 1937. Peirce (65) was the first researcher to derive a comprehensive analysis of the plain weave. Ellis (66) claims that there is no great evidence of his geometry being used in practical problems of textile manufacture. However, he does give him credit, as his work forms the basis for many of the subsequent investigations into woven cloth structure.

Many workers have shown that the physical properties of textile fibres, yarns and fabrics change due to ambient and dynamic conditions. With these unstable properties, some assumptions have to be made for any theoretical approach and Peirce's (65) model, as are all others, is based on simplifying assumptions. Galuszynski (67) has pointed out that it is the correct selection of these various assumptions which plays an important role in any attempt to describe a fabric structure and dynamics of the formation of that particular fabric. Peirce (65), in his model of plain weave fabric, assumed that yarns are flexible, circular cylinders interwoven in a regularly recurring pattern. His model also involved no consideration of internal forces.

In the early 20th century weavers were not the only researchers interested in the properties of plain weave fabrics. With the development of powered airships there were problems with the aerodynamic shape-holding capabilities of the fabric envelope, and engineers such as Haas (19) recognised that an exact knowledge of the properties of the fabric would be required in order to use the fabric to its best advantage, and plan the best shape for the structure.

In 1907 the German Society for the Study of Airships initiated what appears to have been the first large-scale scientific investigation of the mechanical properties of fabrics. This was followed in the next few years by further studies in England, France, and Germany. Probably one of the earliest simple fabric models was described in British aeronautical literature (68), but the most important study dating from this time is the theoretical work done by Haas (19). His work established relations between yarn and fabric parameters for woven cloth under biaxial-stress conditions, and it describes two basic methods for the stress analysis of the plain weave fabric; these were the "trellis model", and the model which considered the yarns to have a circular cross-section. The "trellis model" assumed the yarns to be straight, rigid, and frictionlessly pinned at each yarn junction, as with a common garden trellis. The second method described is more sophisticated, as the model considers the yarns as having circular cross-sections. The yarns were also considered to be inextensible, incompressible, flexible, and frictionless. This model is a more accurate representation of the weave geometry, than the trellis model, because it takes interweaving into account, however, it is more complicated. Davidson (69) referred to this type of model as the "canal model", he states that this name is derived from the fact that surfaces of this type are known as canal surfaces.

Since the research of Haas (19) in 1912, and Peirce (65) in 1937, both of whom produced models of a similar type, numerous other treatise have appeared in the literature on the structure of woven fabrics. A number of these authors have used the trellis model (70), (71), (72), and others have based their work on extensions, modifications or evaluations of the circular cross-section model (73), (74), (75).

Today research into textile mechanics is carried out basically because engineers wish to be able to predict the behaviour of the fabric before it has been manufactured. To enable this to be done some form of mathematical model of the proposed fabric must be produced, and this can be used to help "engineer" a fabric with the required properties, by the manipulation of the independent structural variables. The principles used in modelling of this type depend upon the characteristics desired. With industrial applications the desired characteristics can be expressed in objective terms such as load or extensibility requirements. Other applications, such as home furnishings, may require more subjective properties such as drape or handle.

The mechanical properties of textiles are generally non-linear. The "engineering" design of fabrics is therefore affected by the maximum deformation to which it is subjected in its end-use. For many industrial uses the fabric behaviour in the region of the yield point needs to be considered.

The most basic deformations of woven fabrics are in-plane extensions and shear, bending in a perpendicular plane, and out-of-plane buckling. However, in practical applications these deformations rarely occur in isolation. Deformations in practical end-uses are generally more complex, as all or some of these basic deformations may be acting in combination. As Anandjiwala (76) states, before these complex deformations can be analyzed the fundamental properties, which influence the complex deformations, must be investigated first.

Many previous authors, who have included Kandil (77), Anandjiwala (76), Grosberg (78), and Ellis (79) (66), have surveyed the subject of fabric geometry and mechanics in depth. It has therefore been determined that a further comprehensive survey is not required. This topic shall therefore only be examined superficially in such a manner as to attempt to emphasize its relevance to the engineering and design of fabrics for industrial and engineering end-uses.

2.2 Plain Weave Fabric Models

The geometry of a fabric should generally be known as a starting point for the analysis of the mechanical properties of a structure responding to externally applied forces.

Two different types of models have been put forward for the plain weave. These have been described as geometrical and mechanistic (76) (77). The geometrical models take no account of internal forces produced by yarn rigidities and basically involve nothing more than a description of the yarn positions in the fabric structure. The mechanistic approach, however, attempts to relate the fabric structure and properties with the mechanical properties of the structural constituents, such as fibres and yarns. The advantage of using the descriptive geometrical model is its relative simplicity, but the information obtained is also limited. A mechanistic model can supply more information, provided its idealizations are adequately realistic, but this is generally at the expense of greater complexity.

The geometrical approach proposed by Peirce (65) is considered as a precursor of all other work in this field. He suggested a model with a circular cross-section, and stated that he did not want to develop a model involving elliptic functions as it would be laborious and their practical application would be clumsy and probably no more effective in the study of actual cloth data than the approximate treatment of yarn flattening which he proposed. Kemp (80) and Shanahan and Hearle (81) followed this with similar work, but they used more realistic yarn cross-sectional shapes. Hamilton's (82) work was also quite similar, but he considered other weaves apart from the plain weave.

Other researchers have attempted to modify this geometry by introducing different yarn shapes. One of these is the "saw-tooth" model used by Kawabata et al (83) and Leaf and Kandil (84). The geometry of this model is probably one of the simplest of all models. It further simplifies the flexible thread model by taking the yarn path to be a series of straight lines, and no assumption is made as to the yarn cross-sectional shape. The apexes of the yarns are considered to be joined by a rigid rod at the crossovers. This allows the change in direction of the yarn to be taken as a point rather than an area, and this model has the advantage that the thread has only one path between the yarn spacings in the other major axis , rather than arcs and straight lines as in the flexible thread model. This type of model is less relistic, but its use is probably justified due to its simplicity.

Grosberg (78) has discussed some of the drawbacks of the purely geometrical approach, and he states that Peirce's (65) model can only be used for two types of calculation. First, for the kind which the equation:-

$$\frac{h1}{p2} = \frac{4}{3} c1^{.5} \qquad \text{....................(2.1)}$$

can equally well be used, and for calculations on the jammed condition. Peirce's equations are difficult to work with, and for this reason Peirce (65) and later Love (85) produced curves and graphs to assist calculations. For practical purposes Peirce obtained the relationship shown (2.1) and he stated that this formula estimates the exact values well enough for many practical purposes, and only in a few cases of "extreme structures" does the error amount to 5% and never to 10%.

The models mentioned so far did not consider the forces involved. Peirce (65), considered the effect of internal forces, analyzing a perfectly elastic thread rather than an infinitely flexible one. The resistance to bending of the yarns have a large affect on the geometry of the fabric. As the yarn direction is changing continuously it is, however, difficult to derive simple mathematical descriptions.

Olofsson (86) also proposed a more realistic model of the plain weave. He studied the case when small-order horizontal stress is applied, whereas Peirce (65) dealt only with internal stresses. Olofsson (86) suggested that the yarn shape can be obtained by assuming that the yarn is bent into shape by point loads acting at the intersections. As a result, the yarn takes up the shape of an elastica.

2.3 Tensile Properties

There are numerous difficulties with the study of woven fabrics as they are anisotropic, ie., because of the geometrical asymmetry of the fabric, and differing yarn characteristics in the warp and weft directions, the tensile moduli differ in these directions, and these moduli vary continuously with strain. The mode in which the stresses are applied is an important factor in determining the fabrics tensile properties, and therefore the ratios of the initial moduli and fractional deformations in warp and weft directions may vary considerably for the same fabric under uniaxial and biaxial loading. Higher extensions take place when stresses are applied at angles to the warp and weft, and as Grosberg (87) points out it has been shown that at 45 degrees to the warp and weft, the modulus is almost completely determined by the shear behaviour of the fabric, rather than yarn extension. This is not the case when extensions occur in the warp or weft directions where shear has no part to play.

When a plain woven fabric is initially extended in the warp or weft direction, it is important that the physical changes which occur in both directions are explained. Ordinarily the straightening of the yarns in the load direction is accompanied by a decrease in the crimp, c, crimp amplitude, h, and weave angle θ, while the yarn spacing, p, increases. Due to the contact between warp and weft at the yarn intersections, the fabric extension results in an increase in pressure in this area. This pressure leads to an increase in the crimp of the yarns which are at right angles to the applied load. This increases the crimp amplitude and weave angle, while the yarn spacing decreases. As a consequence of the decrease in the yarn spacings there is a widthwise contraction in the fabric. In a fabric "strip-test" this usually manifests itself as a "waisting" in the fabric specimen near the centre, while the fabric is still held to full width in and around the jaws. The Poisson's ratio for a uniaxial deformation of this type is defined as the ratio of the fractional contraction in the no-load direction to the fractional extension in the load direction.

The load-extension curve of a typical woven fabric is shown in Figure 2.1. This curve, when examined in more detail, can be divided into three sections. In the initial region, OA, the curve has a relatively high tensile modulus due to the high initial bending modulus of the yarns in which the fibres' frictional restraints have an important influence. When this frictional resistance has been overcome, yarn bending in the fabric is easier, and therefore the fabric tensile modulus decreases.

The curve in region, AB, shows crimp interchange and is dependent on both yarns' elastic rigidities and quite likely on their compressabilities. When the crimp has been decreased, further extension in the region, BC, causes the tensile modulus to increase. This is due to fibre and yarn extension, and in this region there is increased flattening of both the warp and weft at the intersections. As Kandil (77) points out the regions mentioned so far are affected by the magnitude of the forces existing between the two yarn systems before extension; hence the degree of fabric set or relaxation will be of appreciable importance.

Extensions beyond the point, C, have a fairly constant tensile modulus, until the yield point, D, is reached. Beyond D, comparatively small increases in load are enough to produce considerable increases in extension. The tensile behaviour of fabric in the vicinity of the yield point is almost entirely determined by the fibre and yarn

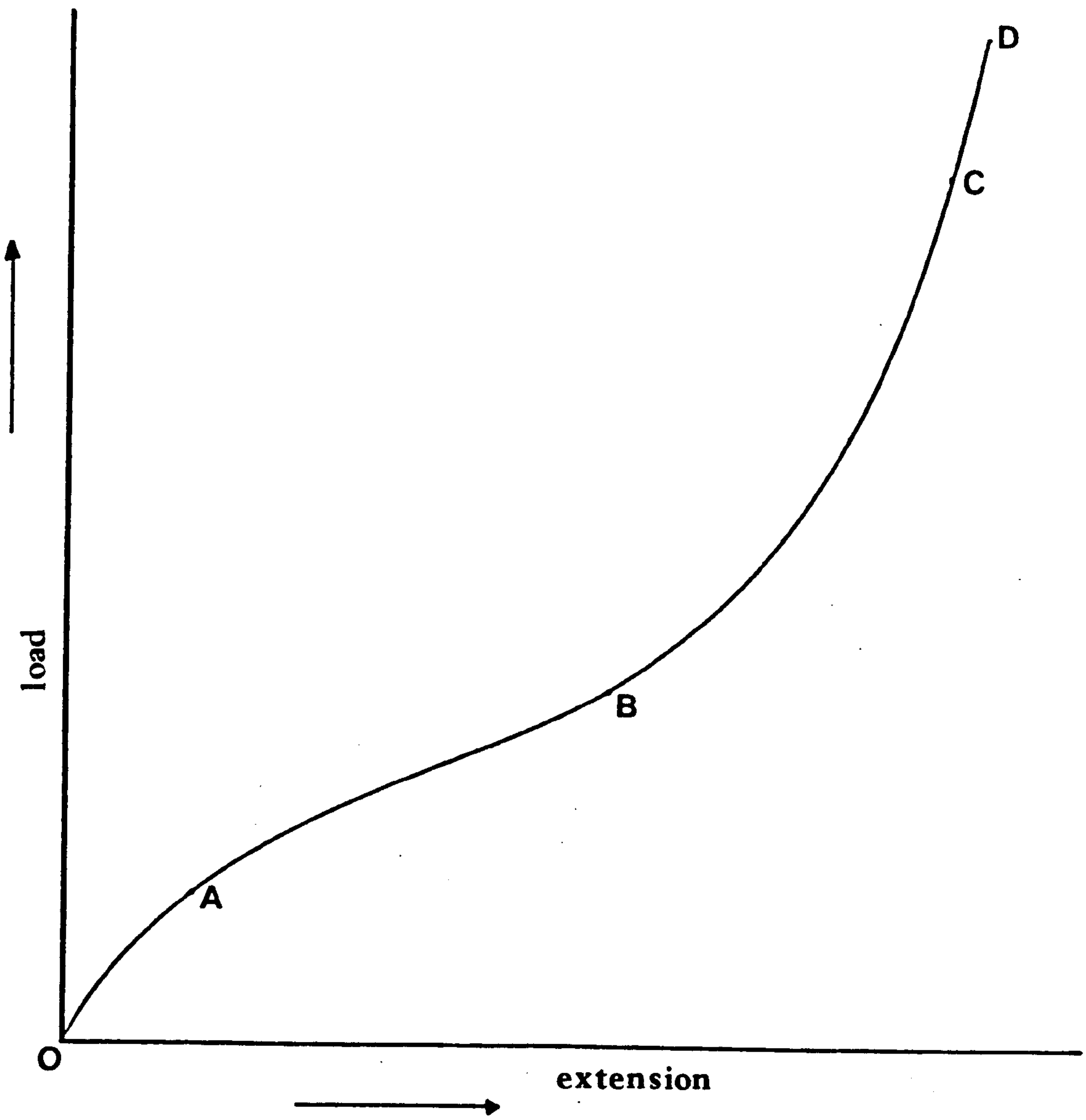


Fig. 2.1 The Load-Extension Curve of a Typical Woven Fabric

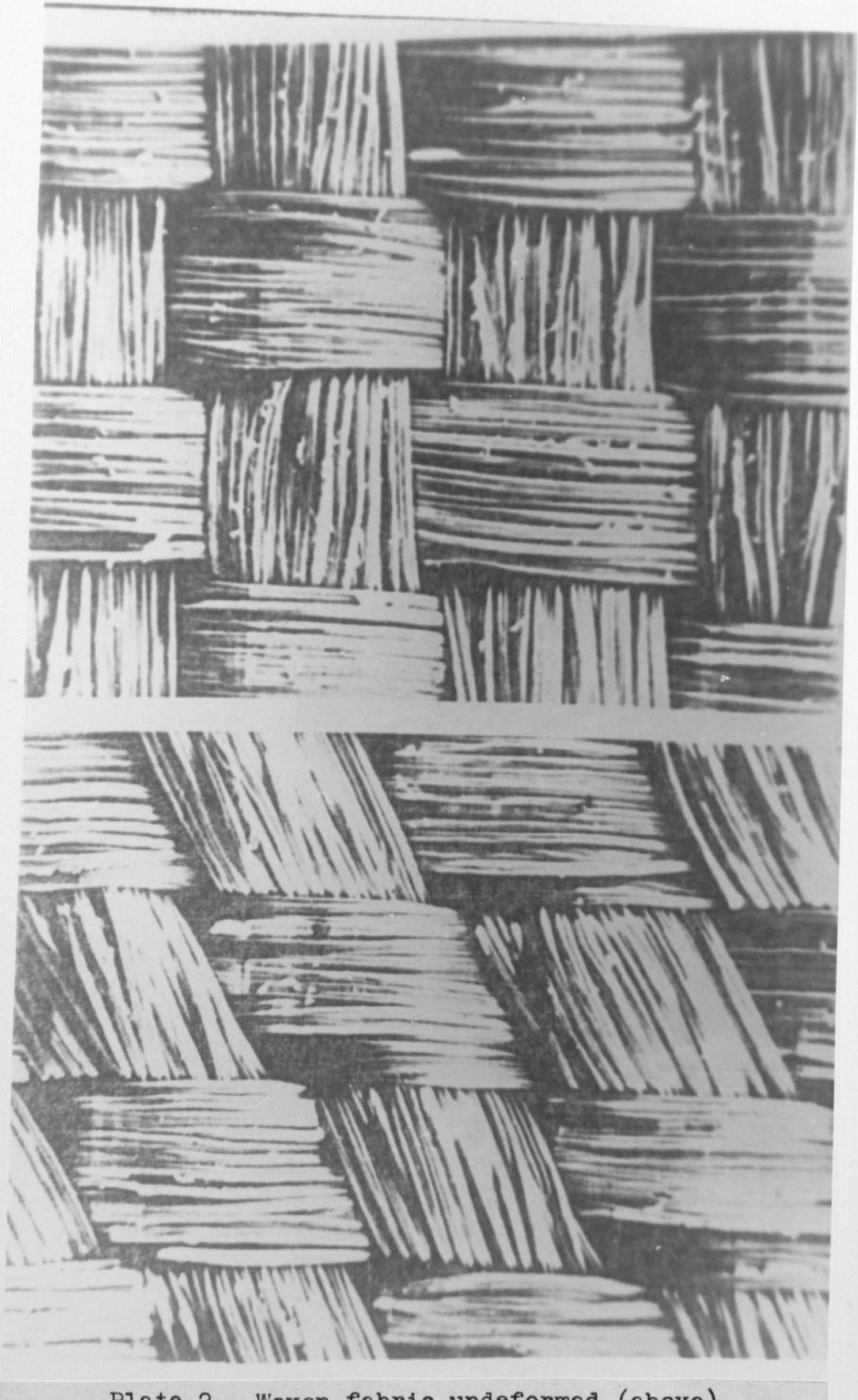


Plate 2 - Woven fabric undeformed (above) and under shear (below).

tensile properties. If extension occurs beyond the yield point, rupture will eventually occur.

Under small loads and extensions the curve is almost linear. In this region the fabric can be considered to obey Hookes′ law.

If the fabric is allowed to recover from a given strain, hysteresis is generally observed. The degree of hysteresis varies with the maximum extension imposed. If this extension is not beyond A, it is likely that the recovery will be elastic.

2.4 Shear in Woven Fabrics

Along with linear extension and bending, a knowledge of the shearing behaviour of a woven fabric is essential to any determination of how the fabric will perform when subjected to a complex range of deformations (see Plate 2). Cusick (88) has pointed out that a woven fabric can be bent into a single curvature without any shear deformations; but if a fabric is bent into double curvature or more complex folds, then shearing must occur. In most fabrics, this shearing is likely to be largely explained by a change of angle between intersecting threads, but it may also be a result of bending and twisting of the yarns between the intersections. Mack and Taylor (89) have shown that for clothing applications, the ability of a fabric to shear is a necessary condition in order that fabric may be fitted to complex surfaces. Grosberg and Park (90) have also indicated that large shearing strains resulting from low shear stress are necessary to fit a fabric which lies in a single plane to the various three-dimensional surfaces required when forming cloth into a garment. The shear mechanism influences the draping, pliablity and handle qualities of woven fabrics.

For certain industrial applications, such as commercial upholstery in aircraft and road vehicles, and protective clothing; where fabrics must be fitted to complex surfaces, shear is necessary. However, for many industrial end-uses, such as sailcloth, fabric shear must be limited; as any deformation which alters the sailmakers built in shape is undesirable. There is a problem, however, because fabrics which are produced from polyester filaments with little or no significant shear potential, generally behave and feel like parchment or laminar sheet materials, and may not possess other of the required properties such as sufficient tear resistance or the handling properties, which are required for ease of stowage.

Generally a racing yacht will require very stable, tightly woven, expensive to produce sailcloth, with a firm resin applied to "lock-in" the sailmakers shape. This will produce a sail which fulfils many of the racing requirements, but compromises must be made for a cruising yachtsman, who considers expense and ease of handling more important than extremely good shape holding properties.

These compromises must be made with certain of the mechanical properties in order that a cloth may be produced in which all the required fabric properties may be maximized. This is indeed the case with most fabric applications.

Kilby (91) discussed methods of increasing the shear modulus of a fabric in order to reduce the degree of anistropy. This, he states, could be achieved using chemical or other additives which increase the coefficient of yarn-on-yarn friction. However, this would have the disadvantage of increasing the amount of mechanical hysteresis and reducing the degree of recovery from a given strain. Alternatives suggested are to flatten the yarns by calendering, so as to increase the degree of yarn interaction. Another would be to introduce a filler with the properties of an elastomer, this would tend to cause some adhesion of the yarns at the areas of contact. He suggests that this would tend to have the advantage of conferring a high degree of elastic recovery from fabric deformations, together with an increase in the value of shear

The manufacturers of sailcloth have realised for sometime that impregnating a cloth with resin can greatly enhance its resistance to stretch, and by playing around with the amount and type of resin, that gets into the fabric, many degrees of stretch resistance can be obtained.

Resin impregnation should of course only be used to enhance the required properties of an already good quality, tightly woven cloth; and not be used to give stretch resistance to cheap fabrics which are relatively loosely woven. This latter case does sometimes occur, and these cheaper products can rapidly lose their shape-holding powers as the resin which is "doing most of the work" soon breaks down in use.

Kilby (91) in his discussion has also pointed out that when one wishes to reduce the shear modulus in order to render the fabric more susceptible to "trellising" this can be accomplished by the use of lubricants to reduce the frictional forces.

Early work on deformations in closed membrane structures was carried out by Haas (19). He was investigating problems with the pitching up of the nose in non-rigid and semi-rigid airships, and he attributed a major part of this to the fabric shearing properties. Haas (19) realised that to form a conception of the deformation to be expected while the envelope was being constructed, and to give a negative curvature to the axis of the envelope, so that it became straight (as is necessary in order to reach the maximum speed and to steer up-wards) only after the load was applied, he must first have a thorough understanding of fabric properties.

Haas (19) pointed out that when a single layer of plain woven fabric, in which the warp and weft intersect at 90 degrees, is subjected to forces, the network will undergo three kinds of deformation, which are due to different and independent causes, but in certain cases affect one another (see Fig.2.2).

In Fig.2.2(a) a force P is applied to a tensed piece of fabric, and action is as follows:

Since the rectangular meshes contain no diagonals the fabric first goes over into the configuration of Fig.2.2(b). This Haas (19) called thread shear. As the thread is crimped it tends to straightened out. Haas (19) called this thread straightening, the fabric now undergoes a lengthening of the kind shown in Fig.2.2(c), this he called thread extension.

Peirce (75) also listed the mechanisms of deformation in the order that they are most likely to occur :-

(a) angle shear and thread bending in the cloth plane.

(b) crimp redistribution

(c) thread compression, with flattening and extension

(d) fibre extension

He points out that in practical applications these deformations are all likely to be combined, but occuring in such a complex and variable combination that it is simpler

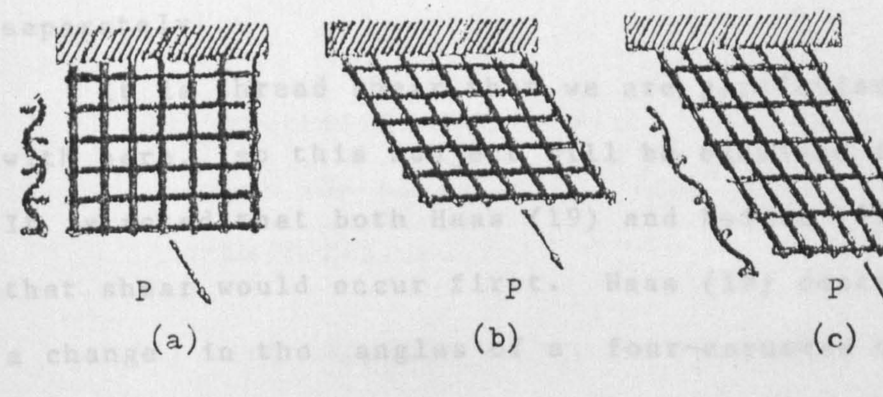


Fig. 2.2 Thread Shear and Thread Straightening
"from Haas (19)"

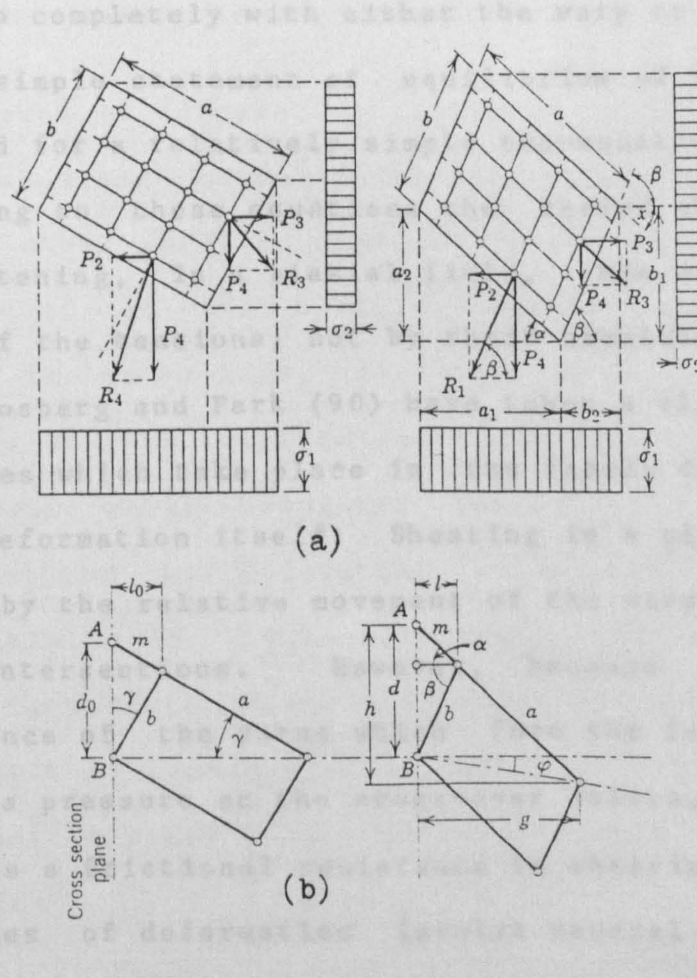


Fig.2.3 Equilibrium diagrams for yarn shear
(from Backer (92))

to consider the different deformation mechanisms separately.

It is thread shear that we are particularly interested with here, so this subject will be examined in more depth. It is noted that both Haas (19) and Peirce (75) recognised that shear would occur first. Haas (19) described shear as a change in the angles of a four-cornered mesh, and as Backer (92) states his analysis of thread shear was based on the assumption that the fabric would shear in a biaxial stress field, as shown in Fig.2.3(a) and (b), until the resultant force at the intersection of warp and weft yarns lined up completely with either the warp or weft yarn. This was a simple statement of equilibrium of forces, and it provided for a relatively simple two-equation relationship. According to these equations the thread shear and thread straightening, in a biaxial field, are determined by the ratio of the tensions; not by their absolute magnitude.

Grosberg and Park (90) have taken a closer look at the processes which take place in the fabric during the actual shear deformation itself. Shearing in a plain weave fabric occurs by the relative movement of the warp and weft at the yarn intersections. However, because of the bending resistance of the yarns which form the fabric, the yarn exerts a pressure at the cross-over joints, which, in turn, produces a frictional resistance to shearing. As a result, the modes of deformation involve several forms depending upon the degree of shear imposed upon the fabric. These are:

(1) Deformation due to rigid intersections when the shear is too small to overcome the friction.

(2) Yarn slippage at the intersections. This takes place gradually.

(3) An elastic deformation when slipping is complete.

(4) Jamming in the structure.

These modes of deformation are shown in Fig.2.4, a typical shear resistance curve. Grosberg and Park (90) state that when a shear force is applied to the fabric it initially acts as if it were a rigid trellis, and so the shear modulus is quite high, as shown by OA. If there was no slippage at the intersecting points in the fabric, the slope would remain along OA, but as slippage begins at the junctions and the frictional resistance takes over, the curve goes to OB. When slippage is completed, there is a linear resistance whose additional resistance seems to be the result of purely elastic bending of the yarn. Further increases in shear will eventually result in jamming of the structure.

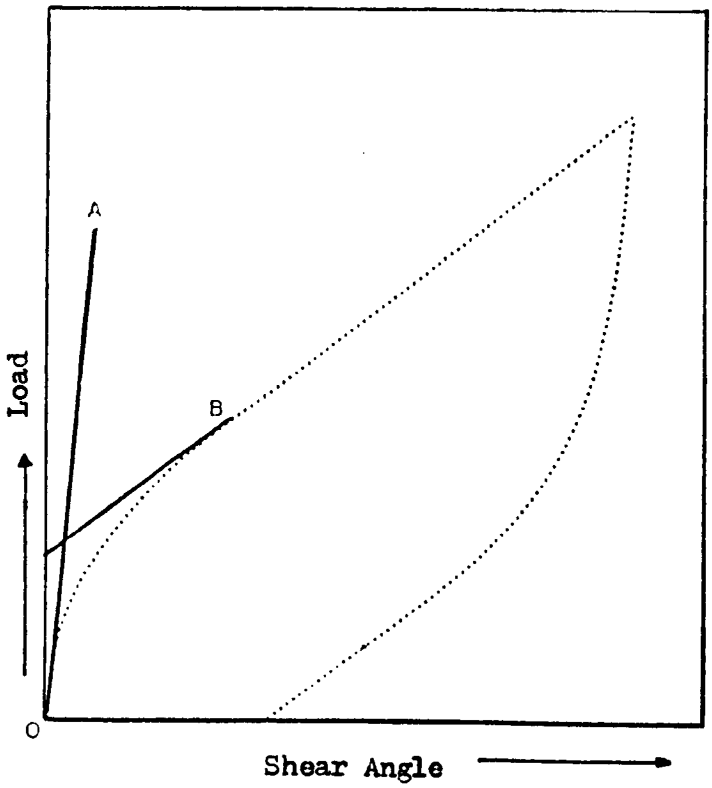


Fig. 2.4 A Typical Shear Resistance Curve

"from Grosberg and Park(90)"

Hysteresis in shear will be mainly determined by the second region mentioned above.

The elastic shear modulus is dealt with by Grosberg, Leaf and Park (93) in more depth in a following paper, and as stated it should be expected when complete slippage has taken place that the shear stress-strain curve would become horizontal, as shown by BF (see Fig.2.5). However, this is not the case as a fabric is not a simple trellis. When the frictional restraint is overcome, the yarns at the intersections have slipped over each other. In a plain trellis this would require no extra force, but in an actual fabric the intersections of the bent yarns in the crimp form require further bending of the yarns. The region after the non-linear portion is linear and recovers on the return curve (see GH in Fig.2.5), so it must be elastic. If the fabric is sheared further, another non-linear region appears, as shown by CD, which is most likely a result of an increase in the normal pressure due to jamming in the structure.

As pointed out by Cusick (88) it is generally found that, when a fabric is sheared to the same angle in the left and right directions, the hysteresis diagram is symmetrical about the axis of zero couple and the axis of zero angle. There are, however, a number of reasons why the diagram may not be symmetrical about the axis, and these include influences of the direction of yarn twist, or

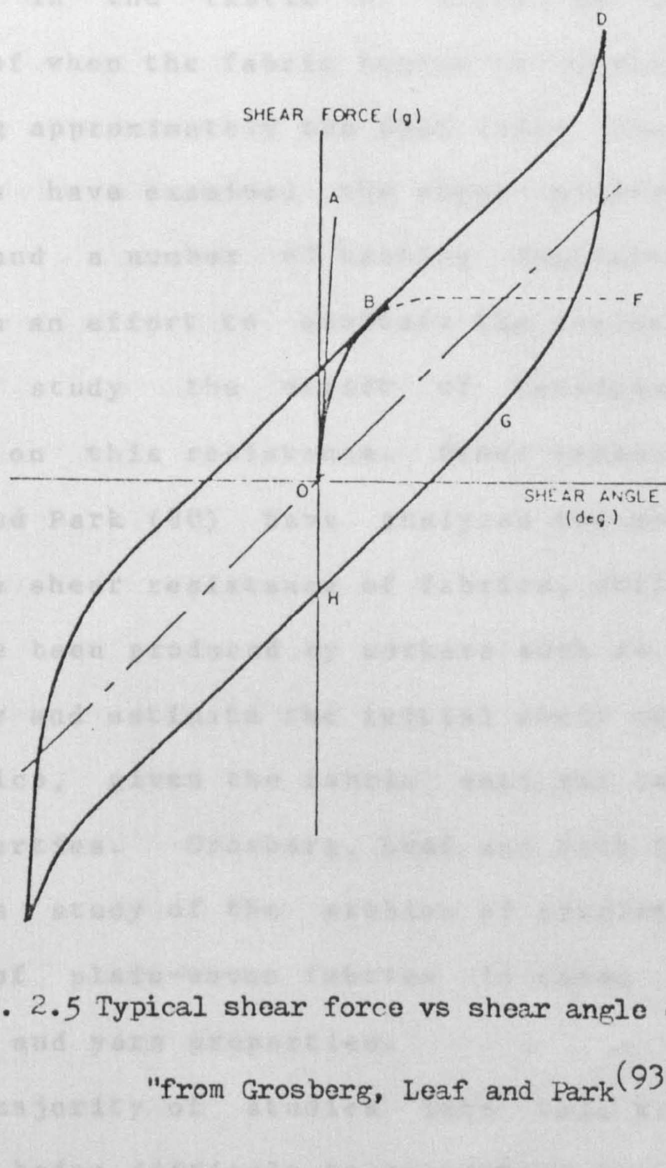


Fig. 2.5 Typical shear force vs shear angle curve.

"from Grosberg, Leaf and Park(93)"

threads not being at right-angles. Also fabrics such as twills may shear more easily in the direction of twill line than in the other. Other problems may be caused by lack of uniformity in the fabric or error in the subjective judgement of when the fabric begins to buckle.

During approximately the past fifty years a number of researchers have examined the shear properties of woven fabrics, and a number of testing instruments have been designed in an effort to quantify the resistance to fabric shear and study the effect of tensions in varying directions on this resistance. Other researchers such as Grosberg and Park (90) have analyzed the mechanisms which explain the shear resistance of fabrics, while mathematical models have been produced by workers such as Leaf and Sheta (94) to try and estimate the initial shear modulus of plain woven fabrics, given the fabric sett and certain yarn and fibre properties. Grosberg, Leaf and Park (93) have also presented a study of the problem of predicting the shear behaviour of plain-woven fabrics in terms of geometrical parameters and yarn properties.

The majority of studies into this topic have the problem of being difficult to comprehend by someone who has limited, or no previous knowledge of woven fabric structure, as it is often taken for granted that the reader has a previous knowledge of the subject. This is, however, not usually the case with those outside this relatively new and narrow field, and often those in industry who most need enlightenment can not get to grasps with the fundamentals of this subject, so that interest in the topic might grow and lead to a greater general awareness. This lack of awareness is probably most apparent from the fact that there is no standard test available for woven fabric shear, and there does not appear to be a great demand for one. The bias extension test is still used to a greater extent, but it is unsatisfactory because of the non-uniformity of stress in the specimen (see Chapter 5.2.3, and Appendix 1), and because there is no standard test available for this method either.

Skelton (95) has gone some of the way to alleviate this problem by producing a relatively simple, but lucid paper on the fundamentals of woven fabric shear. He goes back to basics and quite simply explains the differences between the shear stiffness of a woven fabric and the shear modulus of a lamina. He also compares the shear stiffness of various materials, and has converted the shear properties of some laminar materials into textile terms. This shows how much less the shear stiffness of woven fabrics are when compared to sheet-laminar materials, such as aluminium kitchen foil and paper.

In this paper, fabric shear properties are also compared with stiffness in other more familiar modes of deformation. Skelton (95) also investigates the geometrical limiting factors of fabric shear, and gives some rough approximations, as well as the results of some measurements. A reasonable approximation for shear stiffness is given as:

$$S = 0.3(W^5/H^4) \times 10^{-15}$$

where W is the weight in g/m^2, and H is the thickness in cm.

SECTION ONE

CHAPTER 3

SURVEY OF SELECTIVE STRAIN AND STRESS MEASURING DEVICES

3.1 Extension Measuring Devices for Fabrics

An important factor which should influence the design of every biaxial tensile tester and shear tester is the need to have an area in the specimen in which the stresses and strains are uniform, the strains being measured within this area. The difficulty with this is that the fabric close to the clamps is restrained in a direction parallel to the them, and this makes it impossible to ensure that the test specimen is uniformly strained. The cruciform specimen was one method adopted to try and overcome this problem, as it allowed the specimen to be gripped along lines which were remote from the test region. This method, however, means that strain in the test region of the specimen cannot be accurately determined by measuring the distance between the clamps as the arms of the specimen are under uniaxial strain while the test region is under biaxial strain. Strain must therefore be measured locally in the test region by some form of strain measuring device. A number of authors have described devices which have been used for strain measurement (see Table 3.1), however, they were not all used on the cruciform type of specimen, as a number of other methods have been used to attempt and

Some Fabric Extension Sensors in Chronological Order

Year	Author	Ref.	Description
1953	Reichardt et al	100	LVDT
1955	Topping et al	186	
1959	Klein	102	LVDT (Schaevitz)
1963	Clulow and Taylor	177	Electrical Resistance
1963	Clark	107	Pin attached to one end of machinist's dial and another pin fitted to the end of a long member on the other side of the dial
1965	Fish	104	Thin tube containing containing electrolyte, strain changes resistance
1970	Yendell	105	Vernier
1974	Crosby	103	LVDT (Schaevitz)
1974	Remington and O'Callahan	106	Vernier Calipers
1981	Minami and Nakahara	141	Linear Potentiometer
1981	Bassett	108	Simple Potentiometer

Table 3.1 List of some of the transducers used to determine fabric strain properties

produce a homogeneous test region in the specimen. Strain measuring devices have also found an application in measuring deflections and deformations in fabric structures such as tents, balloons and yacht sails and geotextiles.

The bonded strain gauges regularly used in other branches of engineering, are composed of a metal or semiconductor filament on a backing sheet by which they can be attached to the material to be subjected to strain, so that the filament is correspondingly strained. The strain alters the electrical properties of the filament, this alteration forming the basis of measurement. This type of gauge is however, not generally suitable for textile fabrics because the stiffness of the gauge is high compared to that of most fabrics. Apart from this the strains which can generally be measured by these gauges is relatively low, in the order of 4-5%. There are, however, high elongation strain gauges which have been produced for measurements on wood and and plastics which can measure extensions up to 20%, but for many textile fabrics they are still too stiff, especially when fabric shear is involved. Sluimer and Risseeuw (96) have described a strain-gauge technique for the measurement of deformations in geotextiles. They used high elongation strain gauges (Micro-Measurements, type EP-08-40, CBY-120), which had previously been found suitable for usage with relatively stiff coated fabrics. They were some problems glueing the strain gauges to the geotextiles which these researchers were testing. This type of gauge may be suitable for measuring uniaxial or biaxial deformations in certain stiff fabrics, but as mentioned if shear is involved as well there may be problems.

Due to the problems with this type of strain gauge a number of authors, Freeston et al (97), Checkland et al (98), and Firt (99) have described photographic methods of measuring strain within the test region of the specimen. However, photography has the disadvantage of being difficult to automate. Therefore various other forms of strain measuring devices have been devised. It was essential in the design of these devices that the stiffness and friction in any moving parts were kept to a minimum, also the weight had to be minimized. These devices which are mounted on the fabric can be susceptible to error as the strain is measured between only two discrete points within the test region.

Reichardt et al (100) developed a device which consisted of two deflection gauges which were each based on linear variable differential transformers (LVDT'S)(see Fig.3.1). An LVDT is an electromechanical transducer that produces an electrical output proportional to the displacement of a separate movable core. They have many commendable features which make them useful for a wide variety of applications, but it is their ability to allow

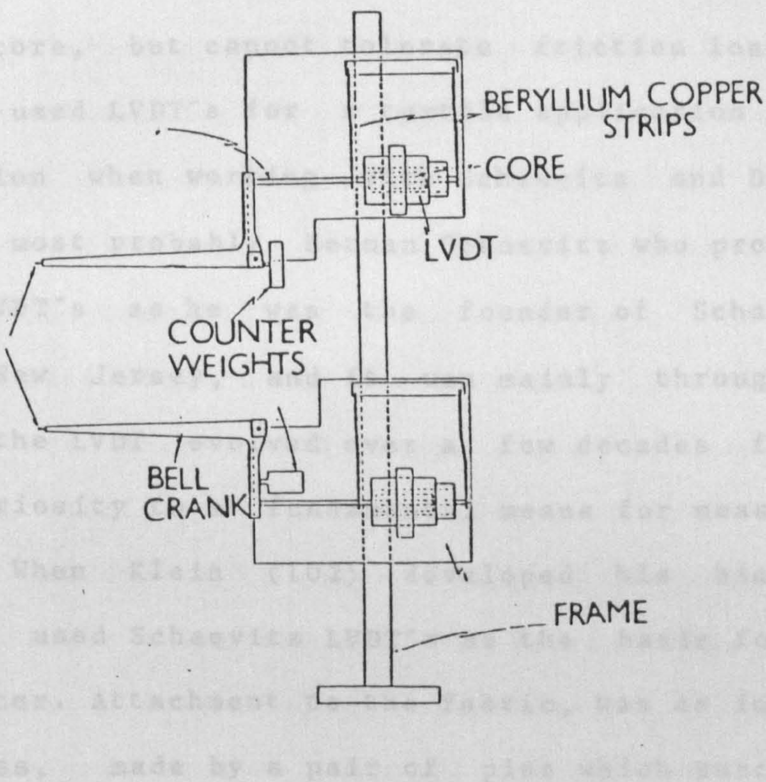


Fig. 3.1 Displacement transducer due to Reichardt et al [100].

almost frictionless measurement that makes them attractive to designers of strain measuring devices for textile fabrics. The LVDT is virtually a frictionless device because ordinarily, there is no physical contact between the movable core and coil structure. This permits its use in critical measurements that can tolerate the addition of the low-mass core, but cannot tolerate friction loading. Reichardt had used LVDT's for a textile application on a previous occasion when working with Schaevitz and Dillon (101). It was most probably Herman Schaevitz who proposed the use of LVDT's as he was the founder of Schaevitz Engineering, New Jersey, and it was mainly through his efforts that the LVDT evolved over a few decades from a rarely used curiosity to a fundamental means for measuring displacement. When Klein (102) developed his biaxial-tester he also used Schaevitz LVDT's as the basis for his strain transducer. Attachment to the fabric, was as in many of these devices, made by a pair of pins which punctured the fabric at a predetermined separation.

Crosby (103) describes a fabric strain monitor which was designed for balloon flight tests. He stated that the art of fabric strain measurement was not well developed and he agreed that bonded strain gauges have insufficient physical ranges. However, he goes on to say that it is possible to use this type of gauge if an arrangement of dividing levers is setup, but he does suggest that the complexity and fragility as well as other objections make this method unattractive. He mentions a number of other gauges, but states that they are unsuitable for his application, Crosby (103) also drew attention to the Mk.1 Fabric Strain Monitor developed by Telta. This gauge used a linear potentiometer as the transducer, but it required a span of 25.4cm (10in) on the fabric to provide acceptable results and was therefore unsuitable. Telta therefore decided to design a new instrument and Crosby (103) states that this was precipitated, in part, by the "discovery" of a nearly ideal transducer. A very extensive search had been carried out and many transducers investigated, but the one eventually selected was an LVDT manufactured by Schaevitz Engineering; the particular model designated 125HCD.

Fish (104) describes a gauge which was developed to measure the strain on a Dracone flexible barge. This gauge consisted of a narrow bore rubber tube containing a strong electrolyte. The ends of the tube were plugged with small electrodes to which the leads were soldered. During this process great care had to be taken to exclude air bubbles from the tube, and the electrolyte and electrodes were chosen for their resistance to gassing. These gauges could be constructed at various lengths and Fish (104) claimed that it was possible to make gauges any length down to 3.5cm. The gauge was attached to the Dracone using rubber adhesive and as extension occurred the gauge tube would become longer and thinner increasing the resistance, this formed the basis of measurement. Fish (104) concluded that this type of gauge was suitable for measuring very high rapid strains of fabrics which are subject to violent motion. However, Yendell (105) claims that this type of gauge is subject to zero drift and very sensitive to temperature variation. For the Dracone application the gauge was operated in sea water, the temperature of which was normally constant over a long period; so that temperature compensation was not required.

Yendell (105) described the direct reading flexible strain gauge which he designed for measuring static strains on model sails in a wind tunnel, and also which could be used on fabric samples in a laboratory testing machine. This gauge basically consisted of two scales of the vernier which were formed photographically on two separate transparent strips of polyester foil. Each scale was attached to a specimen at one end only so that the other end was free to slide over the other scale as the specimen was strained. Despite its simplicity this system does suffer from the disadvantage of being difficult to automate.

Remington and O'Callahan (106) also used a vernier system when examining the deflections in frame supported tents for the U.S. army. Small steel tabs with a cross marked on each were glued to the fabric in a 7.62cm x

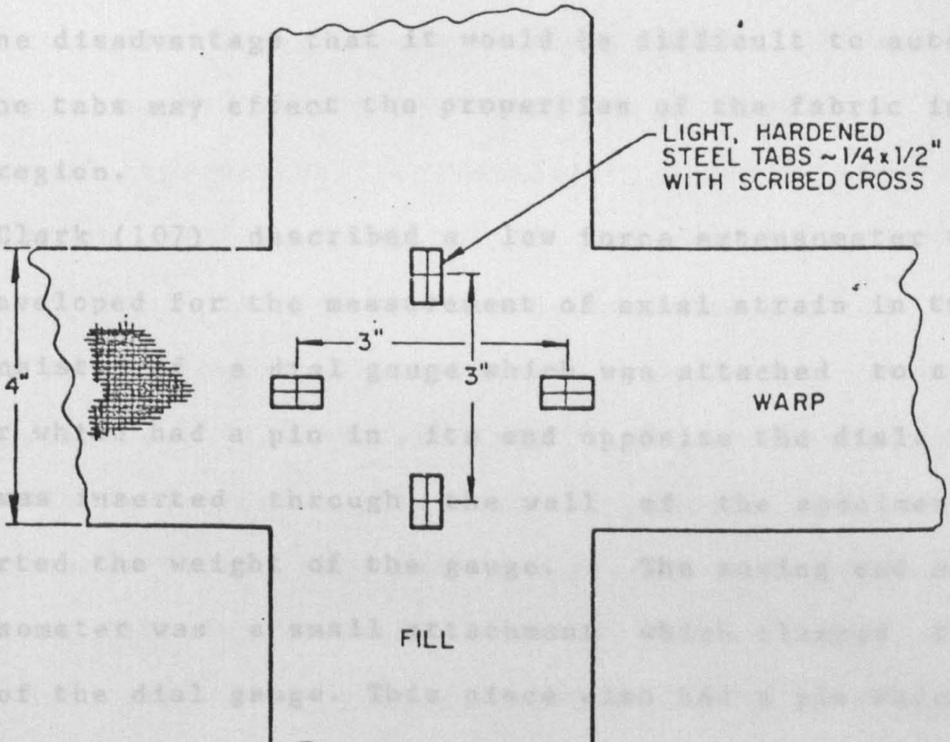


Fig. 3.2 Method used for measuring displacements in fabrics due to Remington and O'Callahan(106).

7.62cm (3" x 3") test region (see Fig.3.2). Knowing the gauge length between the tabs (7.62cm) and the change in spacing between the tabs as the load was applied, the strain could be calculated in both the warp and weft directions. The distance between the tabs was measured with vernier calipers with pins glued to the jaws. This method has the disadvantage that it would be difficult to automate and the tabs may effect the properties of the fabric in the test region.

Clark (107) described a low force extensometer which was developed for the measurement of axial strain in tubes. It consisted of a dial gauge which was attached to a long member which had a pin in its end opposite the dial. This pin was inserted through the wall of the specimen and supported the weight of the gauge. The moving end of the extensometer was a small attachment which clamped to the stem of the dial gauge. This piece also had a pin which was inserted through the wall of the specimen. As the tube was loaded, the dial gauge recorded the change in length of the fabric between the two pins. The weight of this device may not have effected fabric properties of the heavy cord-rubber laminates on which it was being used, but it would almost certainly cause problems on lighter fabrics.

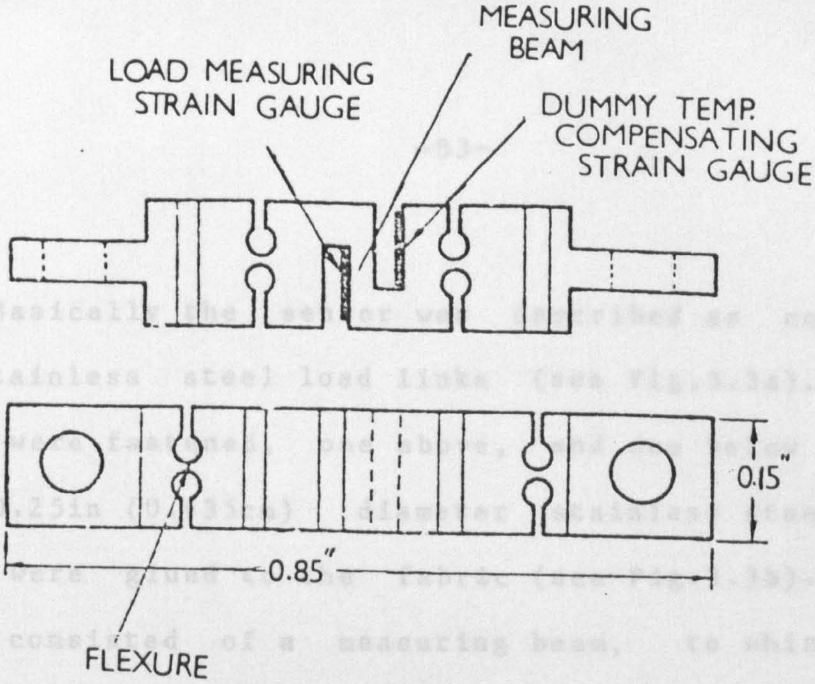
As can be seen various methods have been used to try and measure the strain in fabric membranes. The reasons behind the development of these different devices, which basically perform the same function, have ranged from the need for a cheap and simple instrument used in the laboratory on fabric specimens, to the need for an instrument which is operated remotely in hostile environments, such as balloons in flight or flexible barges on tow in the ocean. The varying end-uses have resulted in many different requirements being made of extension sensors, these include the need to be impervious to all effects of the weather and sunlight, and to operate in temperature ranges of up to 38 degrees centigrade. As Crosby (103) stated, the characteristics desired in any remote sensor include sensitivity, resolution, accuracy, good retrace (no hysteresis), electrical stability, durability and minimum effect on the measured phenomenon.

Bassett (108) suggests that friction may be a problem with all strain measuring devices which operate on a resistive basis. He also suggests that LVDT's may be too heavy and bulky, since three are required to measure all of the strain components. Therefore he predicts that an electro-optical device of analogue or digital type, which could be made light and compact, would appear to be the best option. The author has carried out some preliminary experimental studies on strain gauges, which although not based on the method suggested by Bassett (108), may overcome some of these problems. This subject will be discussed in Chapter 4.

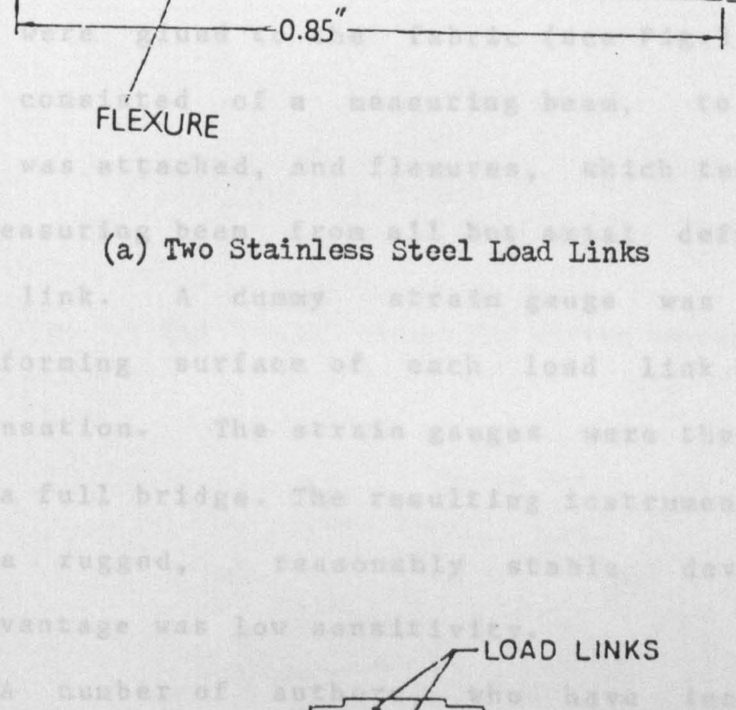
3.2 Stress Measuring Devices for Fabrics

In the present context stress applies to tension per unit width of the membrane material, and as Bassett (108) stated the selective measurement of stress is more difficult than that of strain. Kawabata et al (83) used an instrument which was specially designed so that stress was only measured over the central part of the sides of the specimen. In the Bassett (108) biaxial tensile and shear tester a similar principle was adopted. The two carrier bars, which were attached to the force transducers, carried the larger central region of the specimen edge, while separate carriers carried the wires at the two ends of each specimen edge. This meant that only the forces on the central region of each edge of the specimen were transmitted to the force transducers. For this method to be used the displacement of the central, and edge parts of the carrier bar should be equal. The small deflections of the force transducer had therefore to be ignored.

A force sensor for textile fabrics was described by Remington and O'Callahan (106) (see Fig.3.3). It was much stiffer than the fabric and as a result carried all the loads in the yarns to which it was attached. As Remington and O'Callahan (106) recognised, the disadvantage of this sensor was that it was a rigid inclusion in the fabric, which distorted the strain field. This distortion could be minimized by making the sensor as small as possible.



(a) Two Stainless Steel Load Links



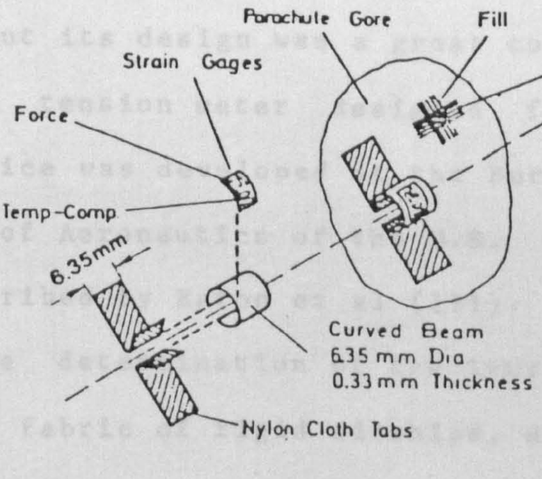
(b) Shows Load Links fastened, by Stainless Steel Buttons, one above and one below the fabric.

Fig. 3.3 Force Sensor for fabrics due to Remington and O'Callahan (106).

Basically the sensor was described as consisting of two stainless steel load links (see Fig.3.3a). The load links were fastened, one above, and one below the fabric, to ~0.25in (0.635cm) diameter stainless steel buttons, which were glued to the fabric (see Fig.3.3b). The load links consisted of a measuring beam, to which a strain gauge was attached, and flexures, which tended to decouple the measuring beam from all but axial deformations of the load link. A dummy strain gauge was attached to a nondeforming surface of each load link for temperature compensation. The strain gauges were then wired together into a full bridge. The resulting instrument was claimed to be a rugged, reasonably stable device whose one disadvantage was low sensitivity.

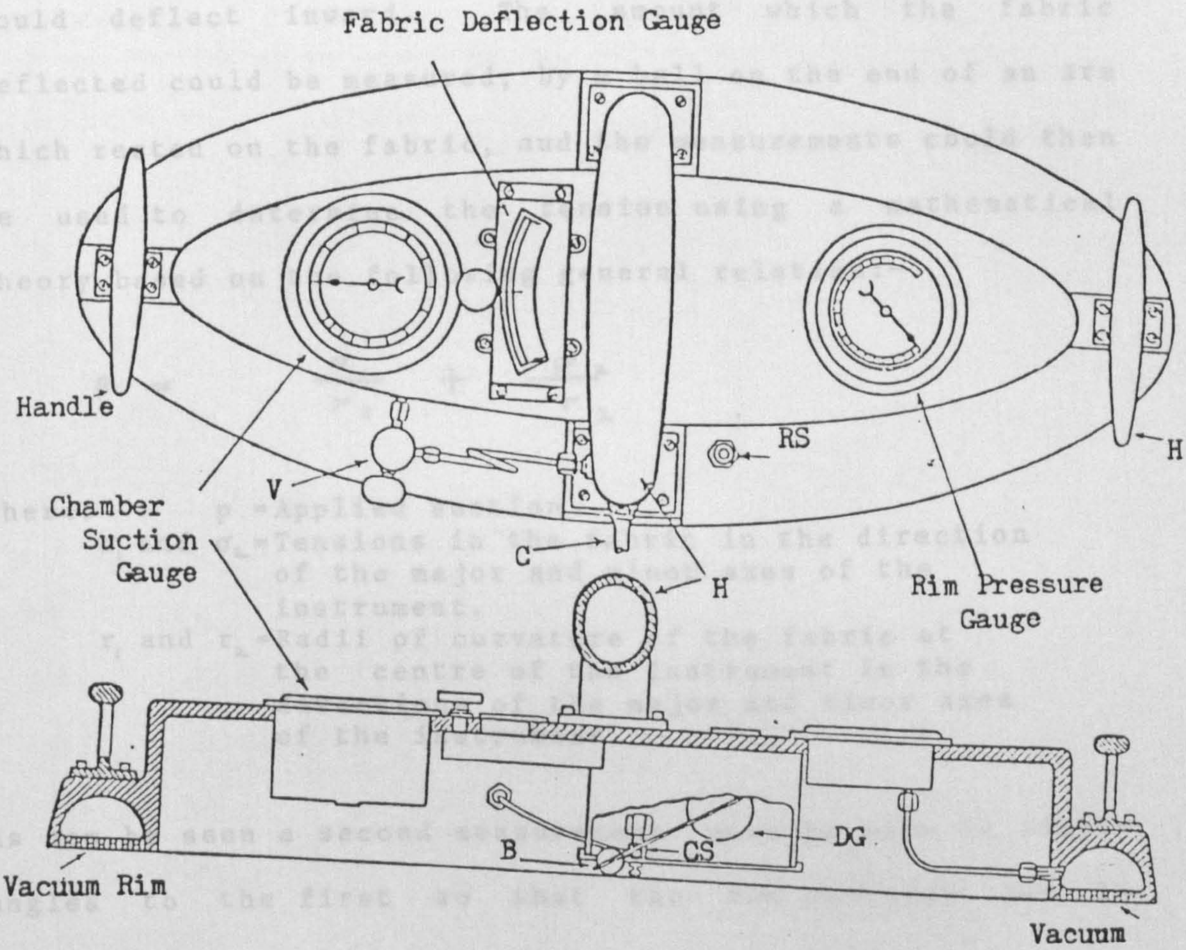
A number of authors, who have included Braun and Doherr (109) and Heinrich and Saari (110), have described the Omega sensor. This device was developed in 1972 by researchers who were trying to measure the stresses in the flexible material of deploying parachute canopies. These researchers recognised that known sensors either provided only the maximum stress value, or caused such large local disturbances and interference that the recorded stress histories were useless. The Omega sensor was shaped like the Greek capital letter omega (see Fig.3.4). This shape allowed flexibility and when stress was applied to the tabs of the sensor, its curved beam was deflected

Fig. 3.4 The "Omega" sensor for stress measurements in fabrics.



"from Braun and Doherr (109)"

and the resulting bending moment was measured by an active 120 ohm strain gauge. A dummy strain gauge was added for temperature compensation. It was found when the sensors were attached to the textile that a small slit in the fabric, just under the slot of the sensor, reduced interference problems. This allowed the sensor signal to become reasonably independent of the specimen, as the sensor carried all the load rather than the "bridge" of fabric. The Omega sensor was tested in both static and dynamic tests, and it was found to have uses during free-flight tests. It did have problems due to its temperature sensitivity, but its design was a great contrast to a much earlier fabric tension meter designed for aeronautical uses. This device was developed at the Bureau of Standards for the Bureau of Aeronautics of the U.S. Navy in 1922-23, and it is described by Eaton et al (111). The device was designed for the determination of the tension existing in the outer cover fabric of rigid airships, and the envelopes of non-rigid and semi-rigid airships. The device basically consisted of a thin-walled aluminium casting, which was 51cm x 20cm (20in x 8in), and weighed approximately 5.4kg (12 lb) (see Fig.3.5). It had an elliptical chamber open at the bottom with a hollow vacuum rim extending around its edge. The bottom face of the vacuum rim was flat and was bored full of small suction holes. This allowed the device to adhere to the fabric by suction in the rim, when placed, and also isolate the



V= Rim and Chamber Suction Control Valve

C= Suction Line

H= Handle

CS= Chamber Safety Valve

DG= Fabric Deflection Gauge

B= Ball Resting on Fabric

RS= Rim Safety Valve

Fig. 3.5 Bureau of Standards Fabric Tension Meter
"from Eaton et al (111)"

elliptical portion of the fabric lying within the rim. If a small suction was then produced in the inner elliptical chamber, this elliptically shaped portion of the fabric could deflect inward. The amount which the fabric deflected could be measured, by a ball on the end of an arm which rested on the fabric, and the measurements could then be used to determine the tension using a mathematical theory based on the following general relation:-

$$p = \frac{\sigma_1}{r_1} + \frac{\sigma_2}{r_2}$$

where: p =Applied suction

σ_1 and σ_2=Tensions in the fabric in the direction of the major and minor axes of the instrument.

r_1 and r_2=Radii of curvature of the fabric at the centre of the instrument in the directions of the major and minor axes of the instrument.

As can be seen a second measurement must be made at right-angles to the first so that the two tensions may be determined.

This instrument was used with very heavy fabrics, so that it might be possible to consider its weight of minor significance, but it would be of little use on lighter industrial fabrics. Eaton et al (111) state that the errors, with this device, are relatively large for low tensions, largely due to local variations in the "modulus" of the fabric. However, they claim that this factor becomes increasingly less important as the stress increases and hence the percentage error decreases. It was suggested that errors of 10-25% might be expected over the range of tensions ordinarily used in the outer covers of rigid airships.

CHAPTER 4

A PROTOTYPE EXTENSION SENSOR FOR FABRIC SPECIMENS

Introduction

Devices which can be used for the determination of strain in fabric specimens and structures have been described in Chapter 3. However, none of these can really be considered as ideal for mounting and operation in the test region of fabric specimens which must be subjected to shear as well as biaxial tension, as each has a number of shortcomings, some of which include the inability to be automated, bulkiness, excess weight, and tensile stiffness. Therefore an attempt was made to design and fabricate a direct-reading strain transducer, which it was hoped would overcome many of these problems; preliminary experimental work carried out to test the viability of this new device will be described in Chapter 5.

Initially a number of different approaches were considered, one of which included fixing a regular engineering strain gauge to a flexible cantilever; this would be fixed vertically at one end below the fabric specimen. The other end was to have a pin attached, which could be pushed through the specimen. The cantilever could then be calibrated against known displacements, and from this the fabric strain could be calculated. However, before the practical viability of any of these methods could be put to the test a relatively new material was discovered, which was pliant, flexible, tough and lightweight. This material is a polymeric piezoelectric film based on polyvinylidene fluoride (PVDF or PVF2), and it shows the highest piezo- and pyroelectric activities of all know polymers. The manufacturers suggest that this material may possibly be used as a strain gauge, but after a quite extensive literature search little evidence could be found of any previous work in this area, apart from some unpublished preliminary studies by Edelman, which has been mentioned by Broadhurst et al (112).

The word piezo is derived from the Greek, ´piezen´- to press. Piezoelectricity could therefore be thought of as "pressure electricity". This effect has been described (113) as:

> "Piezoelectric effect or piezoelectricity- Electric polarization arising in some anisotropic (ie., not possessing a centre of symmetry) crystals (quartz, Rochelle salt, barium titanate) when subject to mechanical strain. An applied electric field will likewise produce mechanical deformation."

This phenomenon was first discovered by Pierre and Jacques Curie in the 1880´s, and its first practical application was by Langevin in 1916. He developed an ultrasonic sending and receiving system which was the forerunner of modern day sonar.

4.1 The Development of Piezo Film

In the 1960's researchers were looking for alternatives to piezoelectric crystals or ceramics, which for certain applications were considered too heavy or inflexible. Naturally occurring materials such as wood and other biological substances(114) were the first piezoelectric polymers to be investigated. Later studies were made on a number of polar and non-polar polymers subjected to a high poling voltage and a high frequency field, and it was discovered that the higher the polarity of the unit cell of the polymer the higher the "induced" piezoelectric effect. In 1969, Kawai(115) discovered that polyvinylidene fluoride (PVDF) could be poled to a level of activity not previously obtained with any other polymeric material. This gave it the highest piezoelectric activity of all known polymers. A piezo film, using PVDF as its base resin, was utilized as the sensory element of the prototype extension transducer, the operation of which will be described later.

The PVDF is described in depth by the Kynar Technical Manual(116) and Marcus (117). Essentially the piezoelectric activity of the polymeric material used for the film arises from its molecular structure. A polymer is a long chain of identical units called monomers. The monomers of PVDF contain hydrogen and fluorine atoms with a repeat unit (CH_2-CF_2). The monomer has a large dipole moment and the monomer units tend to polymerize predominantly "head to tail", ie. -CH2-CF2-CH2-CF2, and thus the polymer may also exhibit a large net dipole moment. PVDF is approximately 50% crystalline and 50% amorphous. The principal crystalline forms are the nonpolar A form and the highly polar B form shown in Figures 4.1(a) and 4.1(b), respectively. High piezo response is associated with the polar B form in which the hydrogen and fluorine atoms are arranged to give the maximum dipole moment per unit cell. Ordinarily, the dipoles in such a material are randomly orientated. However, upon heating of the materials the molecules are rendered mobile and applying a strong electric field tends to orientate the dipoles normal to the plane of the film. Upon cooling, the dipoles are frozen in their new orientation. Consequently, with a significant number of dipoles aligned, any stimulus which changes the thickness of the PVDF film will cause charges to come out on the surface forming a signal appearing either as an electric current or voltage variation.

As stated by Pennwalt(116) the film for poling is usually coated on one or both sides with an evaporated metallic layer such as aluminium, chromium, nickel, silver or another electrode metal to provide an intimate electrical contact with the PVDF film during polarization as well as in subsequent use. The choice of the electrode material is of course dependent on the desired application,

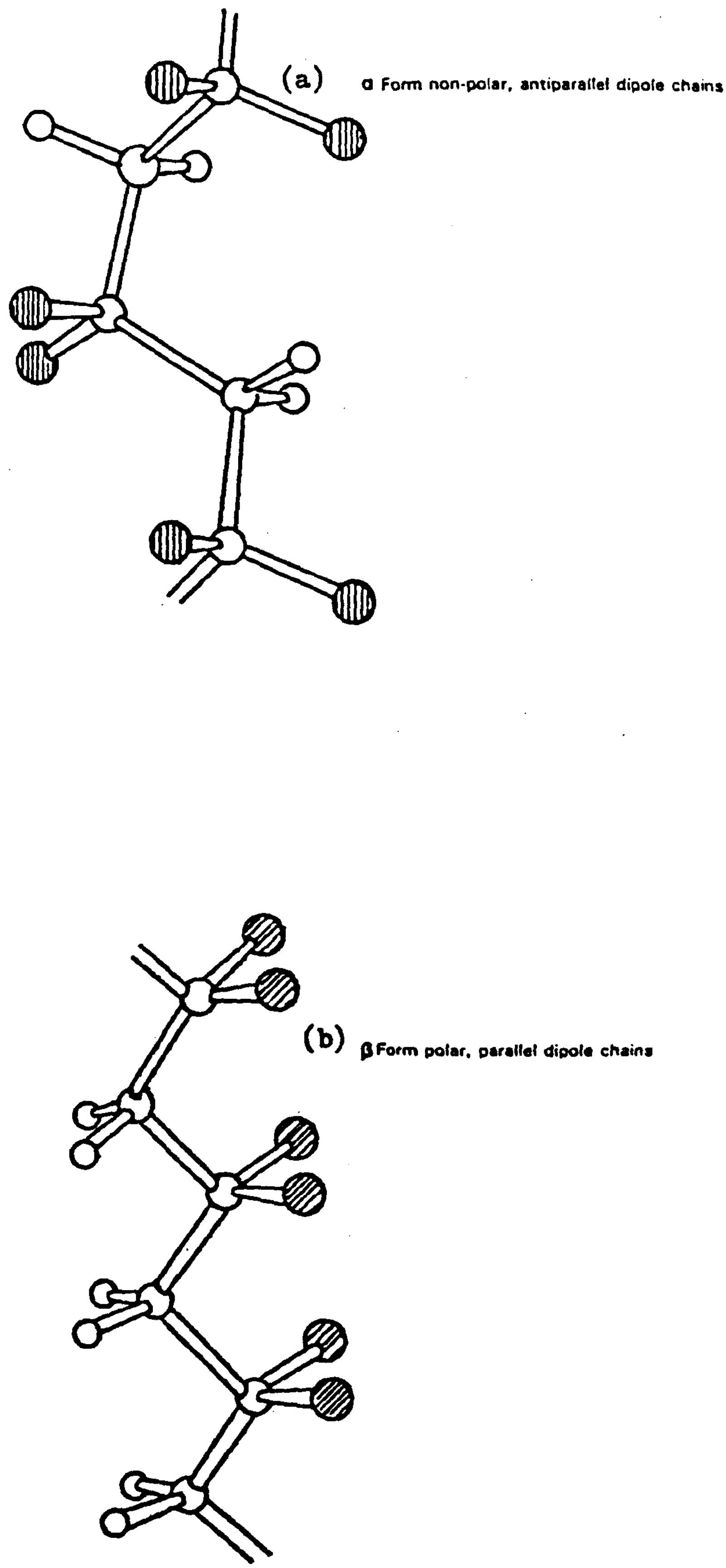
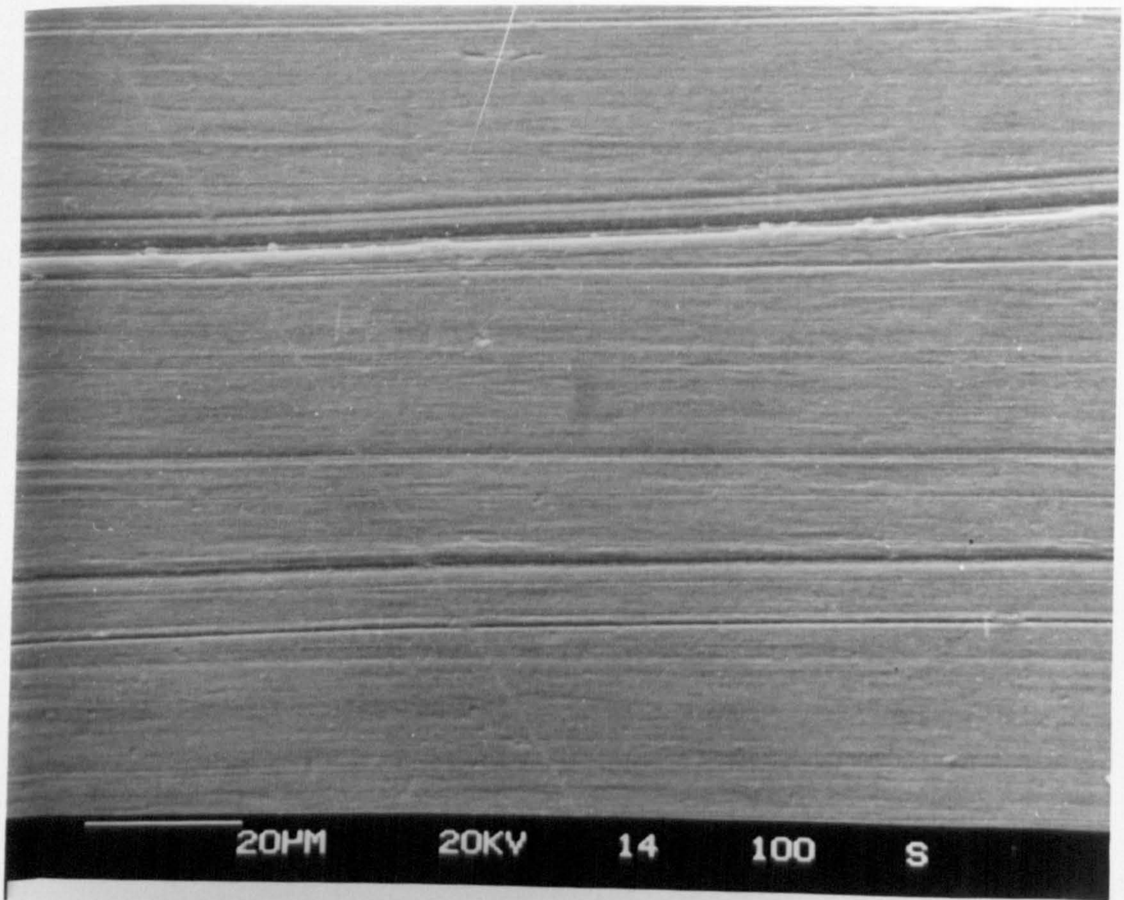


Fig. 4.1 The Principal Crystalline forms of PVDF.
"from Kynar Tech. Man. (116) ".

as the metallization used determines, amongst other things, the surface conductivity, adhesion properties, cost and environmental stability.

When PVDF is initially extruded, the non-piezo, non-polar A-crystallite phase predominates. Orientation of the polymer chains in the plane of the film is necessary to achieve enhanced piezoelectricity. Orientation is accomplished by stretching along one face dimension (uniaxially), usually in the direction of the machine travel, or in both machine and transverse directions (biaxially). Mechanical orientation of the film at elevated temperatures causes partial transformation to the piezoelectric polar B phase and orientates the polymer chains in the direction of stretch. Therefore if the dipoles are aligned along the axis of poling normal to the plane of the Piezo Film, and the crystallite chains are orientated in a direction parallel to the machine, or stretch direction, the piezoelectric activity would then be expected to be directionally dependant. The film is in fact anisotropic, and the electrical, mechanical and electromechanical properties differ for electrical or mechanical excitation along different directions.

The polarity and stretch direction (the direction of highest piezo activity) are indicated on the film by the symbol +>. The arrow lies along the direction of stretch. The stretch direction is parallel to the fine line



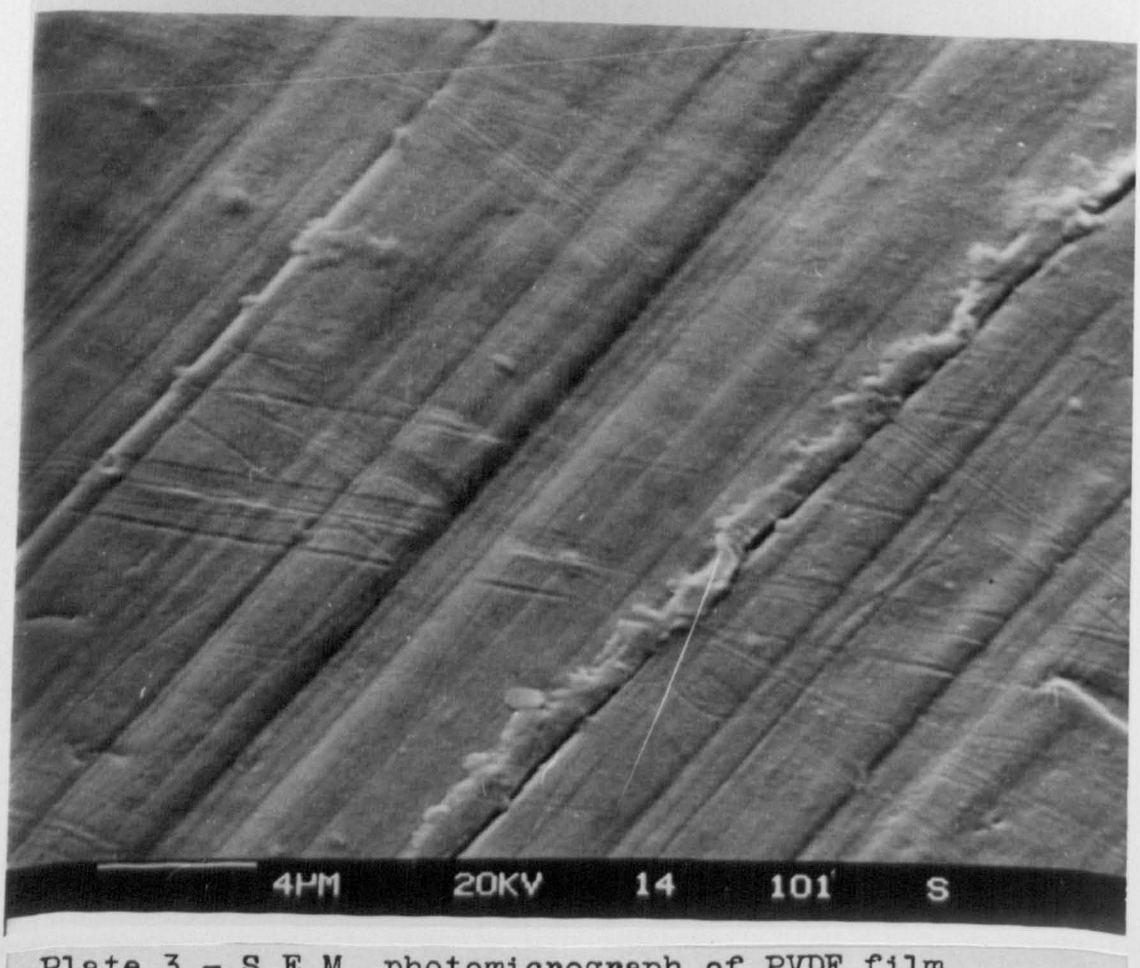


Plate 3 - S.E.M. photomicrograph of PVDF film showing striations in the active direction.
(a) x 1000 tilt 30° --
(b) x 2000 tilt 30°

striations observable on the film surface metallization (see Plates 3 (a)and (b)). The surface exposed to the positive poling voltage is marked as the + surface. Upon compression in the thickness direction or stretching transverse to the thickness, a negative voltage appears on this + surface.

4.2 Characteristics of Piezo Film

Pennwalt (116), the manufacturers of Kynar Piezo Film, state that it is a polymeric material with mechanical properties typical of engineering plastics, with good chemical resistance and excellent electrical properties. The material, as mentioned, is tough, lightweight, transparent and flexible, and is readily manufactured in sheet form in a continuous roll process, and can be fabricated into complex shapes for specific applications. The film is available in standard thicknesses which range from 6um~110um. However, thicker films are available for special applications.

Temperature dependance and ageing characteristics of Piezo Film are important design parameters. Piezo Film activity decay is proportional to working temperature. There is no substantial decay in activity up to a working temperature of 70 degrees centigrade, while quite high activity (50% of initial value) is maintained at a temperature of 110 degrees centigrade.

The Piezo Film will respond to both compressive and tensile strain. However, it is the tensile strain with which we shall be concerned. The resulting deformation causes a change in the surface charge density of the material so that a voltage appears between the electrodes. With a reversal of the force, the resulting voltage is of reverse polarity. A reciprocating force will therefore produce an alternating voltage output. Piezo Film is a dynamic material that develops an electrical charge proportional to a CHANGE in mechanical stress. The charge generally leaks away under static or quasi-static conditions unless buffered by very high impedance following circuitry. The electrical charges developed by Piezo Film decay with a time constant that is not only determined by the input impedance of the interface electronics, but also by the dielectric constant and internal resistance of the film.

Kynar Piezo Film can be cut with a razor blade, sharp scissors, or die-cut to the required dimensions. Care must be taken to prevent contact being made between the top and bottom metallizations by frayed or curling edges. The thinner films (6μm-9μm) are especially susceptible to this problem. However, this is not a problem with the present application, because for displacement transducers in which voltage is generated in response to a physical displacement of the film, thicker films or laminates are desired

(28μm-52μm). Laminates can be used because it is difficult to pole a thick film. Therefore, to gain higher voltage output, because voltage output is proportional to film thickness as well as area, a multilayer stack can be used. A disadvantage of using these thicker films is that they may be stiffer, therefore having a greater effect on the mechanical properties of the fabric under test. However, the stiffness of these thicker films is still relatively insignificant when compared to some other forms of strain gauges, partly because they do not have any added stiffness due to backing material, and most of the industrial fabrics which require this type of testing are generally stiffer, in the yarn directions, than the still quite thin polymer films.

4.3 Tensile Properties of Piezo Polymer Film

Tensile stiffness properties should be important factors in the design of any extension sensor which is to be attached to the surface of a textile fabric. As mentioned in Chapter 3 there is no ideal remote extension sensor available at present with low stiffness and low bulk. Very low stiffness, although an important factor, may not be so crucial in the yarn directions of high modulus industrial fabrics, such as air structure fabrics or sailcloth. It is, however, a serious problem when the fabric is also to be subjected to shear deformations, because the backing materials of, for example, high elongation foil strain gauges, are generally made from paper or plastic which has a much greater shear stiffness than the textile fabric, and this will result in unacceptable local stiffening. The problem is increased with this type of gauge because they are usually rectangular with a low l x w ratio (< 4:1), and they must be attached over their full length and width by adhering the backing material to the surface to be measured. One of the main advantages of the piezo film is that it can be cut and used in almost any desired dimensions, this helps overcome the problem of localized stiffening, and minimizes interference in directions other than that being measured. This is especially important where shear deformation is involved, it was therefore proposed to use long narrow strips of film (l x w ratio >15:1).

Skelton (95) has compared the shear stiffness of a range of familiar materials with some fabric stiffness values taken from the literature. The shear properties of some laminar materials, which include polythene, have been converted to textile terms. As the piezo film is a polymeric material with mechanical properties typical of engineering plastics, it seems reasonable that we should equate it with the polythene mentioned by Skelton (95), which is approximately the same thickness as the thicker piezo films that are used as the active element in the extension sensor. Also given are the shear stiffness values of various polyester fabrics which were used for air-supported structures. This allows us to compare the shear stiffnesses of a polymeric sheet with a typical light industrial fabric, the polythene sheet is at least 80 times the shear stiffness of the 4.0 oz/yd^2 (135.6g/m^2) fabric, and can be as much as 2000 times greater, depending on the finish of the fabric. The shear stiffness of the thinner films will of course be expected to be of a lesser order. This high shear stiffness of the film should not be a serious problem in tests as the extension sensor attached in the yarn directions will be very long and thin (eg. 40mm x 1.5mm), and will only be attached to the fabric by a spot of adhesive at each end. It is possible to attach the piezo film in this manner because in textiles we are only interested in tensile behaviour; unlike conventional materials textile fabrics cannot generally take compression in the fabric plane, therefore it is unnecessary to bond the gauge along its whole length.

Pennwalt (116) states that in the machine direction their Piezo Film will break rather than yield. For thin films they claim that this breakage will occur at between 160-330 x 10^6 N/m^2 and at 25-40% elongation.

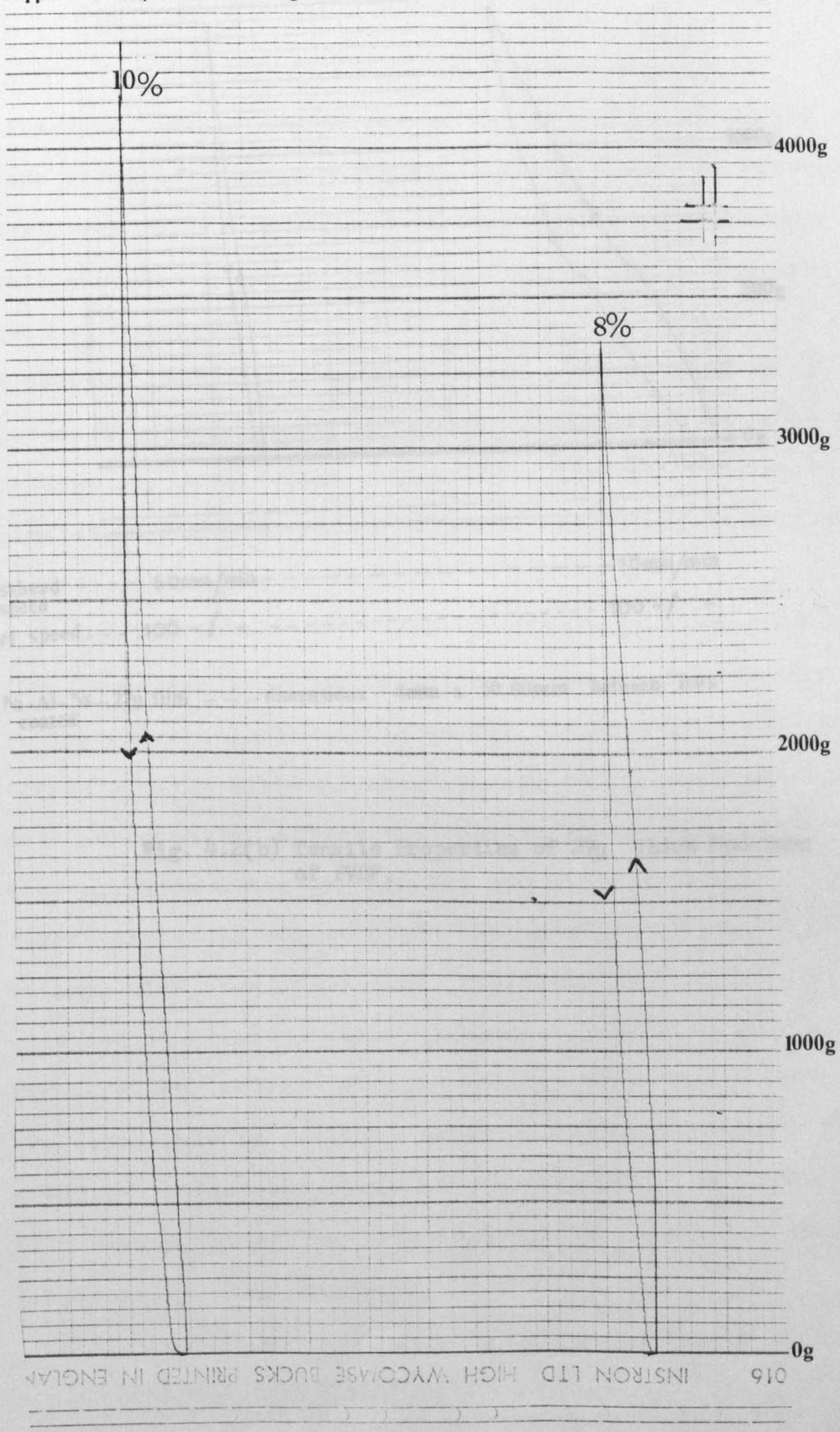
Estimating the tensile strength of a thin film of hypothetical thickness using the means of the figures given by the manufacturers, and converting to textile terms, we find that the thin films have a tensile strength at break

of approximately 505N/50mm. Comparing this with a typical commercial (118) PVC/polyester structural grade coated fabric (820g/m^2, 3700N(wp)/3700N(wf)/50mm), which is used as the membrane system for airhouses. It is found that the fabric has about 7.3 times greater tensile strength at break than the piezo film. If, however, the film is compared at the width which it is attached to the fabric (l x w = 50mm x 2mm) it is found that the 50mm width of fabric has more than 180 times greater tensile strength at the break. This comparison does not of course take extension properties into account. Young's modulus of a thin PVDF film is in the region of 2 x 10^9 N/m^2 this may be compared to the initial Young's modulus of fabrics to be tested.
In the machine (active) direction tests were carried out to determine the tensile stiffness and other mechanical properties of the film. These tests were performed on 52u and 27u thickness films in an Instron extensometer, and an example of the results can be seen in Fig.4.2(a) and (b). These piezo film specimens were all approximately 4mm in width, and the 52μ film required over 1000gf/mm width to produce a 13% extension, and about 670gf/mm width for an 8% extension. The 27μ film, however, required less than 375gf/mm width for an 8% extension.

A few tests were performed on a 200mm x 50mm specimen of 272g/m^2 sailcloth. This fabric required approximately 1000gf/mm width to produce a 7% extension in the warp

Piezo Polymer Film

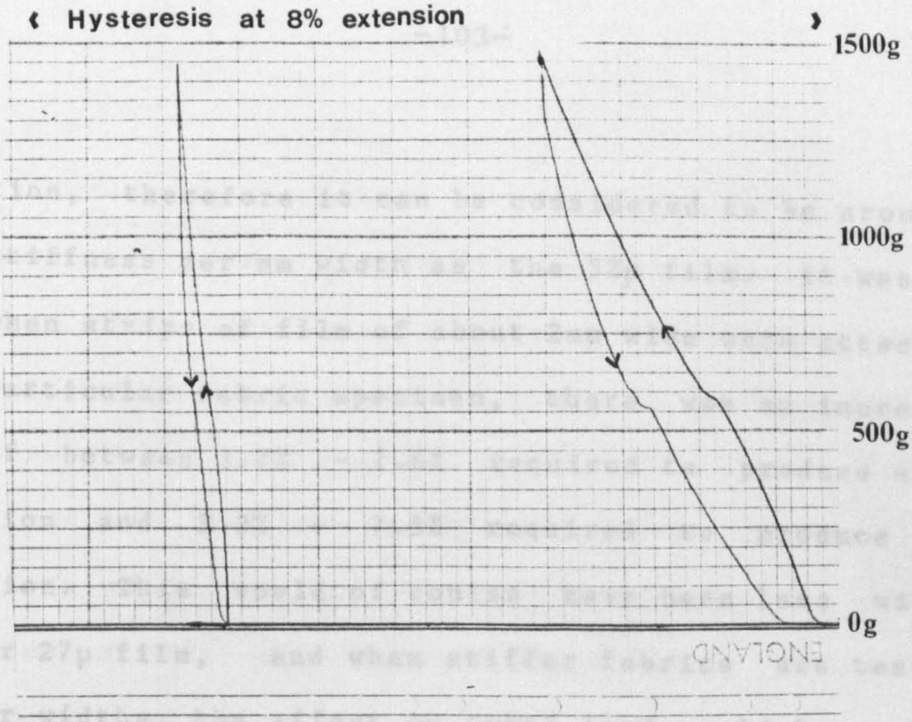
Copper— — —52μ film— test length 3.8mm x 50mm



crosshead speed— — — —50mm/min
chart speed— — — — —100mm/min

Fig. 4.2(a) Tensile Properties of 52μ Thick Specimen of PVDF.

Piezo Polymer Film



crosshead speed ---- 50mm/min ------------------- 10mm/min

chart speed --- 100 -- / -- ------------------- 100 -- / --

Ni-Al-Ni coated – 27μ film ——— dimensions 4mm x 50.00mm between jaws

Fig. 4.2(b) Tensile Properties of 27μ Thick Specimen of PVDF.

direction, therefore it can be considered to be around the same stiffness per mm width as the 52μ film. It was found that when strips of film of about 2mm wide were attached to this particular fabric specimen, there was an increase in load of between 3.7% - 7.6% required to produce a 5.5% extension and 3.3% - 7.5% required to produce a 7% extension. This would of course have been less with the thinner 27μ film, and when stiffer fabrics are tested in greater widths, the affect on total load would be much less significant.

As can be seen the main stiffness problem with this film is during shear deformation, however, this should not be a problem when long thin pieces of film are used (l x w ratio >15:1). Although the film can be attached so that it does not greatly affect the fabrics shear properties when extensions in other directions are being measured, it is almost certainly too stiff to be used for measuring strain in any direction other than the yarn directions during a uniaxial or biaxial test. Bassett (108) has stated that the ratio of initial Young's modulus of a woven fabric* in the major axis to initial shear modulus is typically 120:1 - 500:1. This emphasizes how much greater an affect the film would have on the fabric if used to measure displacements due to shear.

* uncoated, apparel fabric

4.4 The Following Circuitry

With the more standard electrical resistance strain gauge the "instrumentation", as it is often known, includes everything from energizing the gauge to the production of test results in the required form. This type of strain-gauge can be considered as a passive resistor which requires a power source - changes in resistance caused by mechanical strain are measured in a bridge circuit which produces an out-of-plane voltage. This voltage requires amplification and display or storage, or both.

The piezo-electric extension measuring device which is described here differs significantly in that it requires no power source, as mechanical deformation produces an electrical charge; the circuitry must be capable of displaying this in a meaningful form.

As previously mentioned the charge developed by the Piezo Film will generally leak away unless buffered by very high impedance following circuitry. This is especially a problem under static or quasi-static conditions. The relationship between electrical impedance ($Ze = (2\pi fC)^{-1}$) and frequency for various thicknesses of Kynar Piezo film is shown in Fig.4.3.

Initially when the Piezo Film was obtained no indication of the circuitry to be used was available from the manufacturers or suppliers. For source impedances of tens or hundreds of megaohms it is mandatory to use vacuum

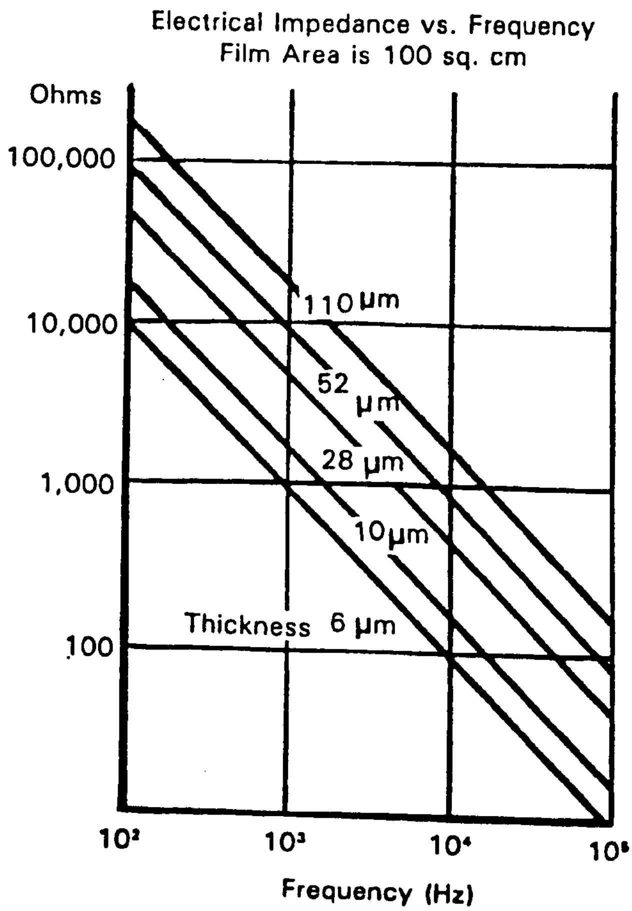


Fig. 4.3 Electrical impedance vs. frequency for PVDF film

"from Kynar Tech. Man.(116)"

tubes or field-effect transistors at the input. Therefore the first approach involved the use of a J-FET (Junction-gate Field-effect Transistor) (119), this has an input resistance in the region of 10^{10} ohms and it was used in the construction of a simple amplifier, the basis of which can be seen in Fig.4.4. This amplifier was used in the piezo-electric measuring circuit as shown in Fig.4.5.

Preliminary tests were carried out using this set-up, and it was found that when the chart-recorder pen was set to zero a trace was produced above the line during extension. However, this was found to decay rapidly and the trace dropped below the line when the load causing the extension was released. With the load completely removed it would not return to zero; even if brought back to zero using the chart-recorder adjustment there were still drift problems. The accuracy of quasistatic measurements is determined by the drift effects of the amplifier, drift being defined as any undesirable change of an output signal in time which is not a function of the measured variable. This could be caused by a leakage of current in the system.

An indication of the rapidity of the charge decay became apparent when a test was carried out in an Instron extensometer. If the test was performed at a rate slower than 200mm/min, and only for relatively low extensions for short periods of time, the charge would decay and the pen would drop towards zero while the specimen was still undergoing extension.

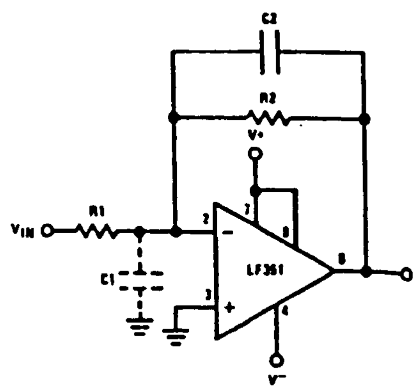


Fig. 4.4 Basis of simple amplifier used in the first tests on the PVDF extension sensor

(From Linear Databook 1980, National Semiconductors Corp., California. Supplied by Farnell Electronic Components, Leeds)

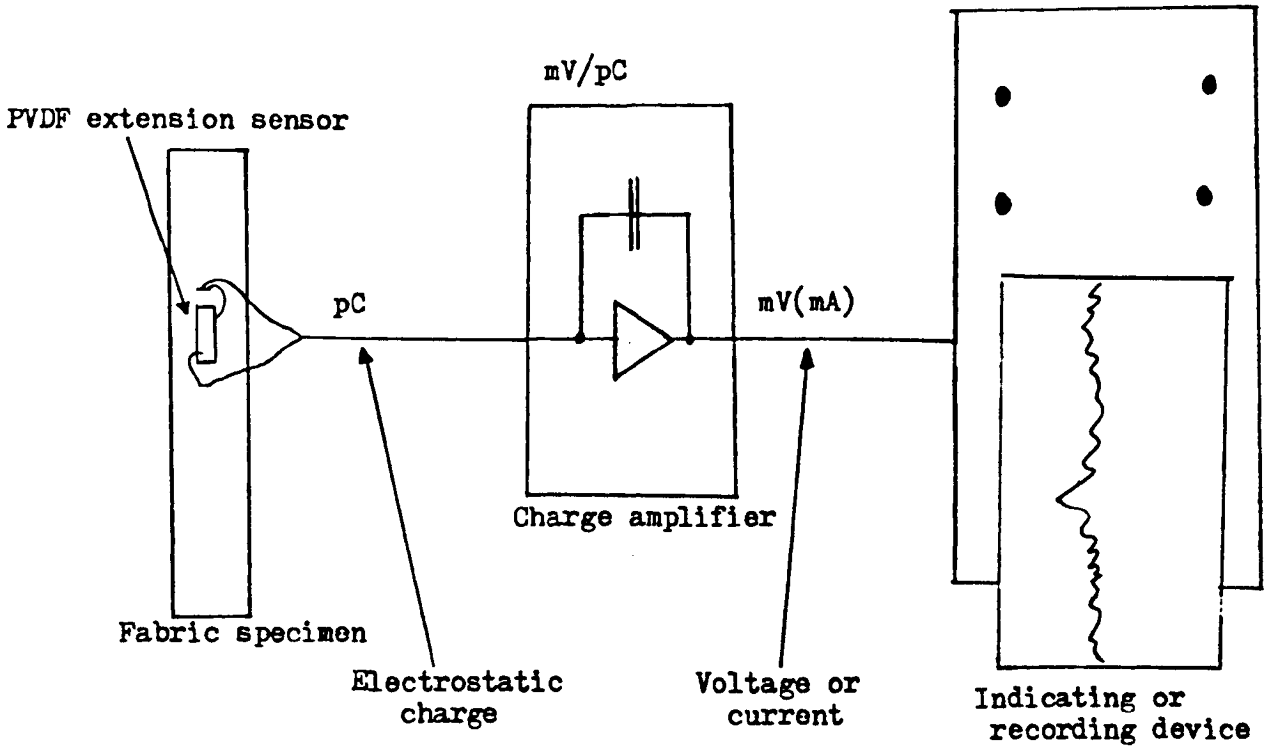


Fig.4.5 Basic circuit for piezo-electric measuring installation

The time constant of the amplifier is determined by that of the feedback capacitor, so attempts were made to overcome the rapid decay of the charge by increasing this capacitance. This gave some improvement, but on the whole it was not satisfactory and most of the problems still remained; noise in the system being one of the more serious of these. It became apparent after consultations with the University Micro-Systems Unit that the design of specialized electronics for this application would be an onerous and time consuming task.

The next approach involved the investigation of the electronics which were used in other forms of piezo-electric measuring devices. This was quite a simple task as at this time fellow workers in the Department were using Kistler Quartz Force Links for drop-tests while researching the mechanical properties of ropes. Therefore piezo-electric measuring electronics were available, the basis of which was a charge amplifier.

Early amplifiers with high insulation at the input, which allowed quasistatic calibration of quartzes, were electrometer amplifiers. These may be regarded as a precursor of the charge amplifier which can be traced back to the physicist W.P.Kistler in the early 1950's. The charge amplifier has a number of advantages over the electrometer amplifier, which include higher linearity, better frequency response, less influence from the cable capacitance, calibrated sensitivity stages and greater stability. The advent of the charge amplifier led to a more widespread use of piezoelectric instruments, and in principle it consists of a high-gain voltage amplifier with a MOSFET or J-FET at the input to attain the high insulation resistance (120). It has negative feedback via a highly insulating range capacitor which acts as an integrator for input currents flowing via the charge input; these are generated by charge changes on the transducer. Thus at the output the integral of the charge changes yielded by the piezoelectric transducer appears, and consequently a signal proportional to the entire charge. Due to the capacitive feedback the charge of the quartz transducer is compensated almost completely.

By the circuitry shown in Fig.4.6 the electrical charge, amenable to direct quantification only with difficulty, is converted into an easily evaluated voltage at the amplifier output. The measuring range is selected by using an appropriate feed-back capacitor (C1....C3). This amplifier with its very high insulation resistance at the input, its high open-loop gain Vi and its purely capacitive feedback has been used for the electrical measurement of mechanical variables in conjunction with piezo-electric transducers since its introduction in 1950.

The function of a charge amplifier can basically be interpreted as follows. The amplifier connected as an

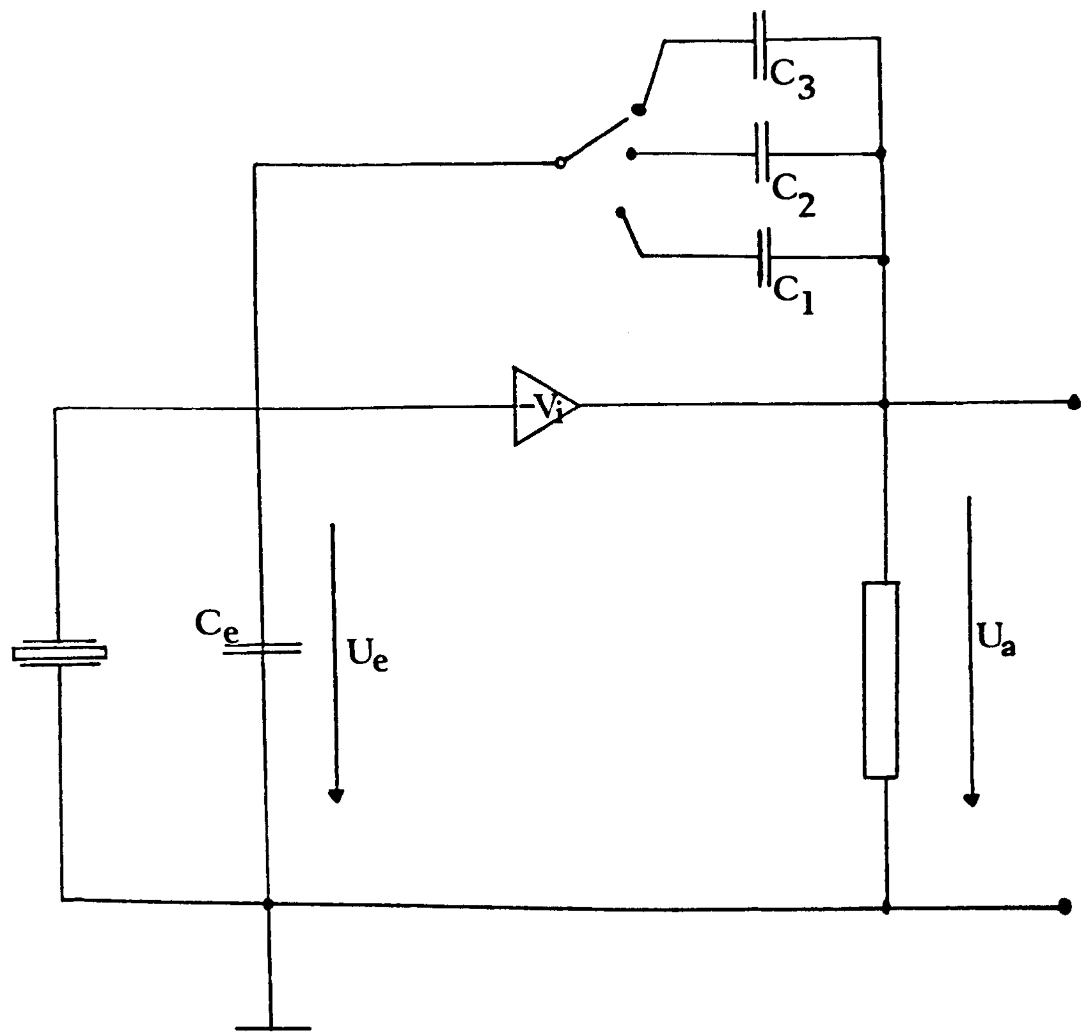


Fig.4.6 Principle of the charge amplifier with quartz transducer (C_e =total capacitance at input, $C_1 \ldots C_3$ =switchable feedback capacitance, v_i =open-loop gain; $v_i \gg 1$)

"from Kail and Mahr[120]"

integrater compensates the electrical charge yielded by a transducer with a charge of equal magnitude but opposite sign, generating a voltage over the range capacitor in accordance with the equation (120):

$$ua = -Q/Cg$$

where ua = output voltage
Q = charge generated by charge source
Cg = feedback capacitance

Describing this instrument as a "charge amplifier" is not quite apt, as this amplifier does not generate a higher charge but converts a charge Q into a voltage ua which can then be processed without difficulty. The various charge amplifier types now obtainable differ mainly in their measuring ranges and sensitivity adjustment. With appropriate adaption of the amplifier, any piezo-electric transducer may be connected to any charge amplifier. However, transducers employing less highly insulating materials than quartz (eg. barium titanate, lead zirconate) require minor alterations to the circuitry. For the particular application described here no alterations were made to the circuitry of the charge amplifier used. This was a Kistler, type 5007 charge amp., which is designed mainly for laboratory use, and it is described in greater depth in the Kistler publication (121) (see Appendix 3 for circuit diagram).

For this preliminary work the charge amplifier was used by the simplest possible method; all the settings were set to the maximum and left at this for all tests, any adjustments required were made at the chart-recorder. Also because of possible affects of changes in the ambient atmospheric conditions all tests were carried out in an atmosphere meeting the requirements of B.S. 1051, to ensure consistency as far as was practical.

Using the charge amplifier helped overcome many of the original problems encountered. However, it was important to ensure that the cable used for connecting the piezo-electric transducer to the charge amplifier met certain special requirements as troublesome electric fields may be created in the presence of a voltage (eg. fluorescent lights where a relatively high voltage is developed to start discharge). Only selected coaxial cables with extremely high insulation resistance and low capacitance could be used, generating only negligible charge signals when moved. On the other hand, for connection between the amplifier output and indicator instrument, the usual coaxial cable could be used. Connectors too had to meet high standards: they had to be highly insulating, tight and insensitive to dirt, and robust. Low insulation in the input circuit can cause drift and values of 10^{14} ohms are typical for the transducers, cables and connectors. It was at the transducer that most care had to be taken in this case, and it was important to avoid handling the film with the bare hand as this could affect the resistance properties, also contacts had to be of a very high standard. These will be described in more depth in Chapter 5. Protection of the transducer from electric fields could be achieved by screening with aluminium foil.

The final part of the basic circuit for the piezo-electric measuring installation was the indicator instrument. In this particular case a KIPP and ZONEN BD8 chart-recorder proved most suitable as the method of displaying the output of the low frequency tests. The trace was useful as a permanent record, or for post processing purposes. The reduction of the trace into a suitable form for analysis was a manual process.

It was realized that there were means available of achieving a higher resolution in the output, but at this stage the chart-recorder proved most convenient.

4.5 Adhesives

The importance of the adhesive used to mount any strain-gauge cannot be over-emphasized, as reliable transmission of the strain in the test surface through the adhesive layer into the gauge is of prime importance. Amongst the effects the adhesive can have on the test results include, creep performance, linearity, hysteresis, instalation resistance as well as heat dissipation characteristics.

According to Morden (122) the ideal adhesive for strain gauge applications should:

(1) Be capable of forming a thin, void free glue-line with high shear strength.

(2) Be compatible with all gauge backings, test materials and test surfaces.

(3) Be capable of working from deep cryogenic temperatures to very high temperatures.

(4) Exhibit good linearity with minimum creep and hysteresis.

(5) Be single part requiring no mixing or weighing out.

(6) Require minimum curing time.

(7) Require no clamping.

(8) Have a long pot life when mixed.

(9) Be capable of high elongation

Another desirable feature is the ability to become tacky soon after application. This allows positioning without any elaborate clamping device.

Of course no adhesive has been produced which exhibits all these characteristics. Therefore one must be careful when selecting the adhesive for any particular application, as it is clear that the gauge can only perform as well as the installation will permit.

Pennwalt (116) have stated that Kynar Piezo Film can be adhered to a structural member using conductive or non-conducting adhesives; non-conducting adhesives were required for this particular application. The selection of the correct adhesive for Kynar Piezo Film depends on the surface material to which it is to be adhered, and of course the desired mechanical properties of the adhesion layer. In all cases, however, the selected adhesive must be non-polar and have low dielectric constants. Adhesives based on toluene, xylene, aliphatic hydrocarbons and aromatic hydrocarbons are recommended, and adhesives such as acetones, ketones and alcohol based formulations, which are highly polar possessing high dielectric constants can have deleterious effects on the film and therefore should be completely avoided.

Suitable non-conductive adhesives include acrylics, urethanes and epoxies; Pennwalt (116) list a number of these which are available on the U.S. market. The present author contacted a number of local adhesive distributors in the hope that they could suggest a suitable adhesive for this application, however, the general response was that they would be unable to offer a suitable product without extensive and expensive investigations, and this would not be justified without a known potential market. Therefore with limited time available a number of readily available adhesives were tried, by carrying out a simple test where the peak height produced by the film on the chart-recorder was compared with the extension of the fabric specimen on the Instron extensometer chart (see Fig.4.7). The adhesive which gave the best correlation over a range of test speeds would be chosen, if the results were considered acceptable.

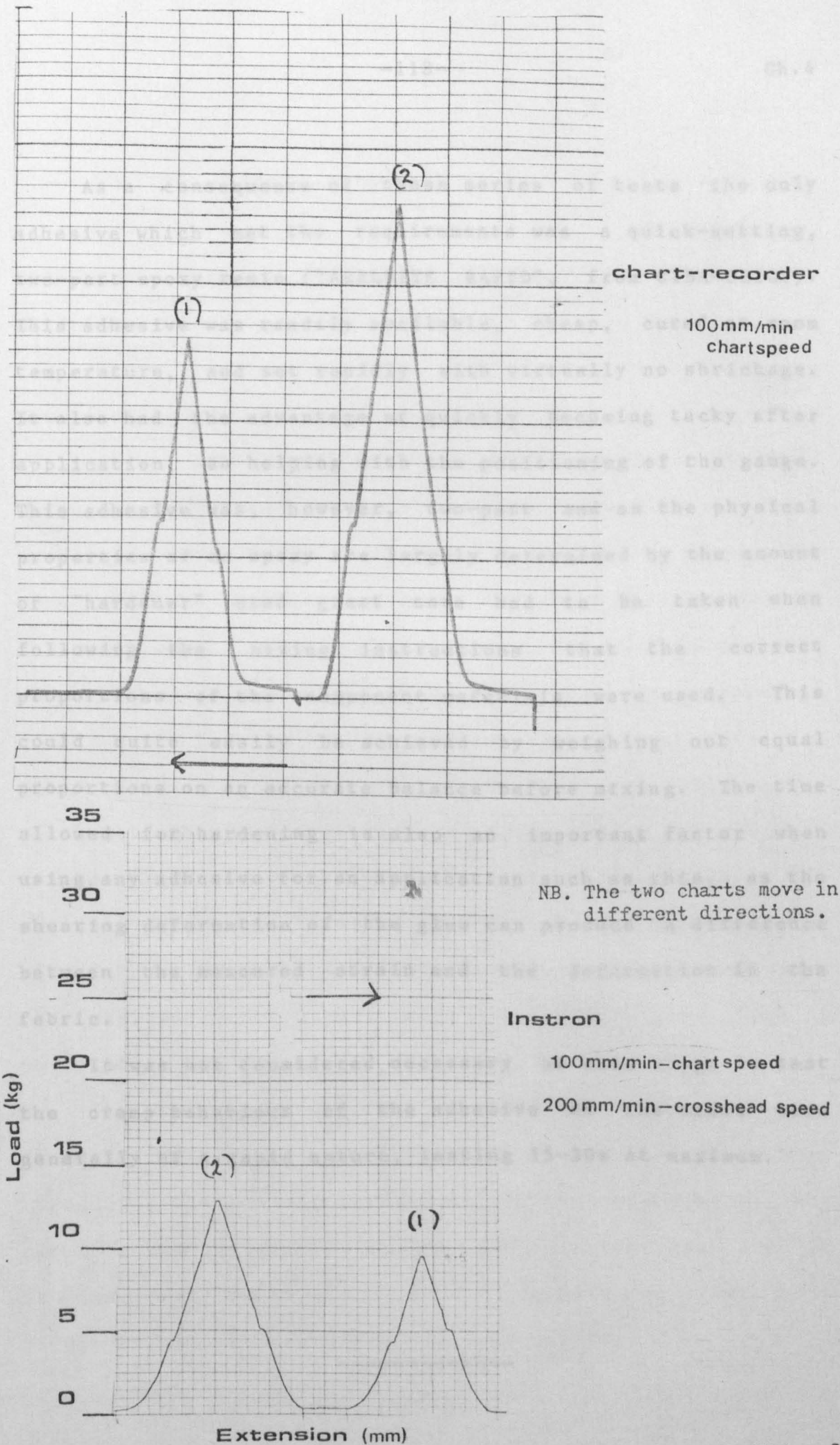


Fig. 4.7 Example of a Test carried out to determine the suitability of the adhesive. The PVDF response was compared with the Instron extension. (Measurements were made manually)

As a consequence of these series of tests the only adhesive which met the requirements was a quick-setting, two-part epoxy resin ("ARALDITE RAPID", from CIBA-GEIGY). This adhesive was readily available, cheap, cured at room temperature, and set rapidly with virtually no shrinkage. It also had the advantage of quickly becoming tacky after application, so helping with the positioning of the gauge. This adhesive was, however, two-part and as the physical properties of an epoxy are largely determined by the amount of "hardener" used great care had to be taken when following the mixing instructions that the correct proportions of the component materials were used. This could quite easily be achieved by weighing out equal proportions on an accurate balance before mixing. The time allowed for hardening is also an important factor when using any adhesive for an application such as this, as the shearing deformation of the glue can produce a difference between the measured strain and the deformation in the fabric.

It was not considered necessary at this stage to test the creep behaviour of the adhesive as the tests were generally of a rapid nature, lasting 15-30s at maximum.

CHAPTER 5

PRELIMINARY TESTS ON THE BEHAVIOUR OF THE NEW EXTENSION SENSOR

Introduction

After the basic circuitry for piezo-electric measurement had been determined, it remained to perform a number of experiments in order to examine the accuracy, repeatablity and behaviour under different test speeds of the newly developed extension sensor. Before this could be done, however, it was realized that some form of consistency had to be brought to each test. This was achieved, firstly by carrying out all tests in a laboratory which met the specifications of B.S. 1051. It has been stated (123) that in terms of strain measurement, an environment may be defined as hostile if it has detrimental affects on the measurement system: experience has shown that any deviation from "ideal laboratory" conditions is potentially hostile.

It was also important to establish some form of standard installation procedure, as it has long been recognised that minor variations in the mounting of any strain gauge can greatly affect the test results. Also it is important to have a code of practice in order that different operators achieve the same results.

5.1 Gauge Installation

This process consists of a number of stages as follows:

5.1.1 Surface Preparation

After selecting the appropriate apparatus and materials, the surface preparation of the test material can probably be considered as the first stage of the installation procedure.

A universal surface preparation procedure that has been tried and tested over many years on solid specimens consists of five basic operations (124):

(1) Solvent degreasing - remove as far as possible organic contamination.

(2) Abrading - most strain gauge adhesives require a relatively smooth surface.

(3) Application of gauge layout lines - cross lines on surface at point where measurements are to be made.

(4) Conditioning - clean after marking lines

(5) Neutralizing - conditioning left surface acidic - therefore neutralize by scrubbing with water based ammonia solution.

This procedure is, however, not wholly suited to this particular textile application as solvent degreasing and abrading are seldom, if ever, appropriate. It is difficult to determine a general procedure for textile fabrics as their surfaces may vary greatly. For tests carried out in this study it was generally found sufficient to select fabric specimens which appeared free from dirt and contamination, and then apply the gauge layout lines. It was important when marking these lines that the marking substance was not applied to the fabric at the points where adhesive was to be applied, as this may affect bonding. The gauge layout lines are of course important as they help guarantee alignment of the film, which has a direct effect upon the level of strain to which the gauge will respond.

It is obvious that the acceptance of a code of practice for the surface preparation of the material to be tested brings a greater degree of consistency to the adhesion process. However, adhesion is a complex process dependent on a number of factors which vary for each particular substrate and adhesive combination. It is evident therefore, that the best surface preparation for a particular combination should be determined experimentally

5.1.2 Mounting

It was important during mounting not to contaminate the polymer film by handling with the fingers. Touching the film (active element) can cause changes in the insulating resistance and also may lead to problems in bonding.

To aid handling and positioning during mounting it was found useful to use a cellophane adhesive tape. A piece of tape could be adhered to each end of the strip of polymer film, and it could then be lifted and positioned on the test material. The film was adhered to the textile fabric using only two small dots of adhesive at each end of the active element (see Fig.5.1). The cellophane tape allowed the polymer film to be held in position while the adhesive cured. A polythene sheet could then be placed on top of the film and a 500g Instron calibration weight placed on top, to help ensure a thin adhesive layer and a consistent clamping strain in the film. When the adhesive had cured it was found that to achieve a satisfactory bond, an extra dot of adhesive had to be placed on top of the two ends of the film and spread over its edges, so that when this second layer of adhesive cured each end of the polymer film was effectively sandwiched between two layers of adhesive.

5.1.3 Terminal Strips

The main function of the terminal strip is to provide an anchor and a junction between the main lead wire and the relatively small and delicate jumper wires to the extension sensor. This method prevents damaging forces being transmitted to the extension sensor via the lead wires, as might occur if the lead wires are accidently subjected to a large force (125). It is important that a strain relief loop should be formed in the jumper wire to avoid a tight connection between the extension sensor and terminal strip (see Fig.5.2).

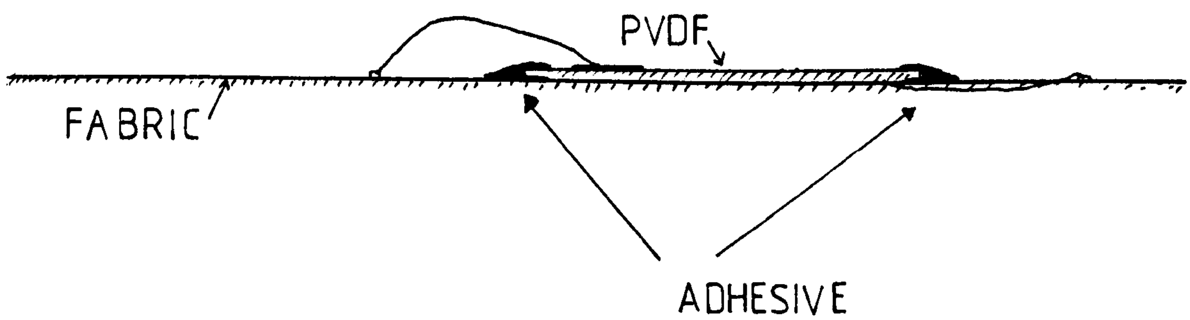


Fig. 5.1 Method of Mounting PVDF to Textile Fabric

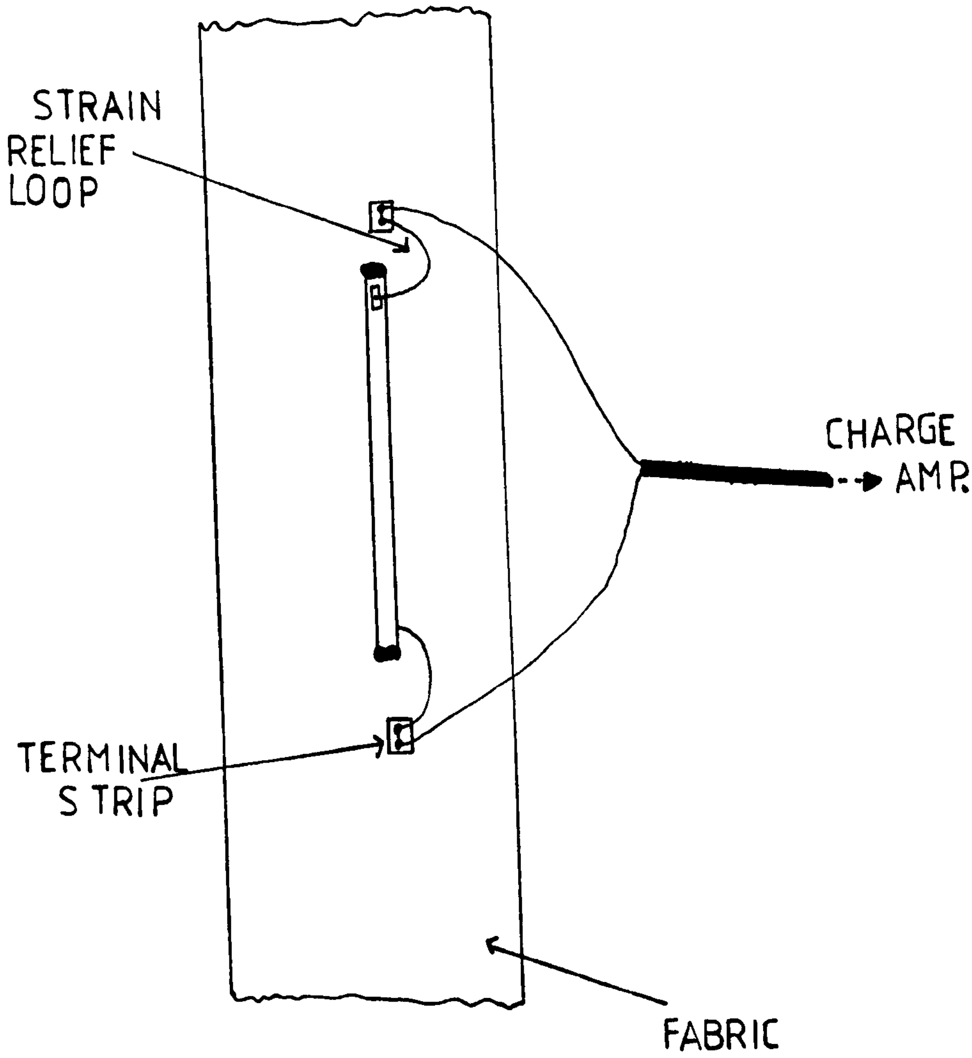


Fig. 5.2 PVDF Gauge Mounted on Fabric Showing Terminal Strips and Strain Relief Loops.

5.1.4 Jumper Wire Connections

There were a number of possible ways of connecting the jumper wires from the terminal strip to the polymer film. The methods used for this particular application involved firstly, and most extensively, the use of copper foil which had a conducting self-adhesive layer. When this was used the wires could be soldered to it before being attached to the PVDF. This was, however, difficult to work with when small connections were to be made.

A second method used low temperature solder (see Appendix 2), but this was used to a lesser extent as it required more time to prepare the connection. It was, however, useful where small, secure connections were required, and guaranteed a better contact. However, it did not appear to be successful with every type of metallized coating, and it did require skill to minimize the localized film shrinkage due to the heat.

The connections had to be made on each side of the film (see Fig.5.3(a) and (b)), however, it was difficult to ascertain which of these two methods shown was the better. It was considered that when the method as shown in Fig.5.3(a) was used, there would be non-uniformity of the strains in the deformed area of film between the spots of adhesive, because of interference from the adhered or soldered connections. If the method as shown in Fig.5.3(b) was used this would not be a problem. However, the ends of the film were free to move about and were not therefore as manageable, unless a further adhesive was used to secure them; but this may add to the localized stiffening in the fabric. It also seemed better to minimize the area of the film which was outside the strained region, as it was only the freely deformed area between the spots of adhesive which was measured for use in calculations. This was because it was difficult to determine the area of film which would be rendered rigid (or less likely to be deformed) by being held between the layers of adhesive. This potentially variable ratio, of rigid film to deformable film, was kept to the minimum practical.

Due to its simplicity and ease of use, the method as shown in Fig.5.3(a), was most often used in the tests which shall be described.

5.2 Preliminary Experimental Tests

These tests were carried out in order to study the behaviour of the PVDF extension sensor. To allow comparisons to be made all tests were performed in an Instron 1122 extensometer. The extension sensor was mounted on a strip of fabric (overall dimensions 30.0cm x 5.0cm, test region 20.0cm x 5.0cm) and the Instron jaws were then programmed to a set displacement, this allowed easy cross-checks to be made with the PVDF readings. It also allowed calibration of these readings.

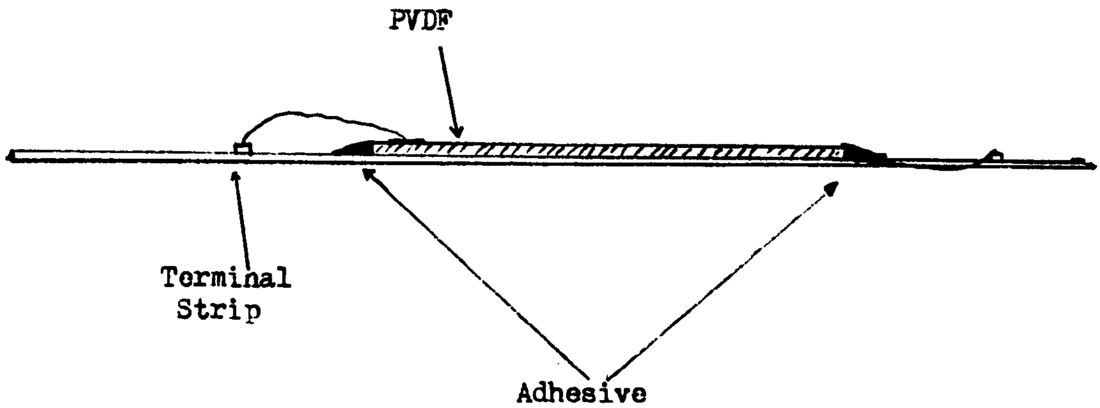


Fig. 5.3(a) Adhesive at Each End of the PVDF Film Strip

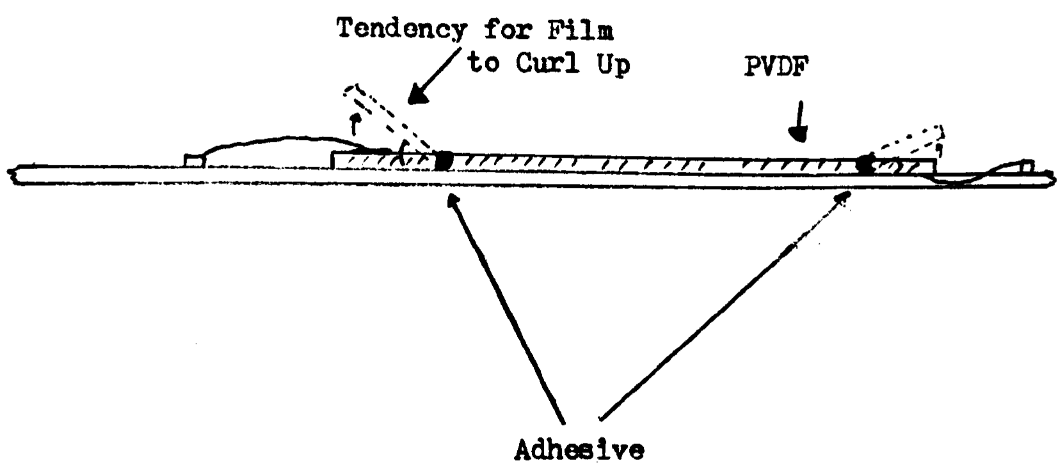


Fig. 5.3(b) Adhesive Not Quite at the End of the PVDF Film

One of the main problems with this test is the choice of the point at which strain is considered to be zero. This can be a source of considerable variation between tests, and it was thought that the most suitable way of dealing with this was by considering the strain to be zero, at a small pre-tension force. With a uniaxial test a force can quite easily be applied using a small weight suspended from the bottom of the specimen.

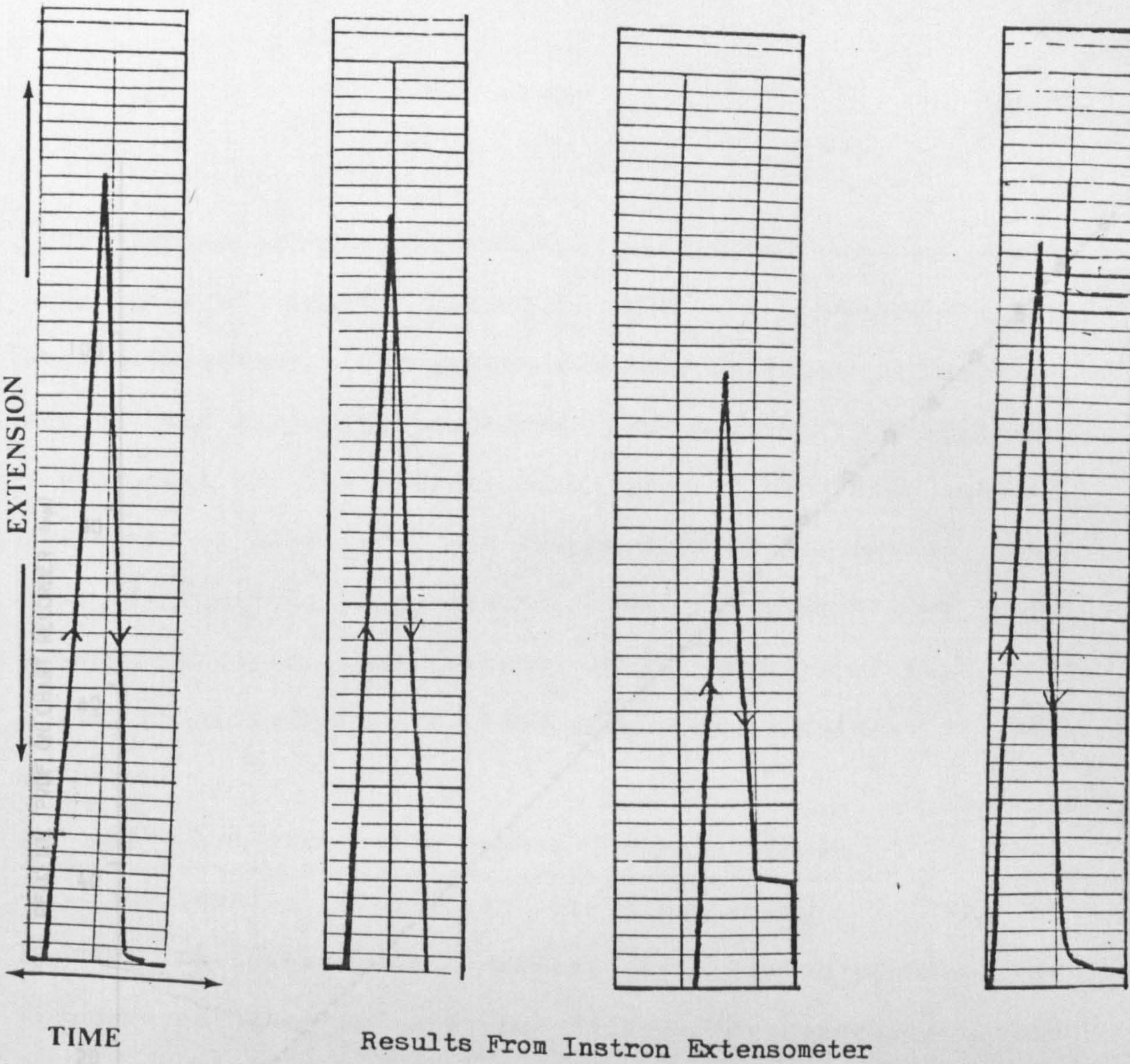
5.2.1 Extension Sensor Behaviour and Response

After determining that there was a suitable response produced on the chart-recorder when the PVDF was subjected to a mechanical deformation, it was then important to verify that this response was consistently proportional to the strain in the fabric, and how the PVDF reacted to different test speeds. It was also important to discover the limits of the new extension sensor's measuring capabilities.

(a)Relationship Between Instron Extension and PVDF Signal

Some of the results of tests which compared the response from the PVDF, as recorded by a chart-recorder, to extension in the fabric as measured on the Instron extensometer can be seen in Fig.5.4(a). The full set of results, 5.4(b), show a clear linear relationship between the elongation in the specimen, x, as measured by the Instron, and the peak height on the chart-recorder, y

Results From Piezo Film (Chartspeed 100mm/min)



Results From Instron Extensometer
(Chartspeed 100mm/min)
(Crosshead speed 100mm/min)

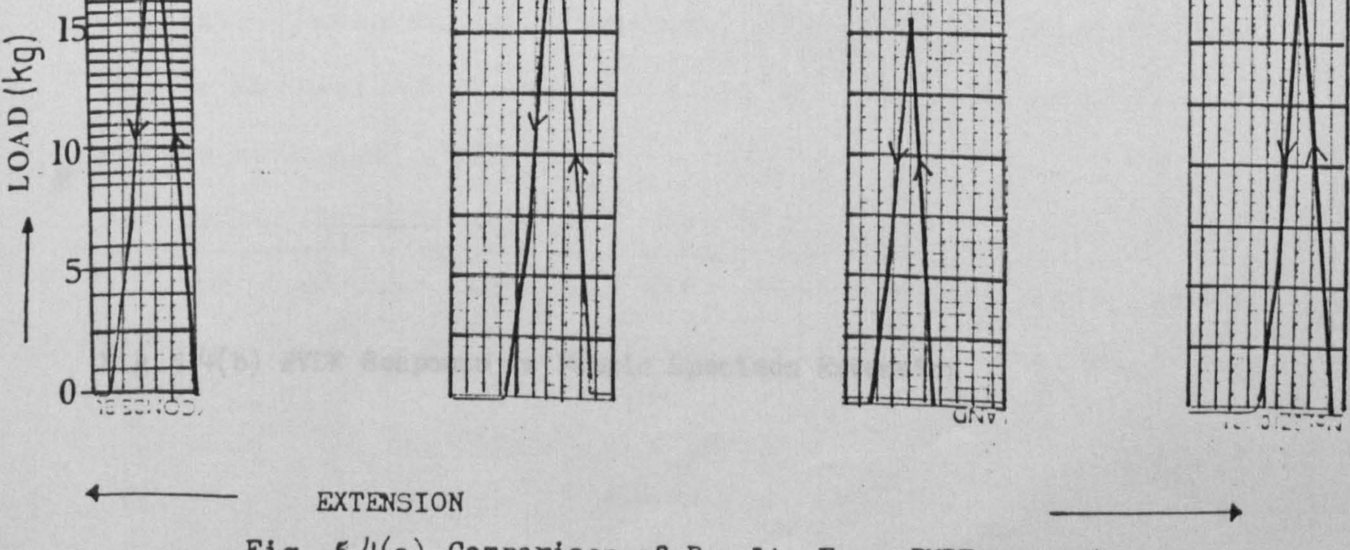


Fig. 5.4(a) Comparison of Results From PVDF to Instron

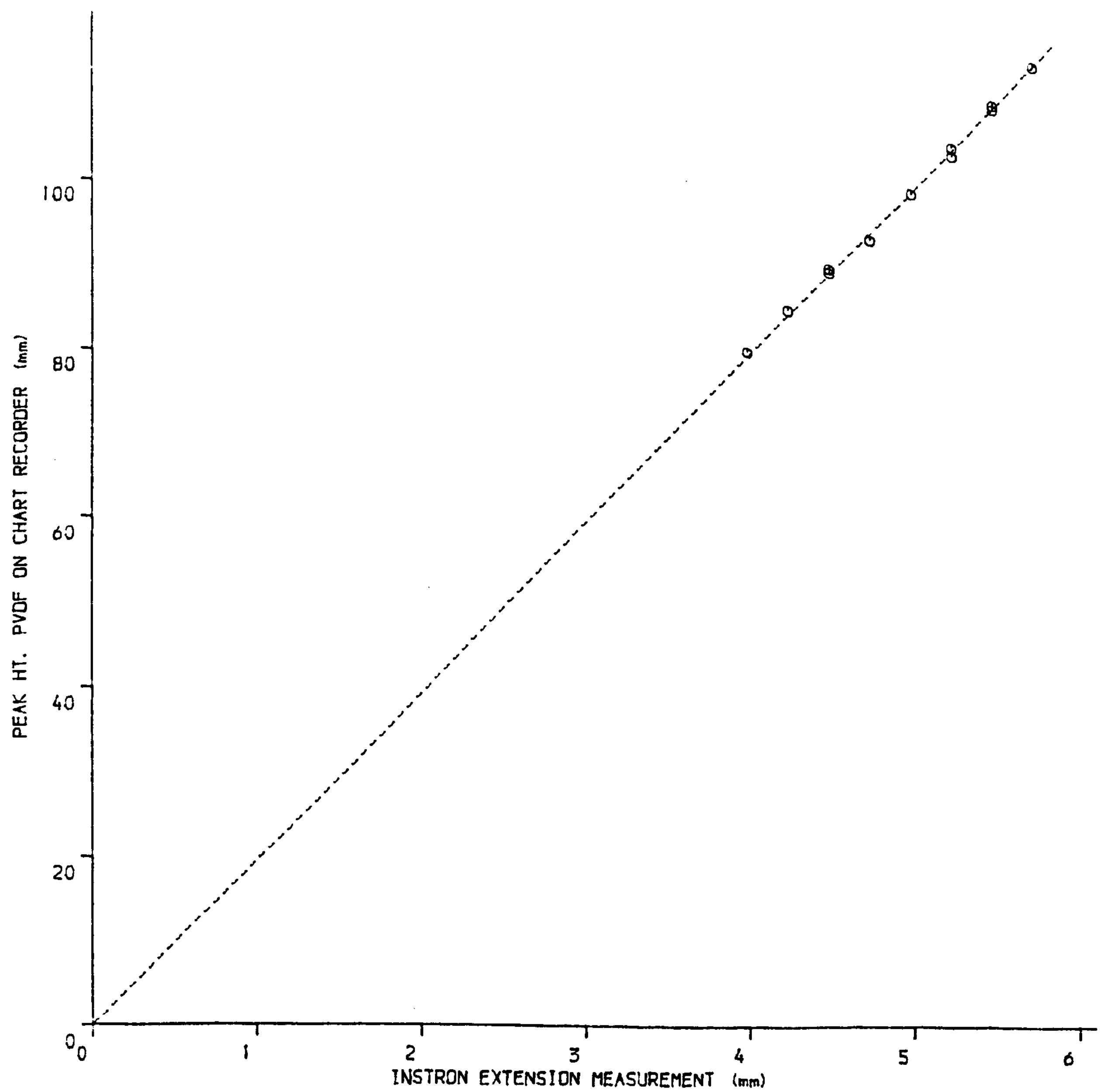


Fig.5.4(b) PVDF Response vs Fabric Specimen Extension

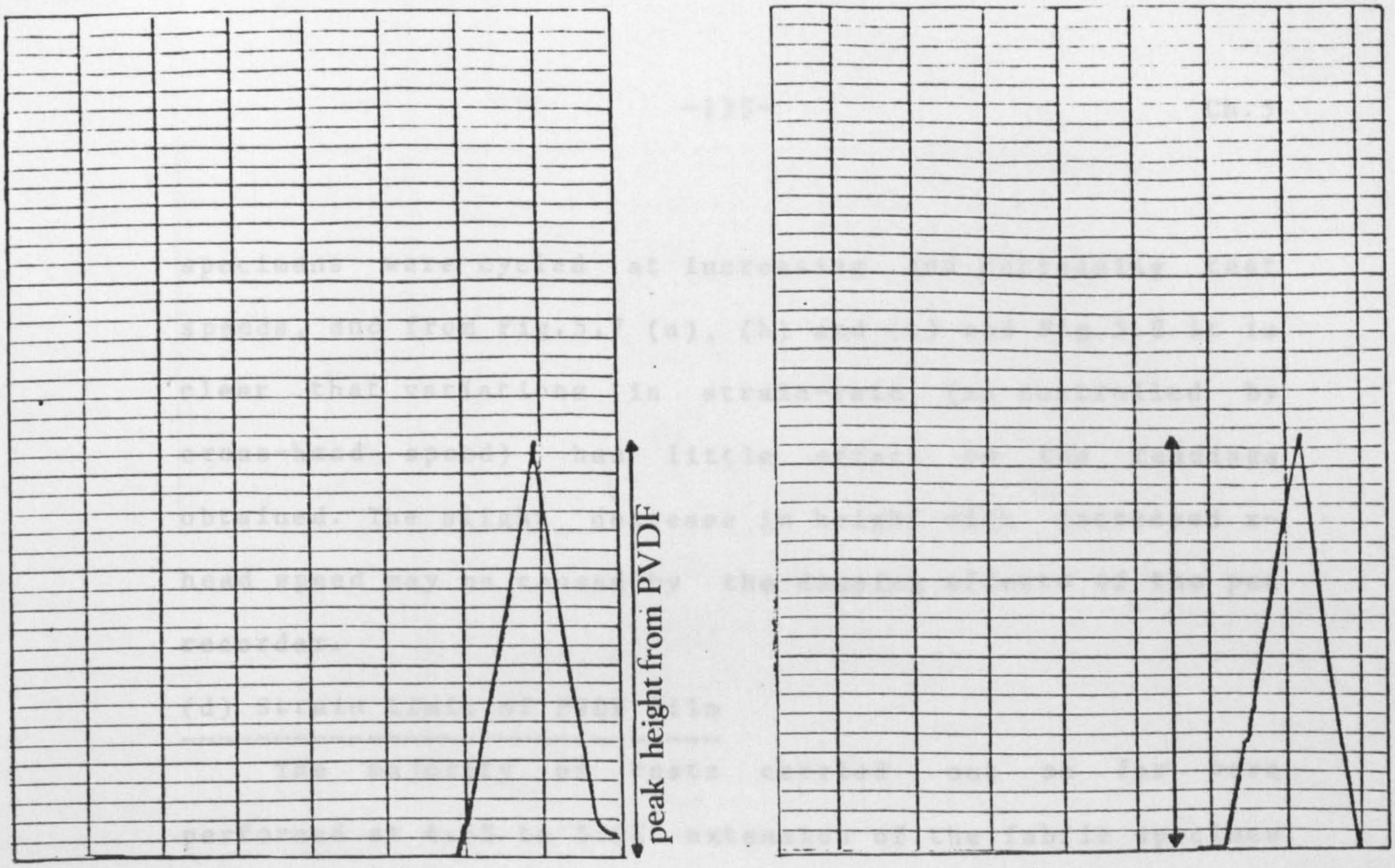
(correlation coefficient =+0.997, see Appendix 5.1). Apart from possible errors caused in the installation of the extension sensor, the greatest source of error is probably due to the measurements taken from the charts, and the measurement of the free surface area of the film between the spots of adhesive. It can be seen in Fig.5.4(a), and some of the following traces, that certain traces have kinks or stepped interruptions, it was determined that this could be attributed to failures, or problems of the adhesive.

(b) Repeatability During Repeated Strain Cycles

The results from these previous tests, as well as showing that there is a strong correlation between the response of the PVDF and the Instron measurements, also show that there is good repeatability between tests. These conclusions are reinforced by the results of tests shown in Fig.5.5 and Fig.5.6. The former shows two examples of traces produced when a number of specimens were extended 5% (see Appendix 6). It is clear from the latter, that repeatability is satisfactory during cycling tests on a specimen, even though there are likely to be inaccuracies due to variations in the tensions of the extension sensor before each cycle commences.

(c) Effect of Varying the Strain-Rate

It now important to determine how the test speed affected the results from the PVDF gauge. A number of



Extension 5% on each specimen (Edmondson 183g/m^2 sailcloth)

Fig. 5.5 Comparison of 28μ Ag Piezo Film on Two Specimens of Fabric (Repeatability Test)

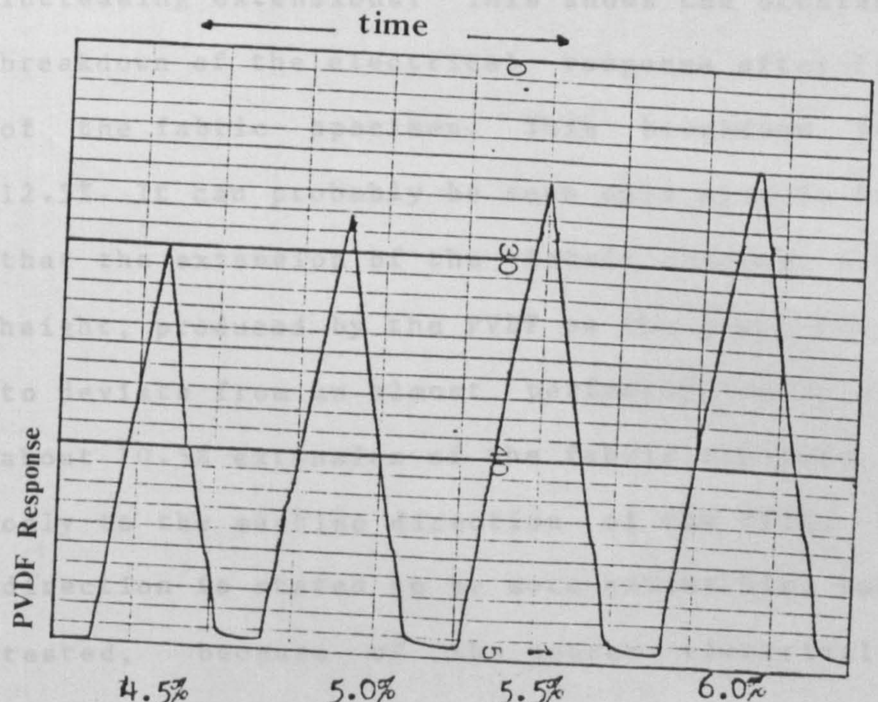
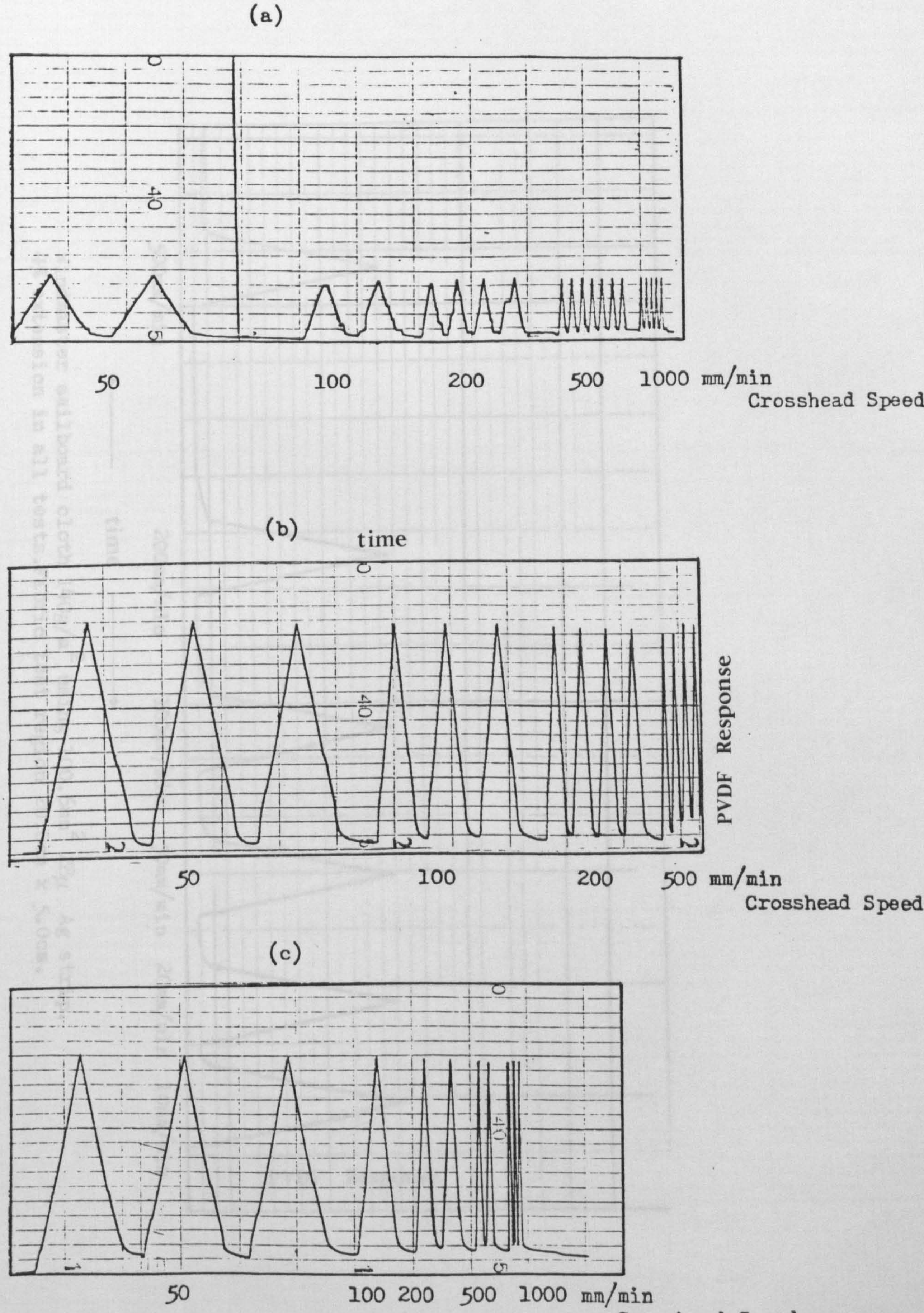


Fig. 5.6 28μ Ag PVDF Mounted on Sailcloth Specimens and Subjected to Increasing Extension

specimens were cycled at increasing and decreasing test speeds, and from Fig.5.7 (a), (b) and (c) and Fig.5.8 it is clear that variations in strain-rate (as controlled by cross-head speed) has little effect on the readings obtained. The slight decrease in height with increased x-head speed may be caused by the damping effects of the pen recorder.

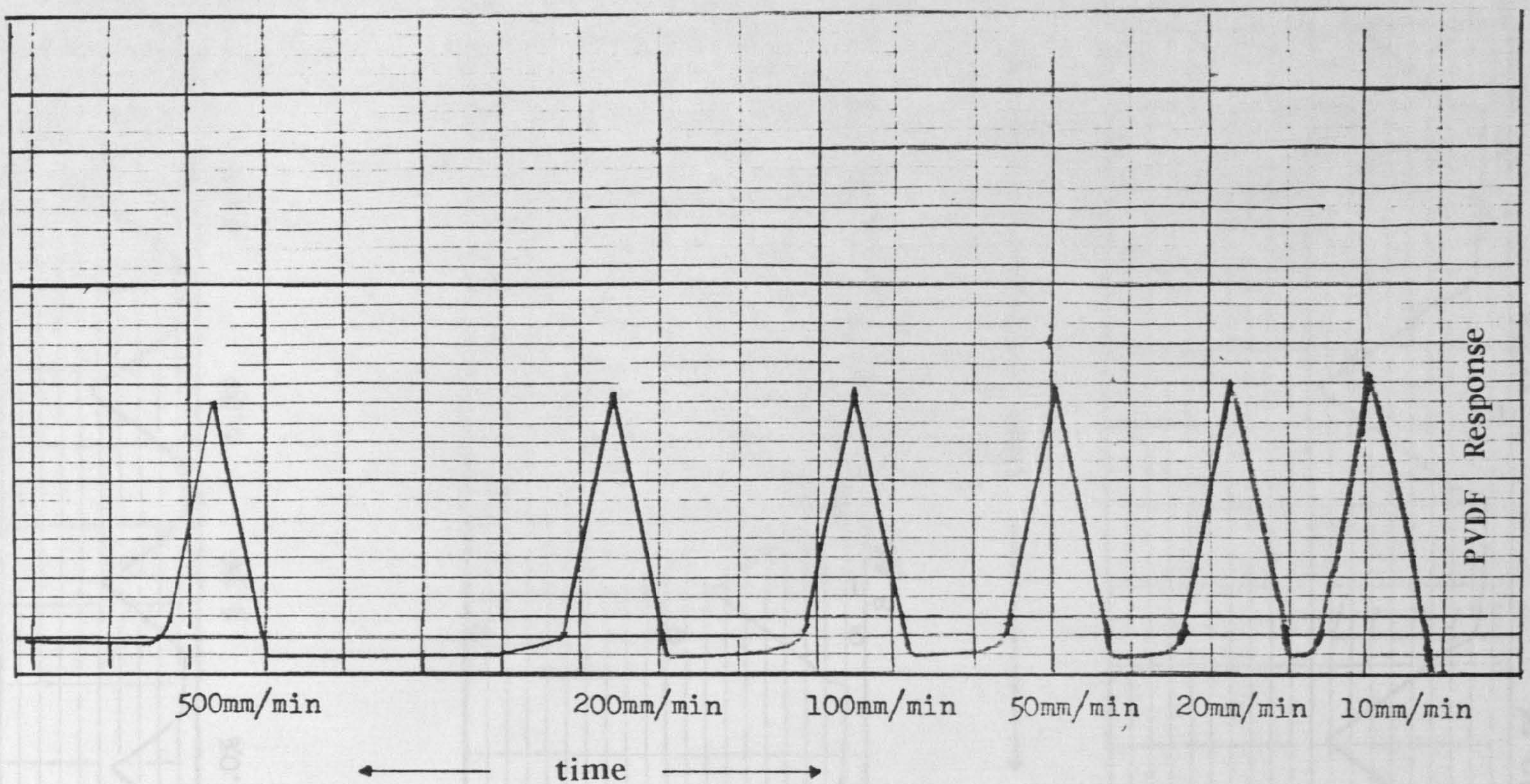
(d) Strain Limit of PVDF Film

The majority of tests carried out so far were performed at 4.5% to 5.0% extension of the fabric specimen (200mm x 50mm test region). The limits of the PVDF extension sensor still had to be determined. Fig.5.9(a) shows the peaks produced on the chart-recorder by the extension sensor when the fabric specimen was cycled at increasing extensions. This shows the occurance of a rapid breakdown of the electrical response after 11.5% extension of the fabric specimen. This breakdown is complete at 12.5%. It can probably be seen more clearly from Fig.5.9(b) that the extension of the fabric specimen against the peak height, produced by the PVDF on the chart-recorder, begins to deviate from an almost perfectly linear relationship at about 10.5% extension of the fabric specimen. This applies only to the machine direction of the film; the transverse direction is stated to be more extensible, but this was not tested, because of the poorer electrical response to strain.



Chartspeed 50mm/min for all readings

Fig. 5.7 Peaks show no significant variation in height for varying test speeds. (184.6mm^2 28μ Ag PVDF mounted on 20.0cm x 5.0cm test region of fabric specimen)



Windmaster sailboard cloth 140g/m^2 using 100.6mm^2 28μ Ag strip.
4% extension in all tests. Fabric test region 20.0cm x 5.0cm.

Chart speed is the same as the Crosshead speed in each case

Fig. 5.8 Shows peak height using varying crosshead speeds.

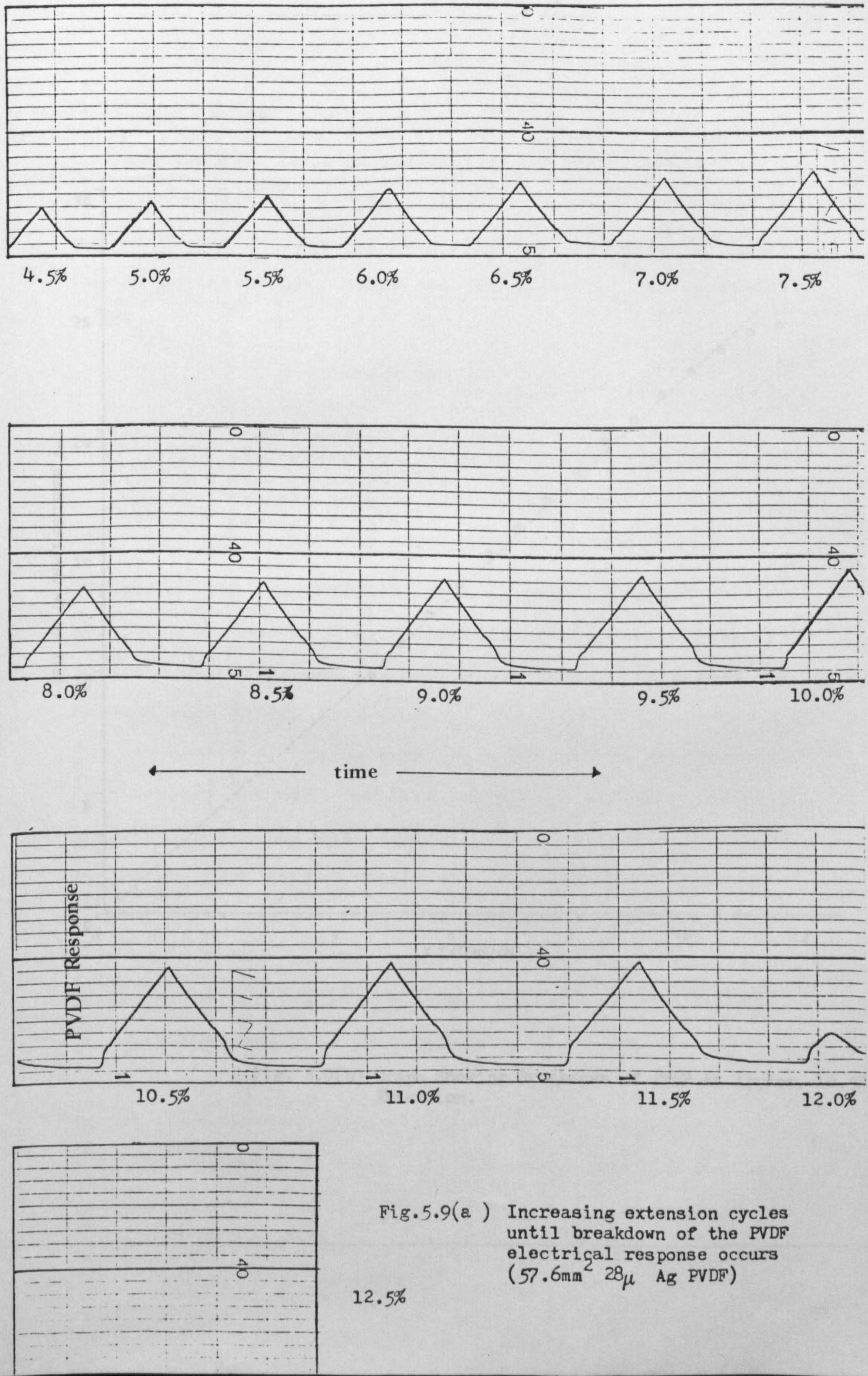


Fig.5.9(a) Increasing extension cycles until breakdown of the PVDF electrical response occurs ($57.6mm^2$ 28μ Ag PVDF)

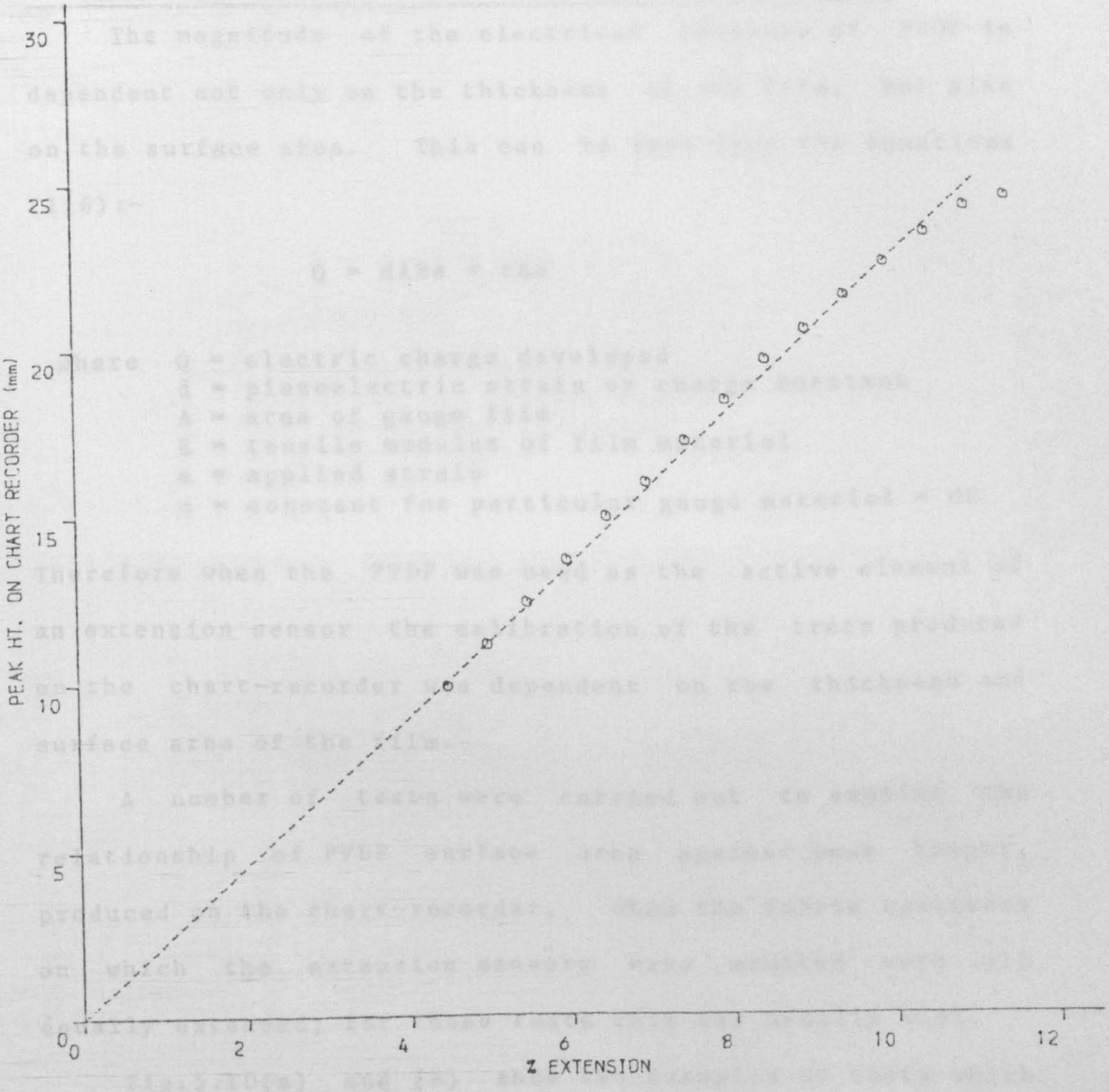


Fig. 5.9(b) Graph Showing Breakdown of PVDF at Approx. 10.5% Extension.

5.2.2 Dependence of Response on Surface Area of PVDF

The magnitude of the electrical response of PVDF is dependent not only on the thickness of the film, but also on the surface area. This can be seen from the equations (116):-

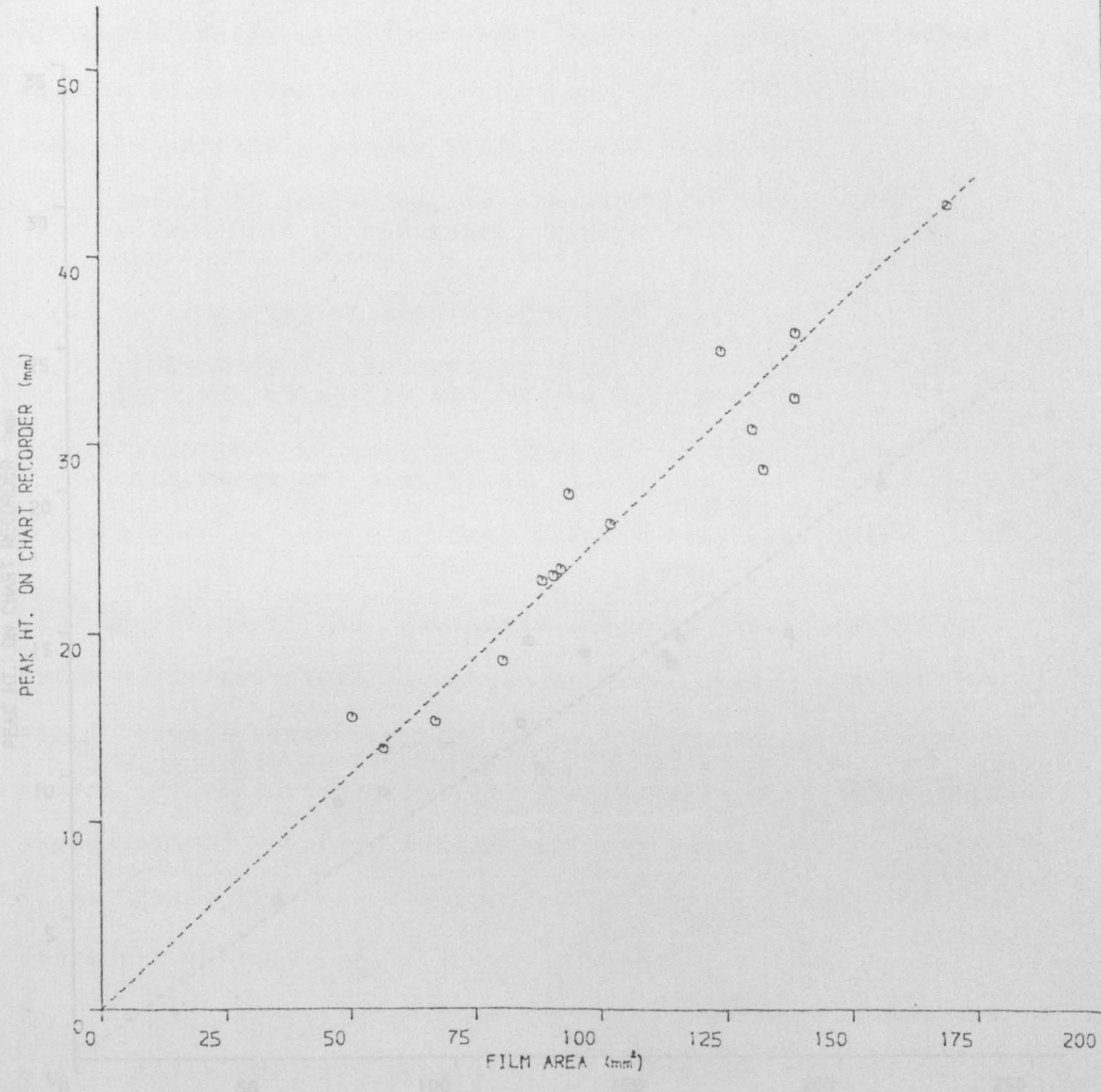
$$Q = dAEe = cAe$$

where Q = electric charge developed
d = piezoelectric strain or charge constant
A = area of gauge film
E = tensile modulus of film material
e = applied strain
c = constant for particular gauge material = dE

Therefore when the PVDF was used as the active element of an extension sensor the calibration of the trace produced on the chart-recorder was dependent on the thickness and surface area of the film.

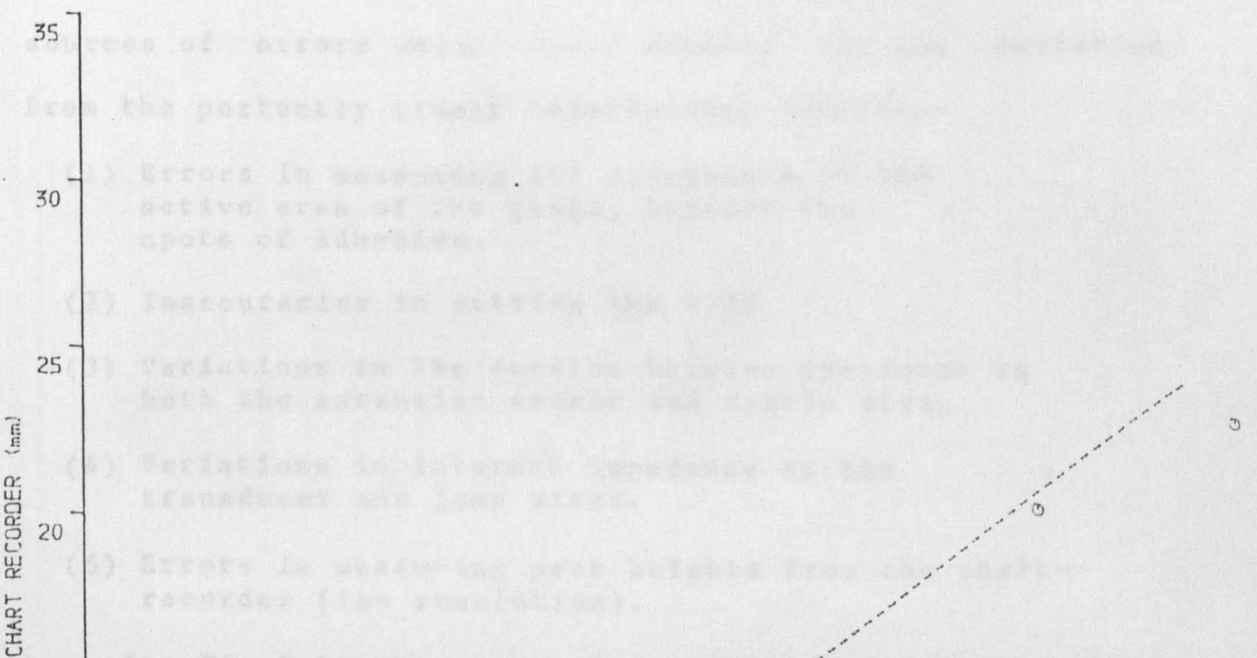
A number of tests were carried out to examine the relationship of PVDF surface area against peak height, produced on the chart-recorder, when the fabric specimens on which the extension sensors were mounted were all equally extended; for these tests this was usually 4.5%.

Fig.5.10(a) and (b) show two examples of tests which examined the relationship between the peak height produced by the PVDF and the film area. Here can be seen a pronounced linear relationship (correlation coefficient = +0.963 and +0.953 respectively, see Appendix 5.2.1 and 5.2.2)). These tests not only give some idea of the best surface area to use for a usable response, but also were useful in determining the



PEAK HEIGHT AGAINST SURFACE AREA OF FILM (all readings taken at 4.5% extension of film)

Fig. 5.10(a) Peak Height of PVDF Dependence on Area of PVDF



PEAK HEIGHT AGAINST SURFACE AREA OF FILM (all readings taken at 4.5% extension of film)

Fig. 5.10 (b) Dependence of Peak Height of PVDF on Film Area.

repeatability and were an aid when attempting to minimize variables which caused errors between tests. Possible sources of errors which could account for the deviation from the perfectly linear relationship include:-

(1) Errors in measuring the dimensions of the active area of the gauge, between the spots of adhesive.

(2) Inaccuracies in cutting the PVDF

(3) Variations in the strains between specimens in both the extension sensor and fabric strip.

(4) Variations in internal impedance at the transducer and jump wires.

(5) Errors in measuring peak heights from the chart-recorder (low resolution).

In Fig.5.11 the extension sensors were mounted on three different fabrics. As can be seen, during these quite rapid tests, there appears to be little or no difference caused by this (correlation coefficient = +0.991, see Appendix 5.3) Larger variations may occur during longer tests owing to the differences in creep behaviour of different fabrics.

As the response of the film depends on the surface area, thickness and metallization it would require quite comprehensive tables to be produced to enable any dimension of film to be cut and used without calibrating every test. Therefore for most purposes it should be satisfactory to use only a few different sizes with each cut out of the film using a die, these known areas and thicknesses having been previously calibrated. The use of a die would have

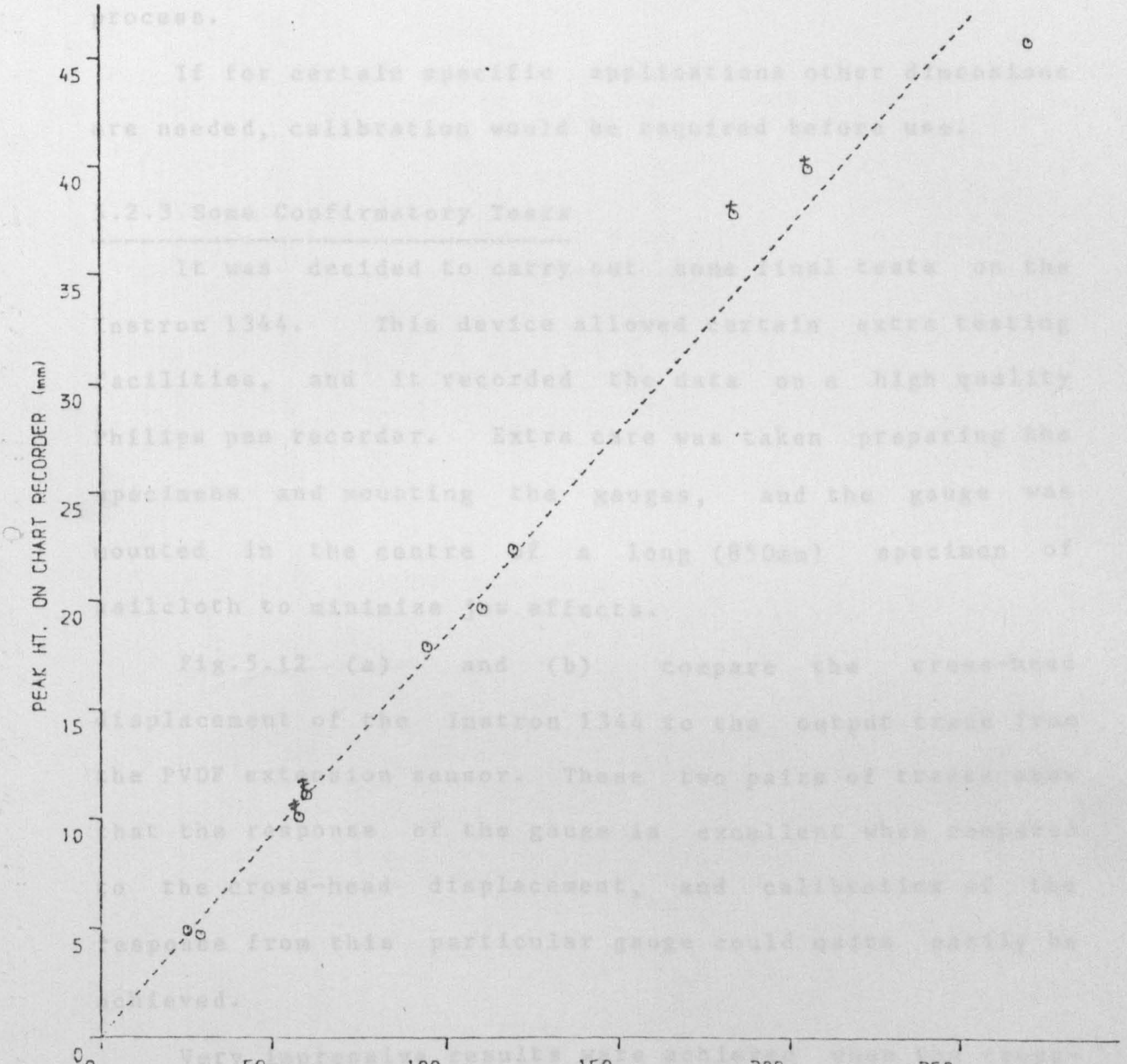


Fig. 5.11 Dependence of Peak Height of PVDF on Film Area
Film Mounted on Three Different Fabrics.

the added benefit of minimizing errors in the cutting process.

If for certain specific applications other dimensions are needed, calibration would be required before use.

5.2.3 Some Confirmatory Tests

It was decided to carry out some final tests on the Instron 1344. This device allowed certain extra testing facilities, and it recorded the data on a high quality Philips pen recorder. Extra care was taken preparing the specimens and mounting the gauges, and the gauge was mounted in the centre of a long (850mm) specimen of sailcloth to minimize jaw effects.

Fig.5.12 (a) and (b) compare the cross-head displacement of the Instron 1344 to the output trace from the PVDF extension sensor. These two pairs of traces show that the response of the gauge is excellent when compared to the cross-head displacement, and calibration of the response from this particular gauge could quite easily be achieved.

Very impressive results were achieved when the cross-head displacement was plotted against the gauge response (see Fig.5.13), calibration of the gauge is made even easier using this trace. The trace is not a perfectly straight line, but this is most likely due to fabric effects.

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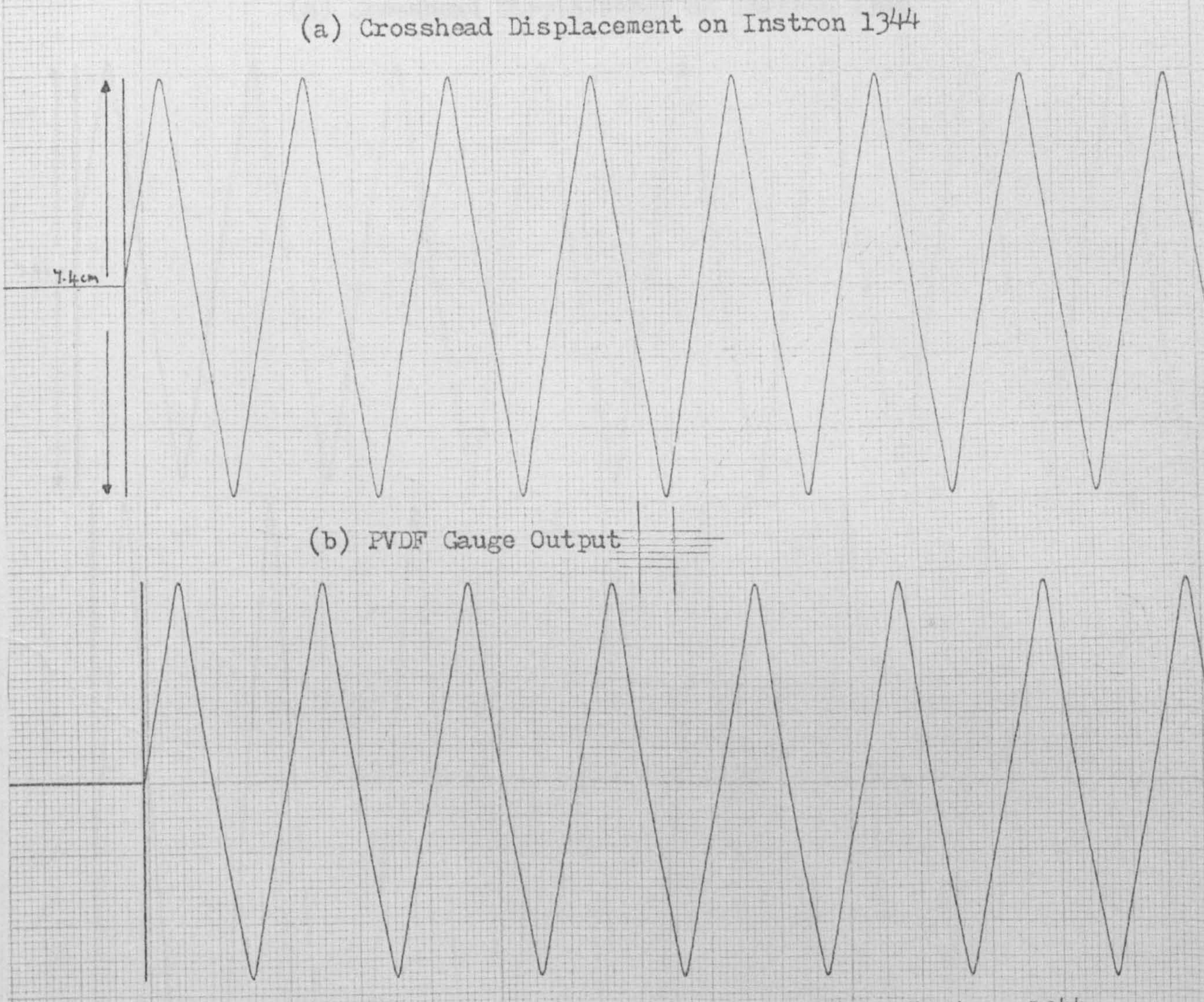

Fig. 5.12(a) Comparison of Crosshead Displacement on Instron 1344 to the Response from the New Gauge (Chart-Speed 10mm/s, Crosshead Speed 7.5mm/s; (a) Crosshead Displacement 1.0v/cm., 1v=12.5mm.
(b) PVDF Displacement 1.0v/cm., 1v=(calibrate by measuring)

(recorder pens staggered 2mm)

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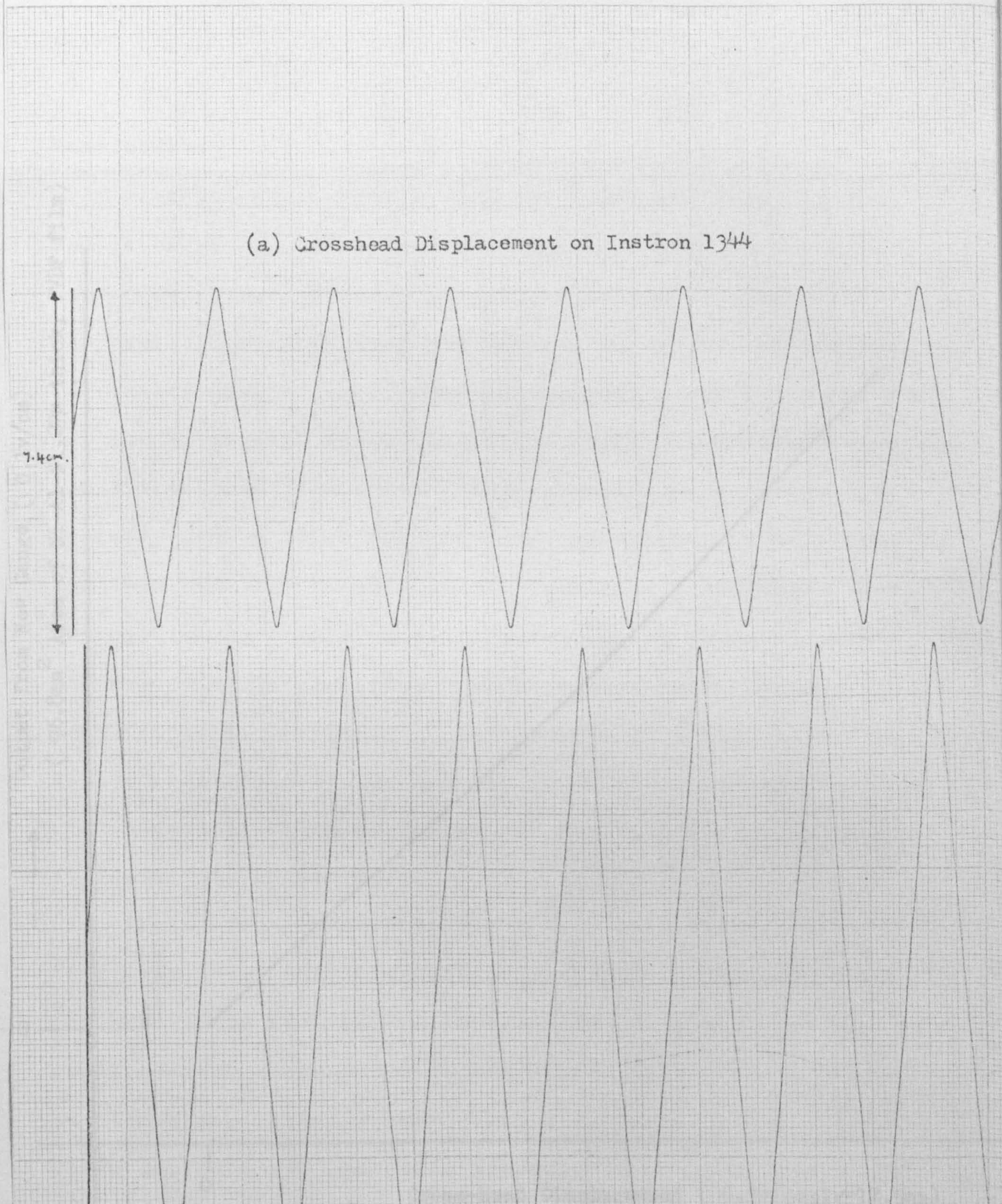


Fig. 5.12(b) Comparison of Crosshead Displacement on Instron 1344 to the PVDF Response (Chart-speed 10mm/s, Crosshead Speed 7.5mm/s; (a) X-Head Displacement 1.0v/cm, 1v=12.5mm (b) PVDF Displacement 0.5v/cm, 1v=(to calibrate))

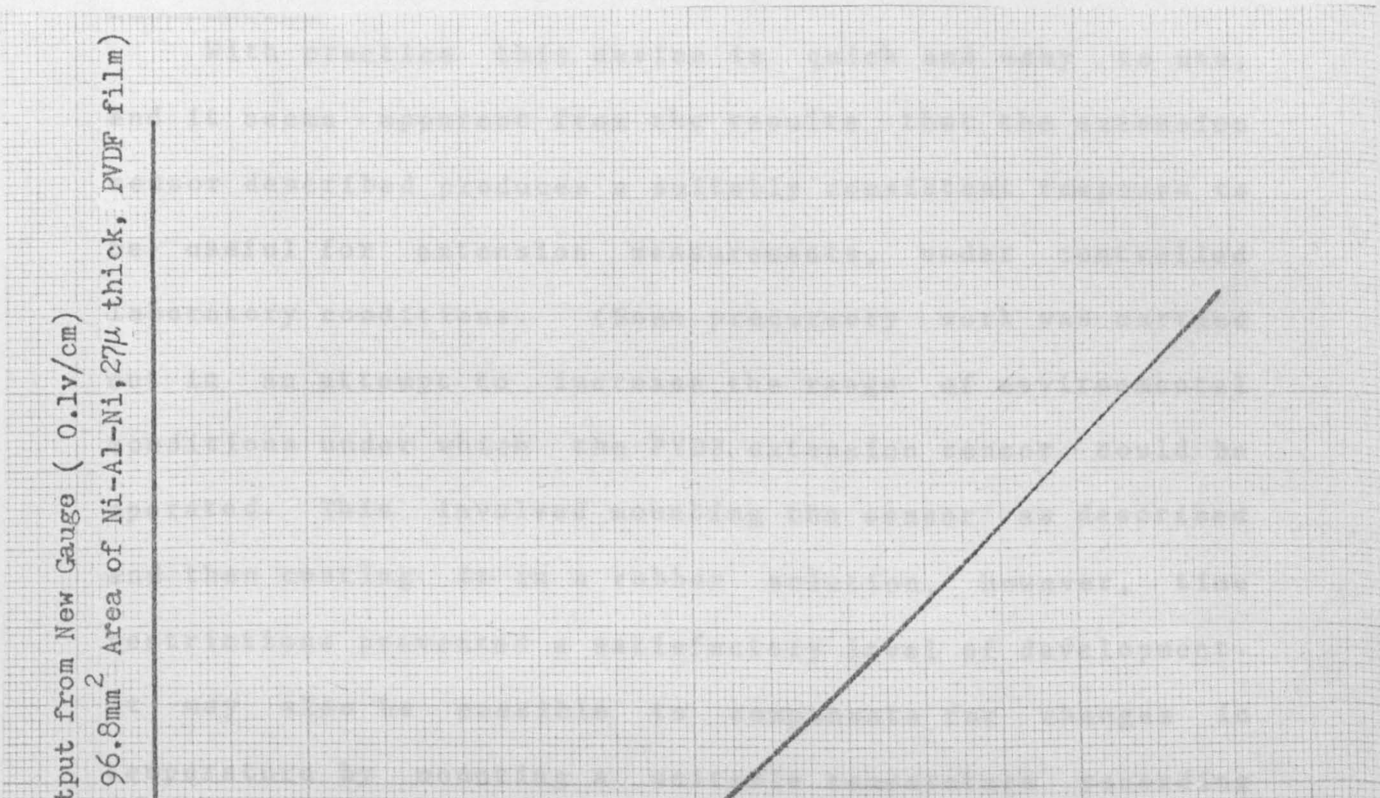


Fig.5.13 Output from Gauge vs X-Head Displacement

Conclusions

With practice this device is quick and easy to use, and it seems apparent from the results that the extension sensor described produces a suitably consistent response to be useful for extension measurements, under controlled laboratory conditions. (Some precursory work was carried out in an attempt to increase the range of environmental conditions under which the PVDF extension sensor could be operated. This involved mounting the sensor as described and then coating it in a rubber solution, however, time restrictions prevented a satisfactory level of development. It may also be possible to compensate for changes in temperature by mounting a suitable temperature recording device near to the gauge and having it feedback information via a computer which could adjust the calibration to allow for temperature changes.)

There are of course problems with all strain gauges of this type, as they basically operate by removing some of the load from the tested material in order to produce a small elastic deformation in the gauge, which then produces an electrical response which can be measured. If the force which deflects the gauge is appreciable compared with the total carried by the fabric strip, the gauge affects the deformation of the material in the vicinity of the gauge. The gauge reading then does not indicate the state of strain in the undisturbed fabric. Therefore it is necessary to ensure that any extension sensor which is to be used on textile fabrics requires a minimum of force to extend it, however, this must not result in excess bulk or complexity.

Time limitations only allowed a preliminary examination of the suitablity of PVDF as an extension sensor, and to its usefulness for the measurement of displacements in industrial fabrics. This work did, however, reveal a number of advantages of this film when used for this application:-

(1) Measurement of extensions of greater than 10%

(2) It is easily cut with a die or blade to any required dimension, allowing shapes which will for example minimize interference in directions other than that being measured.

(3) Cheapness

(4) Low weight and bulk

(5) Relatively low tensile stiffness

(6) Flexibility

There are inevitably disadvantages, which must be pointed out;these include:-

(1) Sensitivity to temperature and electromagnetic interference; this limits it to use in controlled laboratory and experimental conditions.

(2) Electrical following circuitry

is more expensive than that required for resistance and solid state gauges.

(3) Its tensile stiffness confines its use to the yarn directions of high modulus industrial fabrics.

(4) Output signal is a transient, not a continuous signal like a strain gauge. Therefore not suitable for very low frequency or static tests (lasting longer than a few minutes).

On the whole this preliminary investigation shows that this new material should be of some use in the examination of deformations in textile materials. More work is, however, required on a wider range of fabrics and with varying thicknesses of film. More work is also required to refine the installation procedure, but it is hoped that this introductory research will form the basis of future work. It is recognised that this material may have many more uses in textile testing, and is not just confined to this particular application.

SECTION TWO

CHAPTER 6

PREVIOUS EXPERIMENTAL WORK ON THE MECHANICAL PROPERTIES OF FABRIC MEMBRANES

Introduction

Over the past few years the Textile Industries Department at Leeds University has been rationalizing its approach to industrial textiles. Much of the available knowledge and expertise on the mechanical properties of these materials has been brought together under the auspices of the Clothworkers' Textile Structures and Mechanics Laboratory. To help gain a more objective understanding of the physical properties of these fabrics, under more realistic conditions, certain pieces of physical testing equipment were required which were not readily available, these therefore had to be specially designed.

At present the mechanical testing available is confined to the uniaxial mode and tests based on it, however, biaxial tensile and shear tests are essential for a more complete determination of the mechanical properties of a fabric. Therefore one of the objects of the present work was to design a new piece of testing equipment for the Clothworkers' Laboratory, which would meet the requirements of this type of testing. Certain ideas were put forward from within the Department, however, these designs did not prove acceptable. It was therefore recognised that before any worthwhile progress could be made a thorough survey was required of any previous testing equipment in this category. A survey of this type would not only help the present author learn from the successes and mistakes of previous researchers, but would also avoid a re-invention, as appears to have happened in the past. It would also be useful to future researchers in the Unit who may have to design further pieces of test equipment, or develop new test methods.

6.1 Early Experimental Work

In the past experimental work on fabric membrane properties usually considered tensile properties separately to shear properties, and most of the tensile tests were concerned with the application of uniaxial tensile stress and strain only. There have, however, been a number of exceptions and these will be considered later.

In the early part of the twentieth century considerable work was carried out on the uniaxial tensile test in Great Britain, U.S.A., France and Germany as part of their aeronautical research programmes. In Great Britain this work was consolidated by the Advisory Committee for Aeronautics, and many references to early forms of testing can be found in their reports.

Stanton and Booth (41), in 1910, carried out some preliminary work on the mechanical testing of balloon fabrics. The main object was the determination of which mechanical test, when carried out on a sample of fabric, would give the best indication of its suitability when used as a covering of a balloon or dirigible airship. They made comparisons between the uniaxial tensile tests, on fabric strips, and bursting tests on cylinders of fabrics, to determine the maximum air pressure which the fabric would withstand. Before this could be done, however, their first problem was the determination of the most suitable dimensions and forms of the tensile test specimens. Their tests involved the use of rectangular specimens, which were gripped by wooden jaws attached to shackles of a 10 tons force (10.16 tonnes force) testing machine, in the case of heavy specimens. With lighter specimens the upper jaws were held by a crane hook and a sand-box was attached to the lower jaw. This box was fed by a hopper in which the flow of sand could be regulated. Their tests were carried out on a number of different materials and their findings included the discovery that the breaking load per unit width of the fabrics tested, in the manner described, probably diminished slowly to a definite limit as the dimensions are increased. They also concluded that the then usually adopted width of 2 inches (5.8cm) appeared satisfactory. As regards the best length of specimen to adopt, more experimental evidence was considered necessary.

A subsequent A.C.A. report (126), in which the work was carried out at the National Physical Laboratory, describes investigations on the effect of the rate of loading, in tensile tests, on fabrics. A manufacturer had pointed out that there was considerable discrepancy between the results obtained at the N.P.L. and those given by the Manchester Chamber of Commerce, for samples taken from the same piece of fabric. Some of this was due to the difference in test piece dimensions, but tests proved that this was not the only cause. The rate of loading was therefore considered and tests showed that the ultimate strength increased slightly when the rate of loading was increased above slow rates; this increase of ultimate strength ceased after a certain limiting rate of loading was reached.

By late 1910 the apparatus as described earlier, by Stanton and Booth (41), which consisted of two pairs of hard wood shackles and grips for holding the specimens, and a sand-box and hopper for applying the load at a given rate, was found unsuitable and inadequate (127). To ensure greater rapidity of work, a new purpose built tensile testing machine was ordered from Avery. This machine was capable of testing up to 1200 lbf (544kgf) with the compound lever, and 240 lbf (108.9kgf) with the single lever. This testing machine was soon modified to enable rates of loading varying from 50 to 1200kgf per minute to be used. The dimensions of the test specimens used was 20cm x 5cm, 20cm being the length between the jaws of the testing machine. A total additional length of about 8cm was necessary for gripping (128). These test specimen dimensions are basically the same as those recommended today by British Standards (129). The usual rate of loading used was such as to fracture the specimen in not less than two minutes.

A brief, but more precise description of this early Avery tensile tester was given by Watson (130). His research took place at the Department of Textile Manufacture of the Royal Technical College, Glasgow and he attempted to ascertain what effect a difference or an alteration in one or more of the conditions of the test would have on the tensile strength of a fabric. A large number of tests were carried out on aeronautical fabrics and the specimens were tested wet and dry, at varying widths and lengths, with varying rates of loading, and comparisons of the results of different testing machines were made.

Research was also carried out in other countries, which included the U.S.A. Here research was undertaken into such topics as comparisons between the strip and grab methods of uniaxial testing. It was in the U.S.A. that the grab test first became widely used; perhaps to reduce labour costs. With this method one simply took a large area of fabric, of much greater dimensions than the corresponding strip specimen, the test jaws were then clamped somewhere in the middle of the fabric. In this method, the fabric specimen strength or fabric extension properties were a function not only of the yarns actually held in the grips, but there was also some interaction between adjacent yarns which were outside the grips. Researchers in this subject included Walen (131) and Lewis (132). The effects of various types of jaws on fabric strength was investigated by Dunlap et al (133). The aim of their research was to determine a type of jaw which gave a minimum of variation in results.

The common uniaxial tests, as described, have been used for many years in the testing of all types of fabric, but this method of testing was devised mainly on the basis of simplicity, and researchers have recognised for quite a long time that the test results obtained in this manner can often be misleading, since the stresses on fabrics in service are almost always biaxial. In early work at the N.P.L. by Stanton and Booth (41), bursting tests on fabric bags were carried out. These tests were to compare the uniaxial tensile test and the calculated values of the maximum hoop tension in cylinders made of fabric and subjected to internal pressure until fracture occurred. In these tests it was discovered that the calculated hoop tension from the bursting test was, in the case of single fabric, appreciably less than the result given by the uniaxial tensile test. However, the researchers were not completely satisfied with these tests as it appeared that many of the fractures were occuring at the joints.

At approximately the same time it was decided that more information was required on tearing under compound stress. Work was carried out by Booth and Hyde (42) on this subject, and as they stated :-

> "Failing some theory connecting the behaviour under simple and compound stress, and in view of the fact that compound stress tearing tests on cylinders of fabric would be both laborious and expensive (involving the construction of special apparatus for bursting large bags having holes in them and the consumption of much fabric), it was decided to perform a few simple experiments using the form of compound stress test piece originally suggested by Mr. Horace Darwin"

Mr. Horace Darwin, later Sir Horace Darwin M.A., F.R.S. (1851-1928) was the fifth son of Charles Darwin, and was trained as a Civil Engineer. He specialised in the design of scientific instruments and was a member of the Advisory Committee for Aeronautics, as an expert on this subject. The form of compound stress test piece, which it appears he was the first to suggest for textiles, is now referred to as the cruciform specimen, and Booth and Hyde (42) recognised the objections (see later) to this form of test specimen, as well as its advantages; the latter mainly being due to its simplicity. These authors were also involved with compound stress tests using cylinders of fabric under air- pressure. These latter tests were carried out to investigate the elasticity and ultimate strength of rubberised cotton balloon fabrics.

Perhaps better known researchers in this field were Haas and Dietzius (19). Although they were not the first on record to use the cruciform and cylindrical types of specimen, they do appear to be the first on record to have used the cruciform specimen under normal biaxial testing conditions, as Booth and Hyde (42) used "wounded" specimens, ie. they had small circular and linear holes cut in the centre of the specimen and they were tested for tearing.

The airship fabric which Haas and Dietzius (19) were testing was also suitable for the cylindrical type of specimen , as it was impermeable to water, and with this type of specimen it was possible to independently vary the three components of stress and strain. This was not generally the case on the flat type of specimen, in which shear stress and strain was usually measured on separate devices, from tensile stress and strain. In fact, there are little or no records from these early days which describe shear tests which were carried out on the flat form of specimen; in general it appears that the cylindrical specimen was used. The first tests which did use a flat specimen for shear tests, tested this property only, and consisted of two main types. The most common involved gripping a rectangular specimen with clamps on two opposite sides, and then measuring the resistance to lateral movement of one of the clamps. Attempts were also made to measure shear properties by uniaxially extending a specimen in the bias direction.

As can be seen the devices used to test fabric membrane properties can be divided into two main groups. The first group consists of those devices which are not capable of varying the three components of stress or strain independently, and the second group being those which have attempted to overcome this problem. In the early days this latter group appears to have almost entirely consisted of cylindrical specimens.

6.2 Testing Instruments Which Cannot Vary Biaxial Tensile and Shear Parameters Independently

Generally when flat specimen biaxial tensile testers and shear testers were first experimented with, they were built as separate units and could not vary biaxial tensile and shear parameters independently.

6.2.1 The Development of Biaxial Tensile Testing Devices Which Used Flat Specimens

The tensile properties of fabrics are generally given in terms of loads and deformations applied uniaxially to a specimen. The specimens vary according to whether a strip or grab test is used and for many applications the information available is considered adequate (134) (135).

The information available from this form of test is still considered useful, and in 1984 a large uniaxial tester was installed in the Clothworkers' Textile Structures and Mechanics Laboratory, Leeds University (136). This machine is capable of applying loads of 200 tonnes, hitherto unavailable, and is suitable for the testing of heavy industrial textiles.

In many industrial end-uses, however, loads are imposed simultaneously in more than one direction. The biaxial test was therefore a logical progression from the more simple uniaxial test, which was used mainly on the basis of its simplicity. Biaxial tests yield quite different results from those obtained by the more simple test (137), and have introduced complications to fabric testing. Many authors think these extra problems worthwhile, because of the extra, and more realistic information gained. Zender (138) attempted to demonstrate the inadequacy of uniaxial tests in obtaining the stiffness properties to be used in the design and analysis of inflatable fabric structures. He suggested that in order to obtain realistic stiffness values for use in design and analysis of stressed fabric structures, tests on simple models subjected to stress conditions similar to those anticipated in the full-scale design had to be carried out.

One of the complexities introduced by the biaxial tensile test involved the way in which the fabric was gripped, or clamped during the test. The main problem is using a method which allows the fabric to undergo strain in the direction parallel to each clamp. This is also a problem in the uniaxial strip test where "waisting" due to crimp interchange causes the greatest contraction in the middle area of the specimen, which decreases towards the jaws as they restrict contraction in this area. This problem increases the difficulty in interpreting certain information which might be derived from the results. McGown et al (139) describe methods which have attempted to overcome this problem by modifying the uniaxial tensile test. These methods are known as plane strain tests and one involved the use of light brackets which were fitted with strong pins. A number of the brackets were attached across the specimen strip so that it was held to full width over its whole length while the test was being carried out. McGown et al (139) pointed out that this test had faults as concentrations of stresses are produced around the pins, especially those near the free sides of the specimen, thus violating the required conditions of uniform strain.

A number of methods have been used to attempt to overcome this clamping problem in biaxial tensile testing. The first method appears to have been the cruciform specimen (see Table 6.1). In this method the specimen is gripped along lines remote from the test area, so that only the central part of the specimen is under biaxial tension, Chronological Outline of Biaxial Tensile Testers Which Used Flat Cruciform Textile Fabric Specimens

Year	Author(s)	Ref.
3/1912	Booth and Hyde	42
12/1912	Haas and Dietzius	19
1955	Topping et al	186
1956	Baker	176
1959	Klein	102
1963	Clulow and Taylor	177
1964	+Davidson	69
1965	+Milenkovic	140
1967	+Freeston et al	97
1971	Yendell	168
1974	Remington and O'Callahan	106
1976	Reinhardt	142
1977	Viergever, de Feijter and Mouw	144
1981	$Schwarz et al	182
1981	Minami and Nakahara	141
1983	@Firt	99
1984	Ansell et al	135

+ Used biaxial tester built by MRD Division of General American Transportation Corp., under contract to the U.S. Air Force Materials Lab.

$ Biaxial tester for triaxial fabrics. Using fabric in the form of a Maltese Cross.

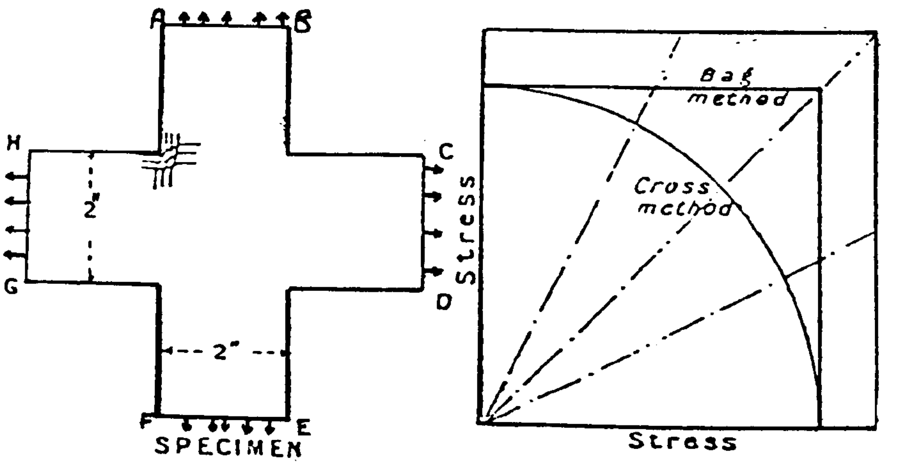
@ Inst. of Theoretical and Applied Mech. at the Czech. Academy of Sciences, Prague. Used from 1971.

Table 6.1

and the arms of the cruciform under uniaxial tension. In this case strain parallel to the clamps can be ignored. This method appears to have been first suggested by Darwin, and first attempted experimentally by Booth and Hyde (42). Even at this early date they recognised the objections to this form of test specimen :-

> "There is an objection to this method of testing in that there is a considerable distortion of the yarns noticeable near the re-entrant angles of the specimen, which shows the presence of enhanced stresses there, whence it follows that the stresses over the middle region are ~~lower than the mean stresses calculated~~ lower than the mean stresses calculated from the applied loads; these conclusions are also supported by the fact that ordinary compound stress tests performed by this method give approximately a quadrant of a circle as the limit of strength, while more exact tests (by bursting bags) give approximately a square contour Fig.6.1(a)
> The consequence is that though the stresses over the greater part of the central square area of the test piece are probably uniform, they are lower than the mean stresses calculated by amounts which are unknown, but are less than the discrepancy between the two curves of Fig.6.1(b)"

Haas (19) also recognised the problem of attaining uniformity in the cruciform specimen. He saw that the mutual influence of the two tensions at the four inner corners were not "conducted" straight across the intersection of the cross-arms, but were bent around the corners into the intersecting arm because of the shear stiffness of the fabric. The tension at the corners of the network was therefore diminished, and the rectangle assumed a barrel-shape. To try and overcome this, four auxiliary stretching clamps were used to stretch the arms out



(a) (b)

Fig. 6.1(a) Cruciform Specimen showing distortion of the yarns near the re-entrant angles.

(b) Visual Comparison of Ordinary Compound Stress Tests on this Fabric by this method and by bursting bags.

"from Booth and Hyde (42)"

laterally in the vicinity of the centre of the cross. However this solution did not prove very satisfactory as it took a lot of time to adjust the auxiliary clamps and they had to be continually watched in the early stages of loading the fabric.

To force the central section of the cruciform specimen to carry the tensile loads Bassett (108) suggested removing all the transverse threads from the fabric in the arms of the cross, but he realised that this would pose problems in the interpretation of the results due to variations in stiffness and initial crimp across the specimen. It could also often be difficult to remove the threads from tightly woven or coated industrial fabrics.

Milenkovic (140) suggested cutting slits in the arms of the cross to ensure the correct stress distribution in the central portion of the specimen. He was, however, mainly considering homogeneous stress during the action of the shear facility of his biaxial tensile and shear testing rig. It is unclear in his text, but the slits may have been cut so that he could disregard the shear resistance of the fabric in the arms during calculations, as the test region was the square central area.

Minami and Nakahara (141) used a cruciform shaped specimen with long and short slits, as shown in Fig.6.2(a). These slits were made in order to relax stress concentrations at the corners. However the use of the

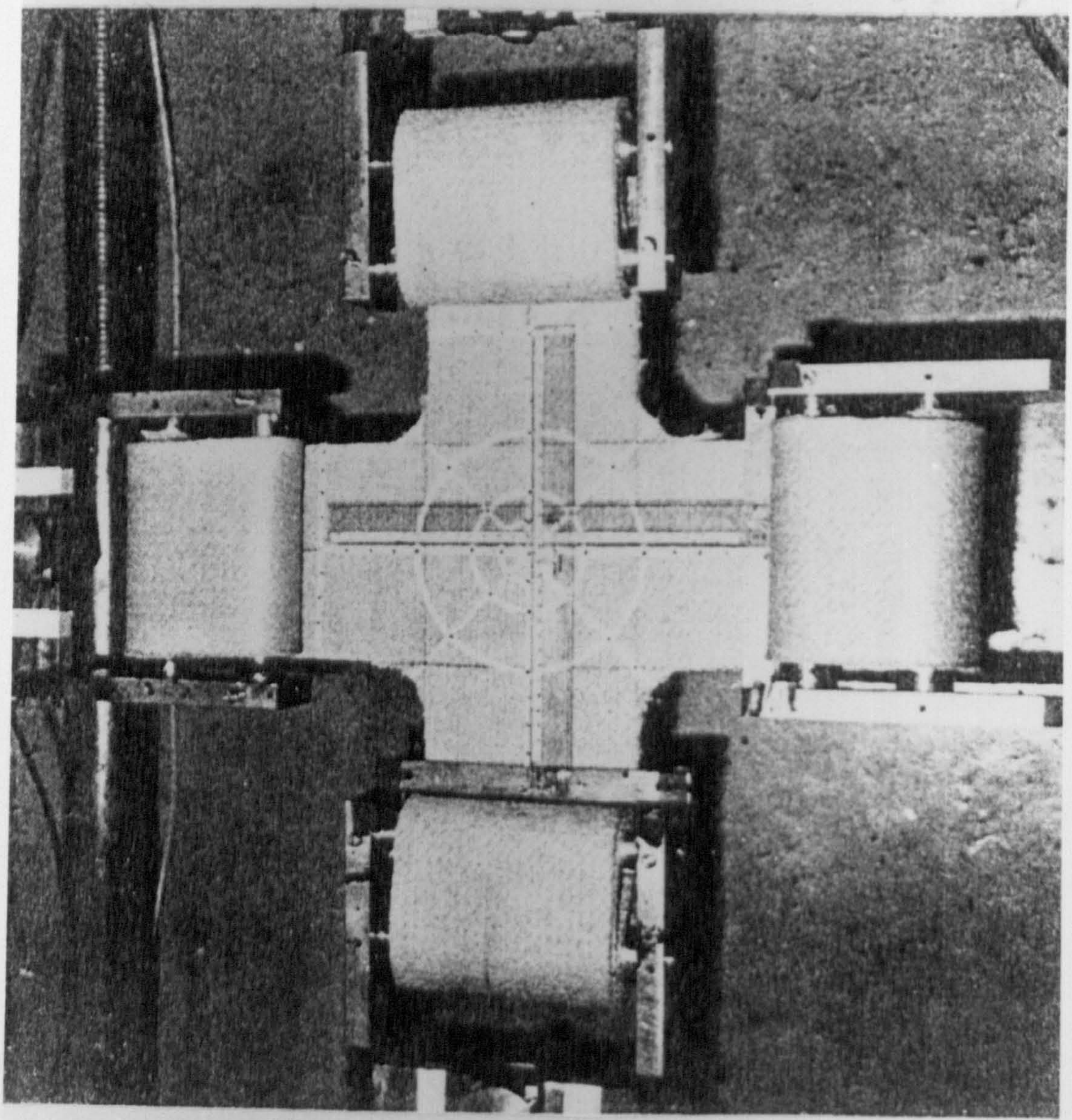


Plate 4 - Example of specimen mounted in self-tightening clamps.

cruciform specimens in such tests still presented a problem. The stress was concentrated at the corners where the cross arms intersected, and this initiated failure in that area under a load considerably smaller than the true breaking load. To overcome this problem specimen holders were designed, as shown in Fig.6.2(b). These holders incorporated a self-tightening clamping device, and a mechanism allowing the parts of the holding device to slide reciprocally across the width of the specimen in order to relax stress concentration at the corners. This allowed larger loads to be applied.

The self-tightening clamps basically operate by gripping tighter as the tension increases. Unlike the standard form of clamp this allows a degree of contraction parallel to the jaws to take place inside the actual clamp (see Plate 4). This allows a more homogeneous distribution of strain, as contraction of the specimen is not totally confined to the central portion. "Waisting" is therefore not such a problem in a uniaxial test.

A number of biaxial testing rigs have been designed at Stuttgart University as part of their work on air-supported structures and convertible roofs. Reinhardt (142) stated that when applying coated fabrics as a roofing material for lightweight wide-span surface structures, the material is stressed in two dimensions. He discussed many different biaxial test methods, but concluded that they did not allow

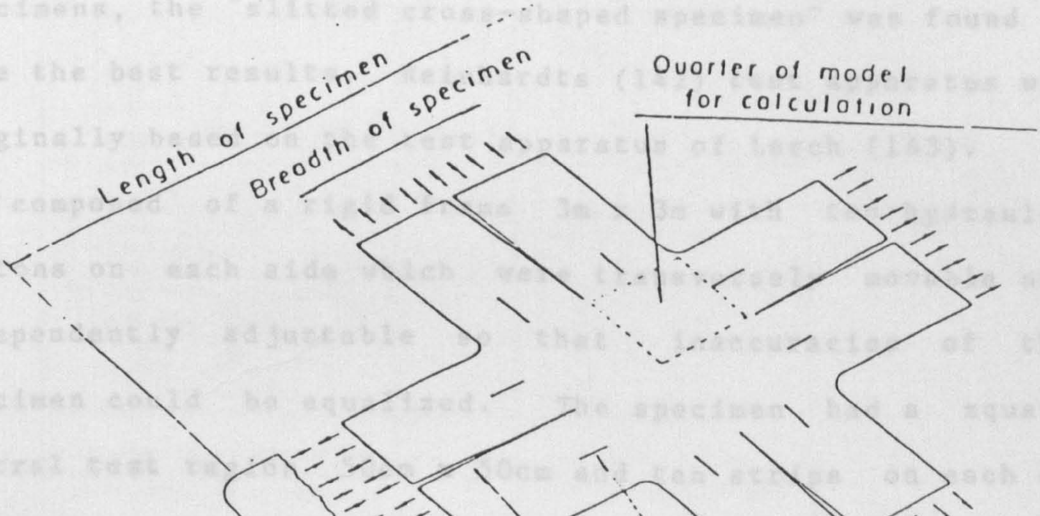


Fig. 6.2 (a) Cruciform shaped specimen with long and short slits.
(b) Specimen holders.

"from Minami and Nakahara (141)"

the measurement of the true biaxial strength. After many attempts at improving the shape and mounting of the specimens, the "slitted cross-shaped specimen" was found to give the best results. Reinhardts (142) test apparatus was originally based on the test apparatus of Losch (143). It was composed of a rigid frame 3m x 3m with ten hydraulic pistons on each side which were transversely movable and independently adjustable so that inaccuracies of the specimen could be equalized. The specimen had a square central test region 50cm x 50cm and ten strips on each of the four sides in order to clamp the specimen to the ten pistons. During loading, photographic pictures were taken of the test region which was marked with concentric squares and circles. Reinhardt (142) pointed out that the test apparatus of Losch (143), although giving the best results for the stress-strain relation of coated fabrics, only yielded up to 40% of the uniaxial strength. Therefore in order to improve the biaxial testing method, tests were carried out on a number of specimens with various modifications. The results of the tests on each form of specimen can be seen in Fig.6.3(a). The specimen which was finally developed avoided the use of seams and welded joints. As shown in Fig.6.3(b), the clamps consisted of a U-shaped steel element into which two steel bolts were welded. This arrangement allowed a strip of the specimen to be fixed only by friction, Fig.6.3(b). This method allowed

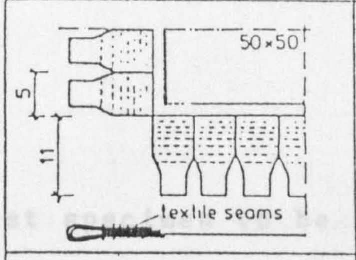
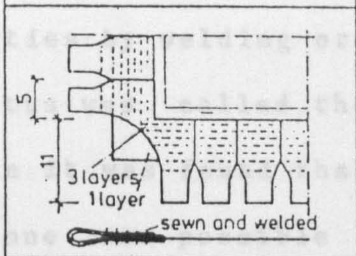
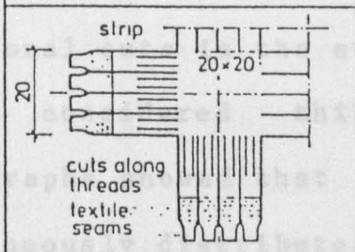
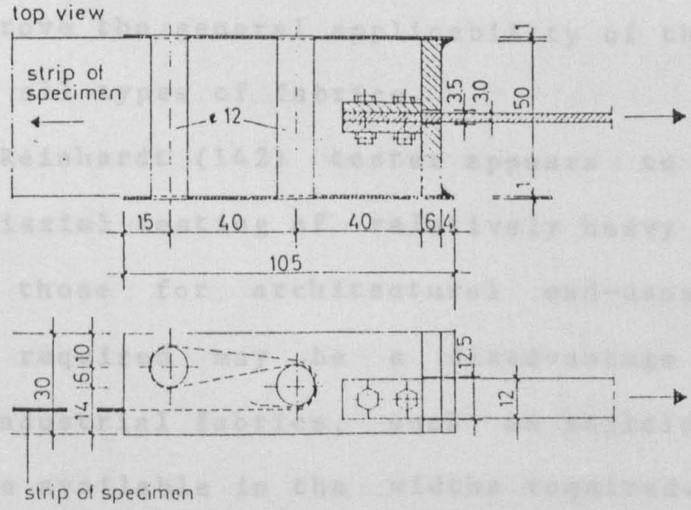
shape of specimen	strength ratio	fracture
	0.45	starts at the corner and runs along edge
	0.66	-starts at the corner and runs along welded joint
	0.76	-along seams of the strips
same cross shaped specimen as above, but using self fixing mounts according to figure	1.0	sudden fracture in the square field

Fig. 6.3(a) Shape, strength ratio and fracture of different types of specimens used in biaxial-loading tests; lengths in cm. Strength ratio is the ratio between the measured biaxial strength (warp stress=1.10 weft stress) and the uniaxial strength.



(b) Self-fixing mounts, lengths in mm.

"from Reinhardt (142)"

the test specimen to be mounted without altering the fabric properties by welding or sewing. The specimen used in this apparatus was called the "slitted cross-shaped specimen", because it was found that greater transverse strain in the edge zone was possible if the cross-shaped specimen had additional cuts in the strips along the threads. Reinhardt (142) considered this test apparatus sound as the photographs showed that the strain in the test region was homogeneously distributed, and that the fractures occurred in this region. He suggested that because this apparatus was available true biaxial strength could now be found, and that the most interesting result of his investigation was that biaxial strength was equal to the uniaxial strength. Reinhardt (142) also suggested that further work could be done to prove the general applicability of the new specimen shape for all types of fabrics.

The Reinhardt (142) tester appears to be most suited for the biaxial testing of relatively heavy coated fabrics such as those for architectural end-uses. The large specimen required may be a disadvantage when testing lighter industrial fabrics, such as sailcloth, which are not always available in the widths required. The article does not make it clear how the hydraulic pistons are independently controlled and adjusted, so that homogeneous strain may be maintained. Also with the considerable use of hydraulics this machine would be very expensive, however, no indication of cost is given. Despite these points this apparatus has many good points, and it appears to be the most successful biaxial tester as far as the achievement of homogeneous strain in the test area is concerned. A more delicate version of this device could be constructed for use with lighter fabrics, and possibly each piston could be automatically controlled by load or displacement transducers so that inaccuracies in the specimen could be equalized, but again this type of machine would be very expensive.

Viergever et al (144), when working with geomembranes, used some of Reinhardts (142) ideas when designing their biaxial tester. However, limiting cost was obviously more important in their design. They used a smaller cruciform specimen with a central test region 0.15m x 0.15m square. The arms of the specimen were 0.15m wide and 0.6m long, of which approximately 0.4m was used for clamping. The clamps were self-tightening, of the roller type, similar to Reinhardts (142), but only one was used on each arm of the specimen. The testing rig as a whole, Fig.6.4(a), is of the same basic design and operates on the same basic principle as all testers of this type. However, there are a few significant differences which are worth a mention. In this design only one of each of the two pairs of clamps possessed a system for applying loads. It is obvious with this situation that as only one side of the specimen is pulled,

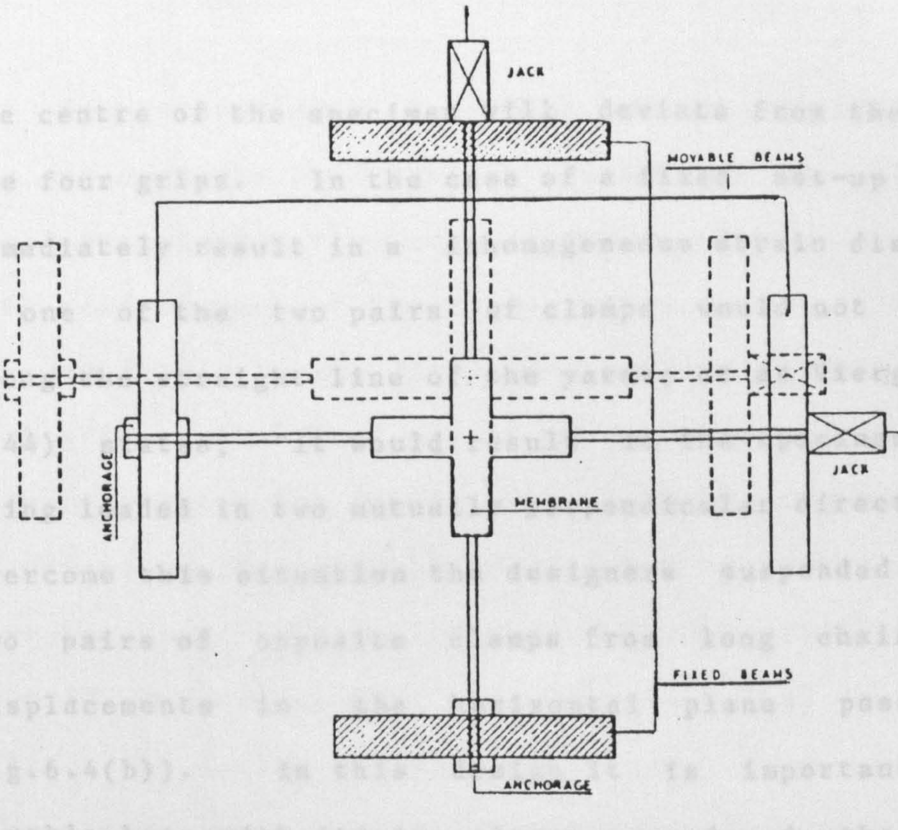


Fig. 6.4(a) Shift of the movable beams in the horizontal plane (due to strain)

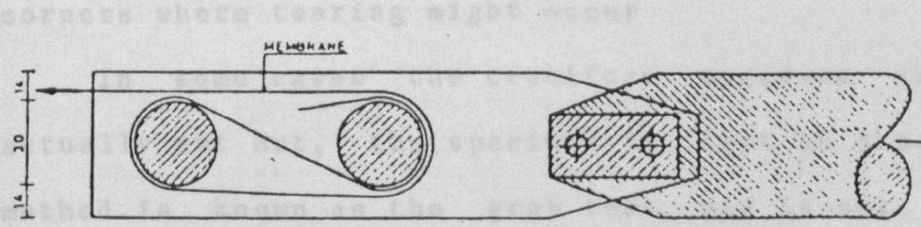


Fig. 6.4(b) View of test specimen in roller clamps.

"from Viergever et al (144)"

the centre of the specimen will deviate from the centre of the four grips. In the case of a fixed set-up this would immediately result in a inhomogeneous strain distribution, as one of the two pairs of clamps would not be pulling along the straight line of the yarns; or as Viergever et al (144) states, "it would result in the specimen no longer being loaded in two mutually perpendicular directions". To overcome this situation the designers suspended one of the two pairs of opposite clamps from long chains to make displacements in the horizontal plane possible (see Fig.6.4(b)). In this design it is important that the movable beam with its two clamps remains in the same plane when it swings, that´s why the chains must be "long".

Another fact concerning the specimen used by Viergever et al (144), which was pointed out by McGown et al (139) is that at the intersections of the arms the material is cut to curve from one limb to the next, thus avoiding sharp corners where tearing might occur

In some cases the cruciform specimen shape is not actually cut out, the specimen is left as a square. This method is known as the grab test and is not as commonly used by researchers (100) (98). This form of specimen tends to be used where speed or simplicity is more important than potentially more accurate results, and the strain is usually measured from a small central area, while stress is taken from the force per unit length of the clamps.

Segmented clamps have been used in certain cases to try and overcome this problem (see Fig.6.5). This method involves gripping the edge of the biaxially strained area with each segment of the clamp. These segments are allowed to move freely in the direction parallel to the edge which they grip. The clamp may be in the form of a row of small clamps gripping the fabric edge, or be in the form of wires or threads pushed through the fabric. Testers of this type have been used by previous authors who include Kawabata et al (83), MacRory et al (145), Bassett (108) and Reinhardt (142). The latter is exceptional as it is a combination of segmented clamps, slit cruciform specimen and self-tightening clamps.

Segmented clamps can produce certain errors in that stresses in the areas between the clamp segments and in the nearby regions are lower than elsewhere, and parts of this area may be only stressed uniaxially.

6.2.2 Flat Specimen Shear Testers

This type of shear tester was probably developed because of its simplicity, and speed and ease of use. The first recorded instrument of this type appears to have been the "Planoflex", designed by Dreby (146), and originally built to measure the "pliablity" of fabrics. This device

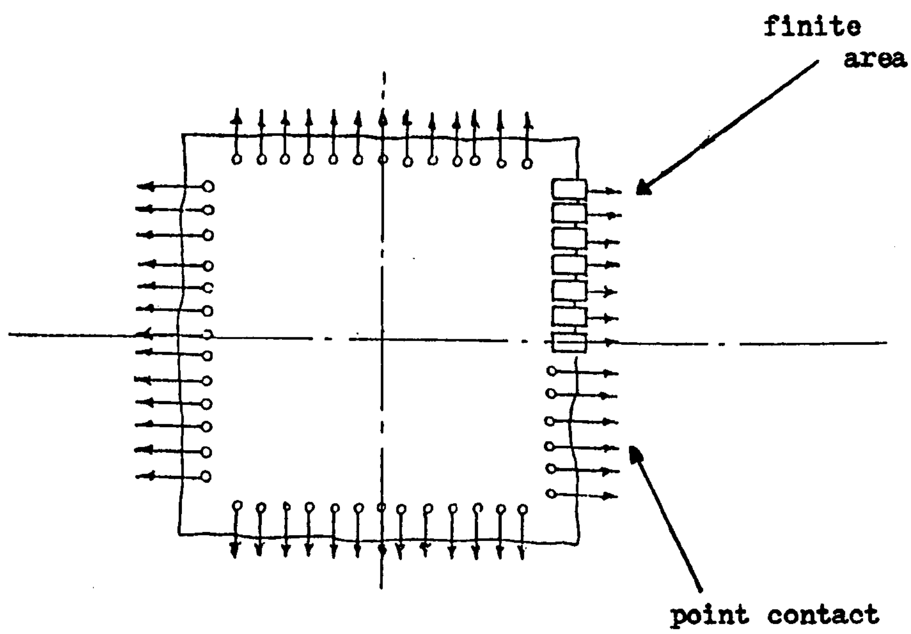


Fig. 6.5 Segmented Clamps

"from Bassett (108)"

(Fig.6.6) consisted of a metal base plate, supported by a wooden frame, to which was fastened a movable clamp, a fixed clamp, and a hinged shelf. The movable clamp was constrained in such a way that it moved in an arc of 15.24cm (6in) radius, remaining parallel to the fixed clamp. A weighted clamp, supported by the hinged shelf, was used to put the 7.62cm x 25.4cm (3in x 10in) specimen under a 907.18g (2lb) tension when mounted. The movable clamp was then slowly moved first to the left and then to the right, to the angles at which longitudinal wrinkles first appeared on the surface of the specimen. The angles could be read on a scale below a pointer on the movable clamp, and the total angle through which the fabric could be distorted was the sum of the readings obtained on the left and right of the centre.

Results obtained from this instrument could be used for evaluating and controlling the effects of different finishing agents and treatments. However, it was not capable of measuring the forces required to deform the specimen and its uses were limited.

Go et al (147) devised an instrument which could be used in the study of the shearing behaviour of fabrics under dynamic conditions. Park (148) describes this device (Fig.6.7) as consisting of two parallel bars which are pivoted together. These bars rest on knife edges and act as a pendulum. The fabric specimen is mounted on two

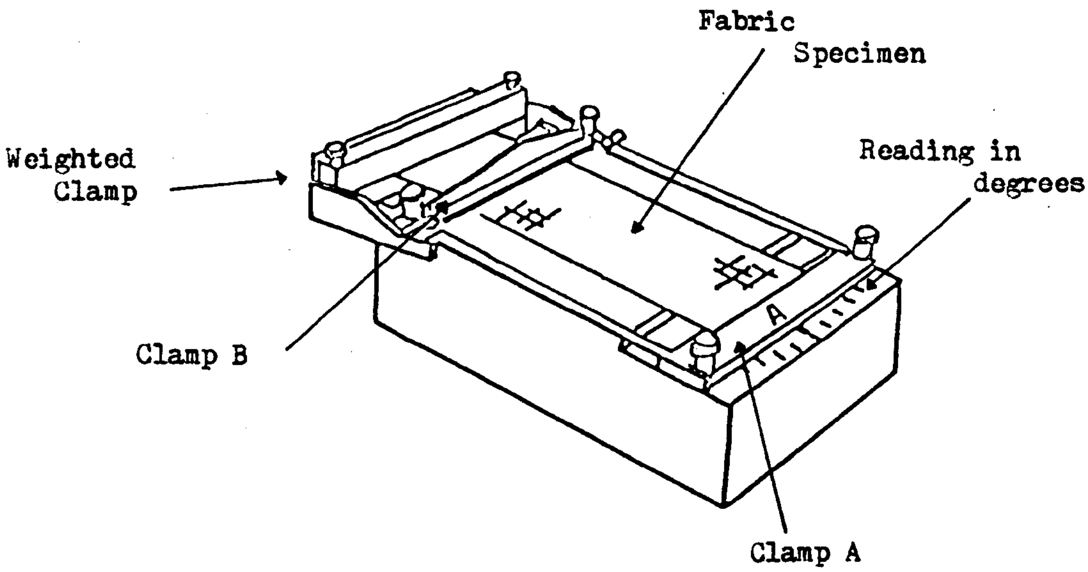


Fig. 6.6 The Planoflex (146).

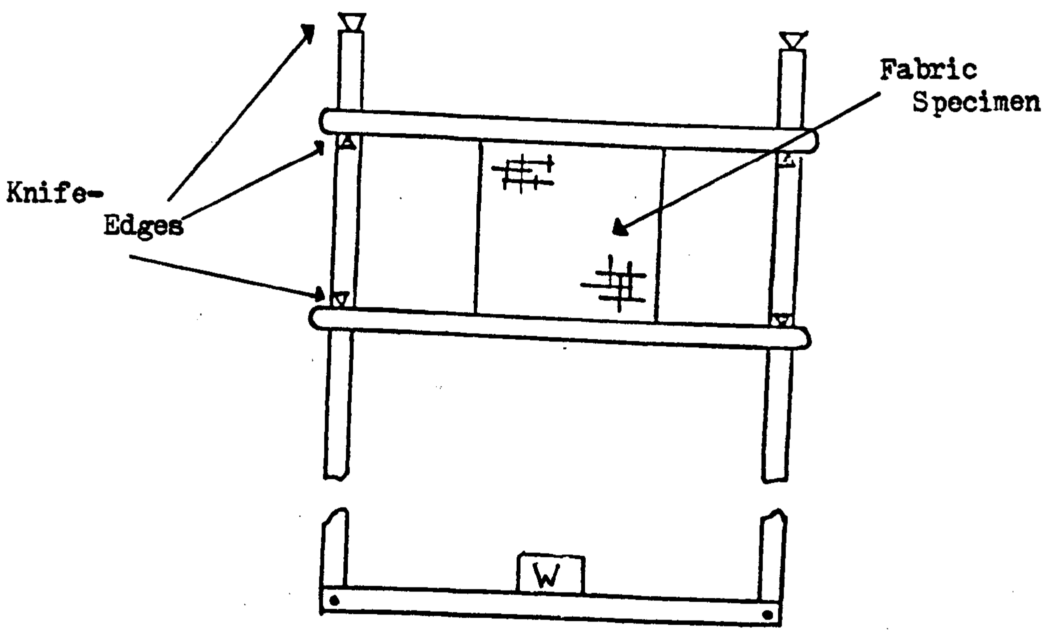


Fig. 6.7 Schematic diagram of apparatus due to Go et al (147).

"from Park (148)"

parallel, horizontal bars and these bars rest on four knife edges which are fixed on the two pendulum bars. When free oscillations of this apparatus are performed the apparent elasticity and frictional damping are deduced from the observed period and rate of decay of the pendulum.

In 1954 the Swedish Institute for Textile Research began a comprehensive investigation of the mechanical properties of fabrics. The purpose of the investigation, as described by Eeg-Olofsson (149), was to find out how to produce the best fabric at a minimum cost when its range of uses was known. It was therefore important to examine the problem from many points of view, and it was decided that an examination of biaxial stress, shear and bending would be an appropriate start, when the mechanical properties of apparel fabrics were to be considered. At the Institute a number of new methods were devised to study all three of these cases, and two basic types of instrument came about which were capable of measuring the shear stress-strain relationships. The first of these instruments was designed by Morner and Eeg-Olofsson (150) and the second by Behre (151), both these devices are described and compared by numerous authors (152) (148) (153) (154) in detail.

Most of the original, flat specimen, shear testing devices are based on variants of the method shown in Fig.6.8. A number have been designed so that they may be fitted onto an Instron testing machine to produce a trace of the curve of shear force against shear deformation.

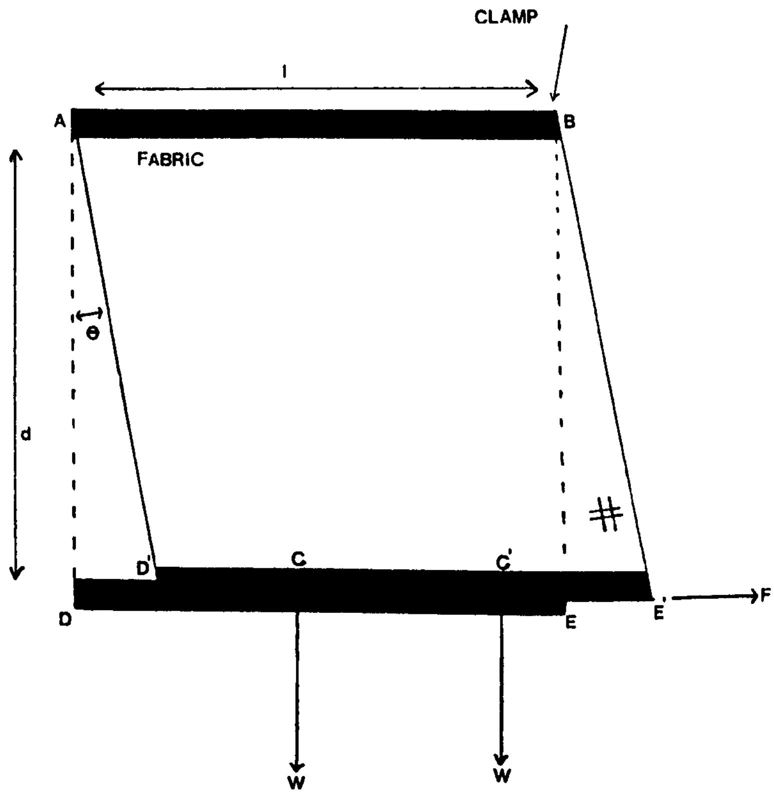


Fig. 6.8 The Basic Principle of a Flat Specimen Shear Test

The basic principle of the method shown in Fig.6.8 involves holding an initially rectangular fabric specimen of length l and width d in a fixed clamp at AB, along the line of either the warp or weft yarns, and in a movable clamp at DE. The movable clamp is moved laterally and the resistance is measured as the fabric is deformed. It was recognised that satisfactory measurements could only be made where the strains remained homogeneous. This set the limits to which a fabric could be sheared to the point where buckling or wrinkling first occurred.

Behre (151) showed that the onset of buckling or wrinkling could be delayed, as shear increased, by applying a tensile stress in a direction perpendicular to the direction of shearing. This can be seen in Fig.6.8 where a load W is applied to the bottom edge of the fabric via the clamp and a lateral force F is applied to pull the clamp to one side and set-up a shear distortion within the fabric. The resultant of the forces F and W gives the force acting on the lower clamp at C, which must, as Hearle (155) states, be opposed by an opposite force from the fabric. This force will be transmitted through the fabric in the same straight line to give the force exerted by the fabric on the clamp AB and its equal and opposite reaction, as shown for a square specimen in Fig.6.9(a). The asymmetry of the situation shown in Fig.6.9(a) makes it clear that the stress distribution will not be uniform. Hearle (155)

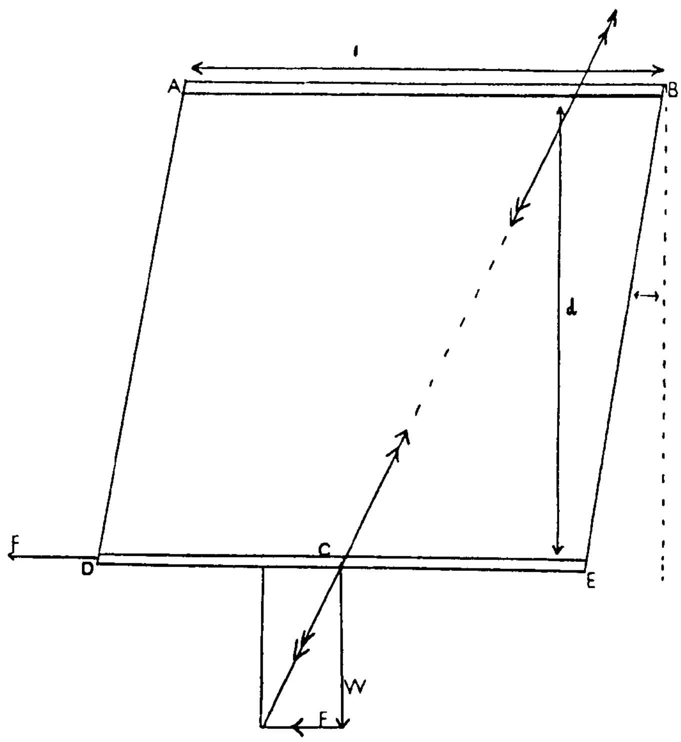


Fig. 6.9 (a) The Asymmetry of the Situation shown makes it clear that the Stress Distribution Will not be Uniform.

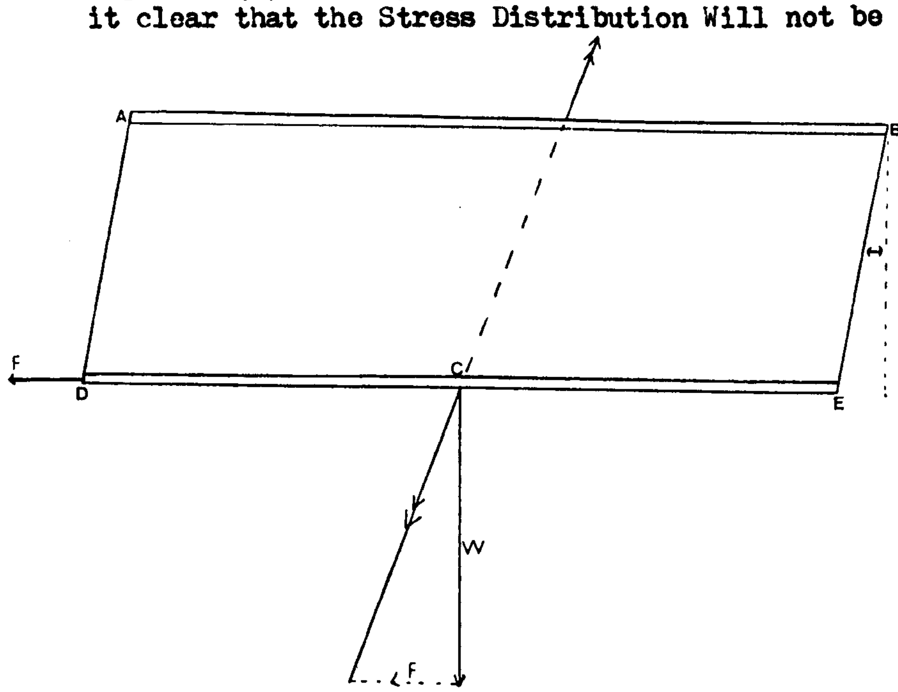


Fig. 6.9 (b) Specimen with High Ratio of Length to Width improves the situation.

goes on to say that the resultant forces between each clamp and the specimen have to be replaced by forces unevenly distributed along their length; and this distribution will be difficult to calculate since it is influenced by the elastic properties (nonlinear and anisotropic) of the specimen. Problems are increased by the fact that the asymmetry, and resulting nonuniformity in stress distribution, varies with shear strain and with the ratio of F to W, and will therefore change during a test.

Treloar (152) has shown that this situation is made much simpler if specimens with a high ratio of length to width are used. This is quite obvious from Fig. 6.9(b).

Although F is the lateral force applied to deflect the specimen to one side the shear force cannot be taken directly as F for the following reason. If the fabric has a zero resistance to shear, the magnitude of the horizontal force, H, is given by :-

$$H = W\tan\theta \qquad (6.1)$$

This is due to the fact that a horizontal force $W\tan\theta$ would be needed to maintain this hypothetical fabric at an angle θ to the vertical. If however the fabric has resistance to shear deformation, an additional force is required. If the total force applied is F, then the force R associated with the shear of the fabric is given by :-

$$R = F - H = F - W\tan\theta \qquad (6.2)$$

Treloar (152) drew attention to the fact that the use of this previous equation (6.2) to define the resistance to shearing is to a certain extent arbitrary, and although it may be possible to extend its use from free threads, with no shear resistance, to woven fabric, it would not be meaningful for materials of widely different structure, such as knitted fabrics or paper or other sheet materials. He suggested that this was due to the departure from simple shear, as the distance between the clamps did not remain constant, and also because this definition is based essentially on a model in which the only stresses present are tensile stresses in the direction of the initially vertical threads and torsional stresses at the points of contact between threads. This model is reasonably valid for the study of woven fabrics, but it is not suitable for the other sheet materials. Even for woven fabrics the model is not accurate as the finite flexural rigidity of the yarn elements, internal friction, etc., may lead to a more complex stress distribution than envisaged.

Hearle (155) suggests a more general definition of which equation (6.2) may be regarded as a special case. If the point of application of the force F is displaced through a distance dx, parallel to F (see Fig.6.10), the work done will be Fdx. If the weight W is raised by an amount dy, its potential energy will be increased by Wdy. The difference between these two quantities will be the

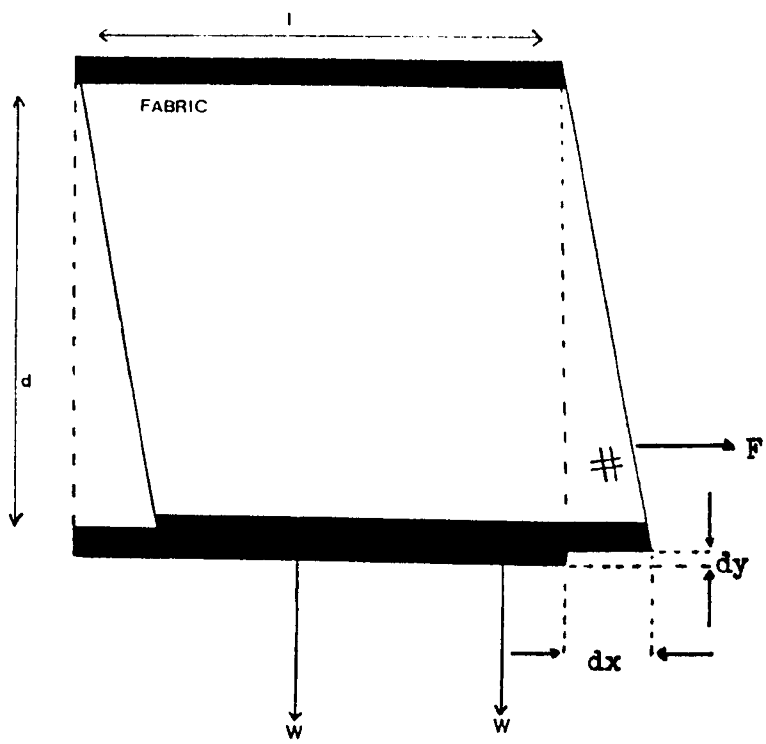


Fig. 6.10 Energy Method of Dealing with Fabric Shear.

work done in deforming the fabric, and will be stored as shear strain energy if the deformation is elastic. Therefore :-

$$\text{work done in shearing fabric} = Fdx - Wdy = (F - Wdy/dx)dx \qquad (6.3)$$

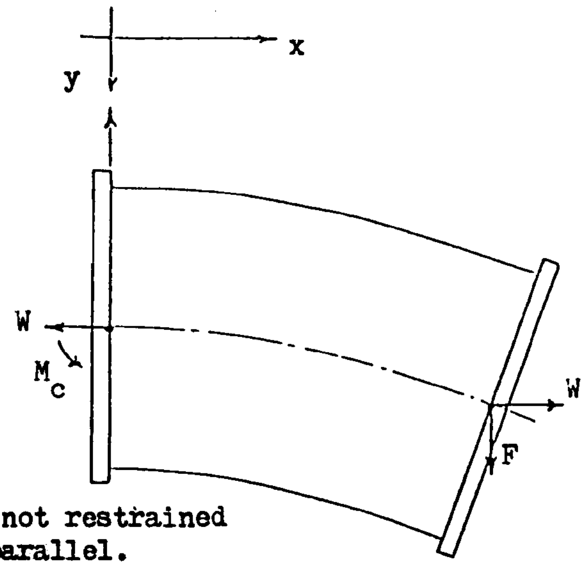
$$\text{or effective shear force} = R = F - Wdy/dx \qquad (6.4)$$

If the deformation is at a constant length of thread $dy/dx = \tan\theta$

A number of researchers at this time began to consider that applying a large tensile stress in the direction perpendicular to the direction of shearing may affect the shearing characteristics of the fabric. Cusick (88) showed that there was a tendency for the modulus to increase as the weight of the lower clamp was increased. Treloar (152) found that the maximum shear strain which could be applied without the occurrence of wrinkling was dependent on the shape of the specimen, as well as on the applied tensile stress. Most of the researchers at this time used square specimens. Treloar (152) showed experimentally that using a specimen with a high length to width ratio (eg.10:1), gave higher values of shear modulus, before wrinkling, and less dependence on fabric tension. Spivak (156) agreed with Treloar (152) and he also showed that it was better to test a specimen having an increased ratio of length to width as opposed to a square specimen, as they were much less sensitive to the normal stress. Tandon (157) agreed that there were a number of problems with the square specimen, and he modified Behre's (151) shear testing apparatus to enable it to test a rectangular specimen of 20cm x 5cm.

Both Treloar (152) and Spivak (156) disagreed with the buckling theory proposed by Behre (151), in which he considered the stress distribution in the sheared specimen by regarding the specimen as a cantilever in which the height is much larger than the width. Treloar (152) proposed a theory which showed that a tensile stress in the direction normal to the direction of shearing could not eliminate compressive stresses in certain directions in the sheet. It could not in that case eliminate the inherent tendency which a fabric has to buckle, even when subjected to a homogeneous shear strain. He predicted that buckling would always occur if shear stress was applied while tensile stress in one yarn direction was zero, regardless of the magnitude of the stress in the other yarn direction. Goswami (158), however, who used Spivak's (156) apparatus in his work found that Behre's (151) theoretical prediction for the incidence of wrinkling showed reasonably good agreement with the experimental results for the fabrics heat set in boiling water under no-shrinkage conditions. He suggests that this shows that the shear behaviour of fabrics is strongly dependent on the state of relaxation of yarns in the fabric and may account for the poor agreement observed by Spivak (156).

Bassett (108) suggests that a more detailed study of the method which was used by Behre (151) to determine his buckling criterion could yield further useful information. He illustrates the conventional two clamp textile shear tester rotated 90 degrees and analyses it as a cantilever beam. The illustrations show how constraining the clamps to remain parallel halves the effective length of the beam for such calculations (see Fig.6.11). Bassett (108) goes on to say that this would suggest that constraining the clamps to remain parallel has the same effect as halving the length to width ratio. However experimental observations by Bassett (108) showed that this was not strictly true. He compared two specimens, one which was in a rig in which the clamps were constrained to remain parallel, and the other which had not got the clamps constrained. The curvature of the central course of the knitted specimen was much diminished in the constrained clamping system, but not eliminated. Consider the alternatives of constraining the clamps to remain parallel with the specimen length to width ratio equal to one, versus placing an unconstrained clamp on the central course of a specimen, with length to width ratio of 1:2. These alternatives can be considered as equivalent, except that in the latter case the central course would be forced to remain straight. Therefore it can be seen that halving the length to width ratio would have a greater effect than constraining the clamps to remain parallel.



(a) Clamps not restrained to remain parallel.

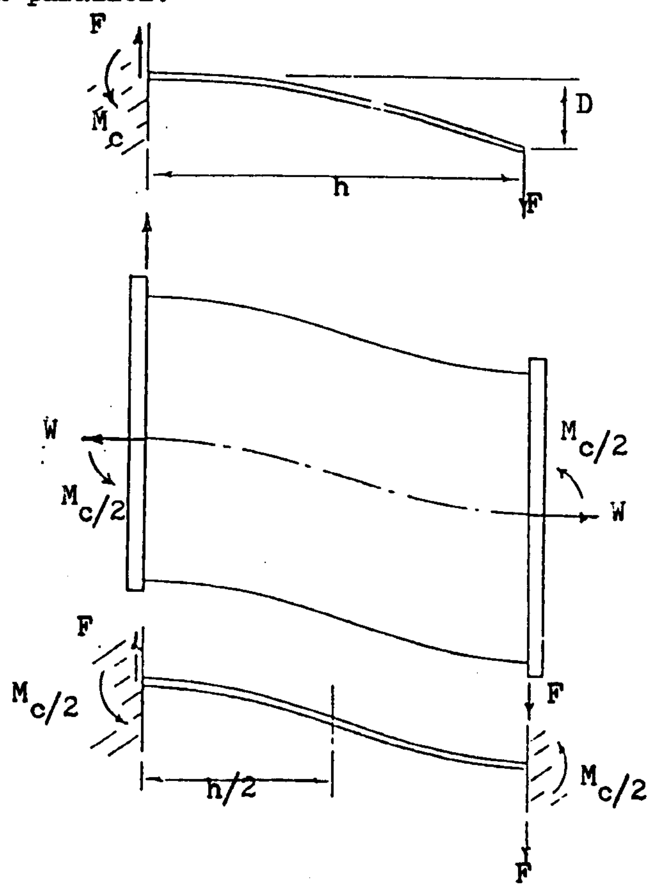


Fig. 6.11 (b) Clamps constrained to remain parallel.

"from Bassett (108)"

All the shear testing instruments mentioned so far have had unconstrained clamps. Kawabata et al (83) designed a biaxial tensile tester which could be converted to operate as a shear tester, though only uniaxial tension could be applied in this mode. This device was similar in principle to one previously used by Van Holde and Williams (159) which they called the parallel plate viscoelastometer. This was constructed for the study of the viscoelastic behaviour of polyisobutylene and other high polymers under constant shear stress (see Fig.6.12).

A number of other shear testing devices have been used for flat specimens and they can be seen in chronological order in Table 6.2.

6.2.3 Measurement of Fabric Shear by Using Bias Extension Tests

The experimental measurement of shear can be rather complicated. However as a number of authors (eg. Lindberg et al (160), Cooper (161), Weissenberg (72), Haas (19), Skelton (95), Kilby (91) and Hearle (155)) have pointed out the simple bias extension test is geometrically similar, for plain-woven cloths. This test requires no extra apparatus and involves a uniaxial tensile test on fabrics in the direction 45 degrees to the warp and weft (see Appendix 1).

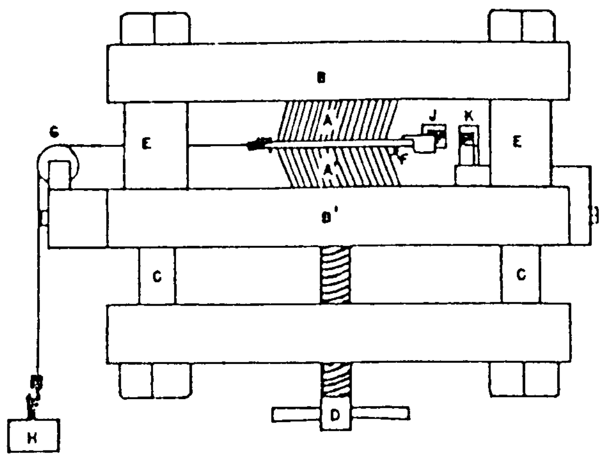


Fig. 6.12 The Parallel Plate "Viscoelastometer"

"from Van Holde and Williams (159)"

Lindberg et al (160) pointed out the relationship between compressibility of fabrics in the bias direction and the shear properties.

Cooper (161) attempted to draw attention to the possible advantages of the simple bias test. However he did not investigate the conditions required for exact correspondence between the results of the two types of test. Cooper (161) noted that this test is open to criticism due to the fact that the strip is held to width at the jaws, but is free to contract elsewhere. However he does say that the effect of the jaws will be small compared with the length of the strip. He also pointed out that because of the absence of compression, mechanical conditioning is unsymmetrical about zero. Chadwick et al (70) showed that roller-grips could be used to overcome the inhomogeneous strain conditions in the neighbourhood of the fabric jaws. The specimen is in the form of an endless belt and this allows some widthwise contraction in the area of the grips, limited by the friction between the fabric and the roller. A PTFE coating on the roller may increase the widthwise contraction which may be achieved.

Spivak and Treloar (162) carried out quite a detailed investigation of the relation between bias extension and simple shear. They pointed out the differences between the two tests and noted that in simple shear the normal stress W remains constant during the test, while in bias extension, the normal component W is continually changing as F (tensile force) increases. Methods of lessening this dissimilarity were discussed, but attention was drawn to the fact that the value of R is not very sensitive to variations in W. Also, as Cooper (161) had previously pointed out, Spivak and Treloar (162) noted that the test in simple shear is symmetrical about a point of zero strain, and positive and negative values may be obtained. In the bias extension test, however, extensional or positive values may only be obtained. Spivak and Treloar (162) also found that if the same effective shear strain was maintained in the two test methods, the resulting values for the resistance to shearing, R, were found to deviate in different fabrics in various ways from the predicted relationship. This suggested to them that one could not simply and directly, either theoretically or empirically, obtain the complete stress-strain properties of a fabric in shear from a test in bias extension. There would only be a very rough approximation between the two tests and results must be used in that context. They were particularly concerned about the edge effect that arises in bias extension as some threads will be held at one end and others will have both ends free. They concluded that the bias extension test could only give a very rough estimate of resistance to shearing and if proper values were required they must be obtained from a test in simple shear.

6.3 Testing Instruments Which Can Vary Biaxial Tensile and Shear Parameters Independently

6.3.1 Testers Which Used Fabric Specimens in the Form of a Cylinder

This form of test almost certainly evolved in the early 20th century due to the nature of one specific end-use. This was the production of dirigibles, especially those of the semi-rigid and non-rigid constructions where rigidity in the envelope was only maintained by the enclosed gas. These pressurized airships had a tendency to bend and deform, and the nose could pitch up due to low shear rigidity in the fabric, especially when the airship was moving at speed. It was recognised, even at this early date, that tests of this nature on cylindrical fabric specimens, which were very similar in form to the cigar shaped airships, afforded much more useful information than the tensile tests of the ordinary character which were performed uniaxially on fabric strips.

The basic principle of this test method is illustrated in Fig.6.13. If the fabric is impermeable to air as in the test due to Anderson (163), or water as in the test due to Haas (19), stress in the circumferential direction can be applied by air or hydrostatic pressure inside the cylinder. Tensile stress in the axial direction can be varied independently by applying a force to the ends of the cylinder.

Chronological Outline of Flat Specimen Shear Testers for Textile Fabrics

Year	Author(s)	Specimen Dim.	Ref.
1941	Dreby, E.C.	15.24cm x 7.62cm	146
1956	Go, Y.; Shinohara, A.; Matsuhashi, F.	not available	147
1957	Morner, B.; Eeg-Olofsson, T.	10.0cm x 10.0cm	150
1961	Behre, B.	10.0cm x 10.0cm	151
1965	Treloar, L.R.G.	20.0cm x 20.0cm 20.0cm x 2.0cm	152
1966	Spivak, S.M.	10.0cm x 10.0cm 20.0cm x 20.0cm 10.0cm x 2.0cm 20.0cm x 2.0cm 20.0cm x 1.0cm	156
1973	+Kawabata, S.; Masako Niwa; Kawai, H.	20.0cm x 4.0cm	188
1974	+Carnaby, G.A.; $Postle, R.	10.0cm x 10.0cm	183
1975	Prevorsek, D.C.; et al	not available	185
1976	+Hamilton, R.J.; $Postle, R.	10.0cm x 10.0cm	184
1984	Tandon, S.K	20.0cm x 5.0cm	157

+ Clamps constrained to remain parallel

$ Knitted fabrics

Table 6.2

It appears from the literature that this procedure of applying a force to the ends of a pressurized fabric cylinder was first used by the National Physical Laboratory (128), in 1910. (see Fig.6.14). Fabric shear stress could also be imposed by applying torques to the cylinder ends. The apparatus had the facility to measure shearing strain, but the fabric cylinders were not intentionally sheared. It was found that during tests on cylinders of diagonally doubled fabric rotation of the cylinder occurred about its axis, showing shear strain due to the diagonal application to each other of two layers of woven fabric, in each of which the warp and weft coefficients of elasticity were unequal. The new apparatus for compound stress tests on cylinderical fabric specimens was therefore designed to measure this shearing strain when present. It appears that Haas (19) was the first researcher to actually apply torque to the cylinder from which the shear stress could be computed (see Fig.6.15).

In this form of test three independent variables are available. However, the early researchers (41) used only one independent variable and that was with cylindrical fabric specimens, or bags as they were described, with the ends made of flat pieces of the same fabric. These specimens were made-up to attempt to make a comparison between the uniaxial tensile test and the calculated values of the maximum hoop tension in fabric cylinders. They found that the calculated hoop tension at failure from the

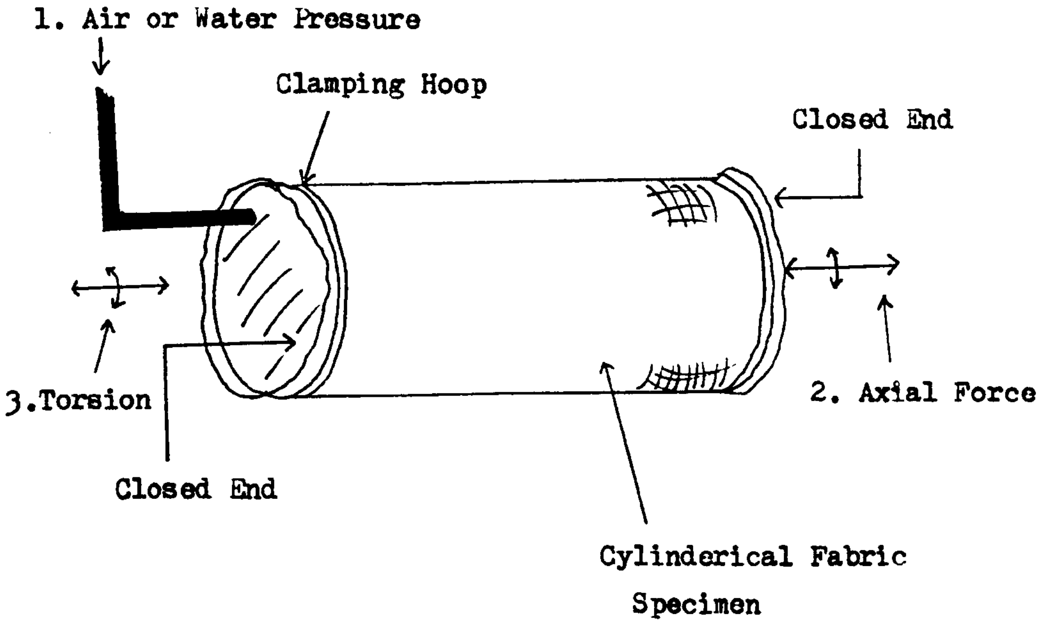


Fig. 6.13 The Principle of the Cylinder Test

(After Bassett (108))

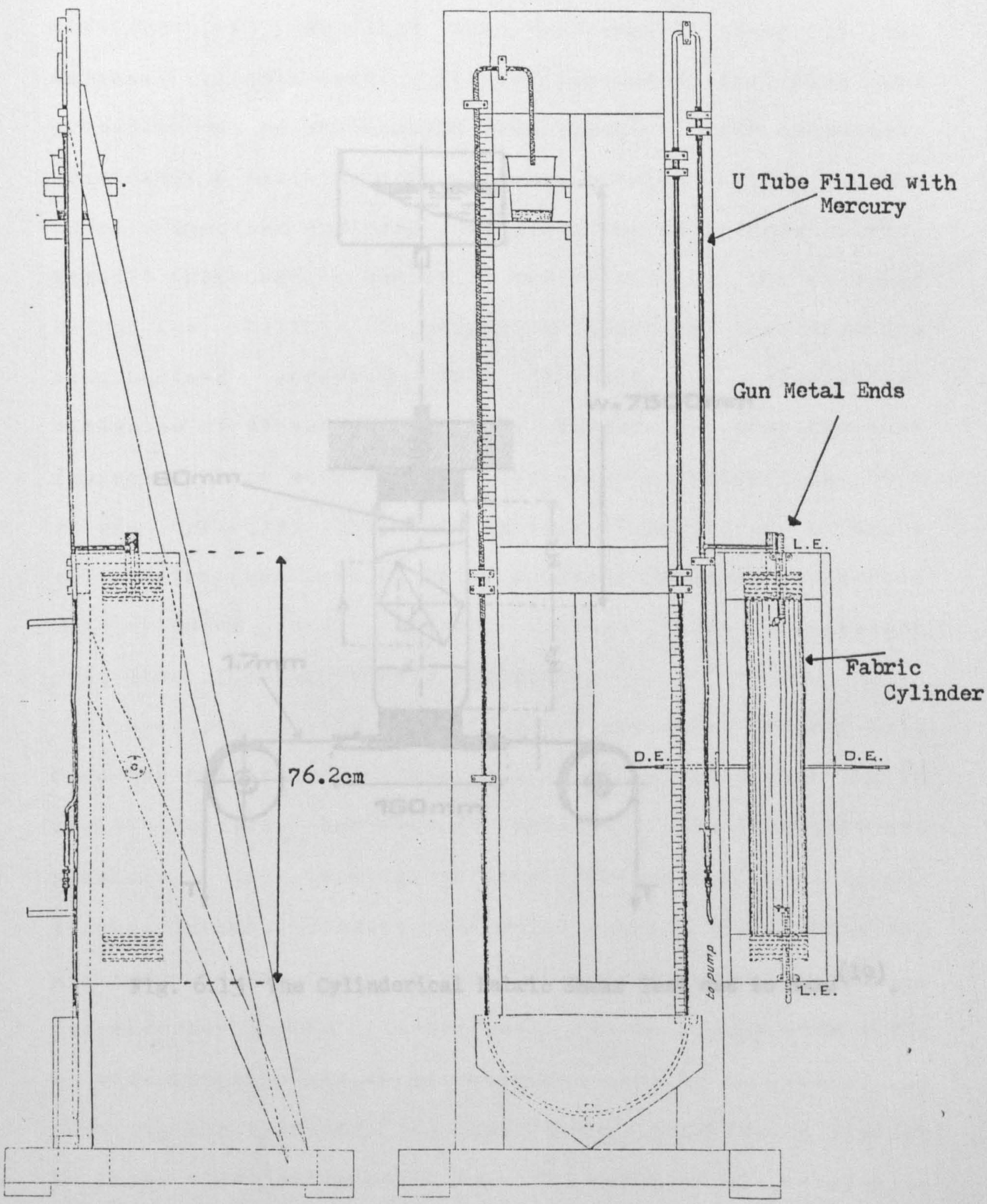


Fig. 6.14 National Physical Laboratory Apparatus for Balloon Fabric Bursting Tests

" from A.C.A., Rept. and Mem., No.27[128]"

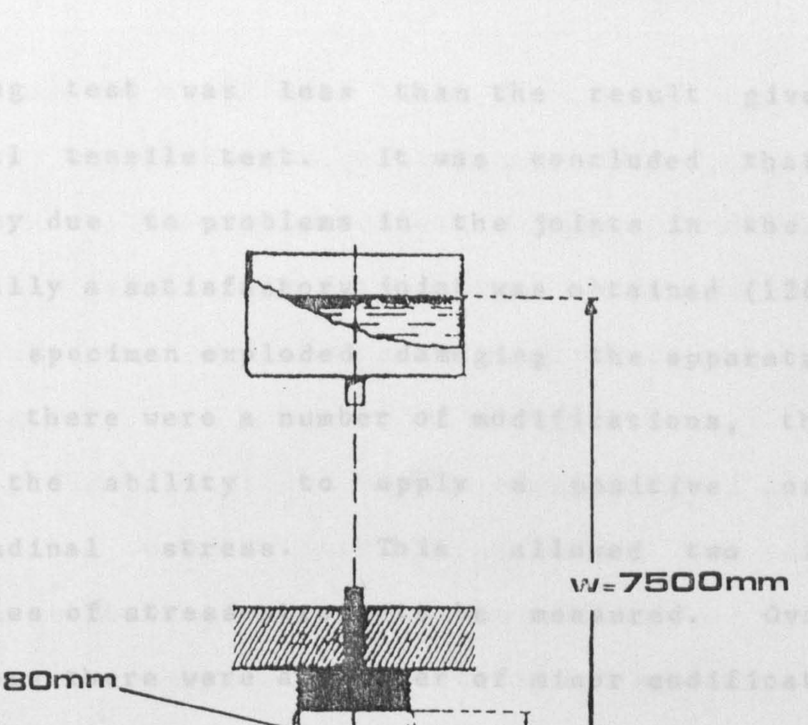


Fig. 6.15 The Cylinderical Fabric Shear Test due to Haas [19].

bursting test was less than the result given by the uniaxial tensile test. It was concluded that this was probably due to problems in the joints in the cylinders. Eventually a satisfactory joint was obtained (128), but the fabric specimen exploded damaging the apparatus. When rebuilt there were a number of modifications, the main one being the ability to apply a positive or negative longitudinal stress. This allowed two independent variables of stress-strain to be measured. Over the next few years there were a number of minor modifications, but it was Haas (19) who, it appears, was first to use a cylinderical specimen to which a torque could be applied to the cylinder end, thereby making three independent variables of stress-strain available.

Specimens in the form of hollow cylinders are not only used for the investigations of the mechanical properties of textile fabrics, but also on materials such as metals and plastics. This form of specimen has been found useful because internal pressure and axial compression or tension, are independent of each other. Therefore the ratio between the stresses in the cylinder wall can be varied over quite a wide range, and shear stresses can be introduced by twisting the cylinder. The shear stress analysis is similar to that used by engineers for the analysis of torsion in hollow shafts.

Bassett (108) drew attention to the fact that the roller clamp system, such as described by Chadwick et al

(70), can be considered to be a cylinder tester in which fluid or gas pressure is replaced by a pair of rollers inside the cylinder, parallel to the cylinder axis. This method may be suitable for permeable fabrics, but neither axial tension or torsion can be applied to the cylinderical specimen.

Eeg-Olofsson (164) used a simple method which did not require the use of internal pressure and enabled the biaxial stressing of permeable fabrics. This method involved gripping a cylinderical fabric specimen with circular clamps. These clamps held the cylinder ends to constant diameter, and when a load was applied along the axis of the cylinder, causing an extension (x), waisting (r) occurred at a distance from the clamps in the radial direction. This produced a circumferential stress which was dependent upon dr/dx. MacRory and McNamara (165) pointed out that the values of r, dr/dx and d^2r/dx^2, which were required in the formula, which related the stress ratio and the profile of the cylinderical specimen, could be obtained by photographing the sample, and then projecting the photograph onto a screen and measuring the projection. MacRory and McNamara (165) used this method to investigate the biaxial behaviour of knitted fabrics, but they claimed that its use was limited, so they were designing a more flexible two-dimensional load-extension tester.

Horino and Kawanashi (166) used a cylinderical specimen to investigate the biaxial tensile behaviour of woven fabrics sewn with open lock stitches. They had previously studied fabrics sewn with open lock stitches stretched in a direction perpendicular to the seam line, and analyzed by considering a mechanical model in which the fabric element and the seam element were connected in series. However the stitch interval decreased when the specimen was stretched and therefore analysis of the tensile behaviour was confined to the low load region in which the stitch interval could be considered unchanged. To overcome this problem the woven fabrics were sewn to form cylinders into which a Teflon rod, which kept frictional resistance to a minimum, was inserted to keep the circumferential strain zero when the specimen was stretched along the rod axis. The results were analyzed using mechanically equivalent models. They concluded that when fabrics are sewn together, it is necessary to increase the seam strength by balancing both the tensions of the needle thread and the bobbin thread (though they did not comment on the practicability of this suggestion).

Another method which can be used to test cylinderical specimens of permeable fabric, is to insert a bladder of some impermeable material inside. Mellen (167) used a light-weight elastomeric bladder as the pressure retaining component, and the fabric cylinder restrained the excessive inflation and stretching of this bladder. However if the bladder consists of an isotropic material such as rubber, its shear stiffness will almost certainly be high compared to that of the fabric cylinder, and this could cause inaccuracies in the calculations. Also there are likely to be serious end effects at the rigid clamps if the hoop strains are large.

From the literature survey it appears that the use of cylinderical specimens is one of the most commonly used methods when investigating the biaxial properties of impermeable industrial fabrics. However Reinhardt (142) points out that the seam, which cannot be avoided except in certain cases, influences the stress-strain behaviour, and he goes as far as to say that test results have shown that the cylinder test is not suited to determine the true biaxial strength. However this has probably been the most commonly used method and many authors have described research in which cylinderical specimens have been used to study the mechanical properties of textile fabrics. Some of these authors are listed in Table 6.3.

Some Previous Tests Using Cylinderical Specimens

Author(s).	Ref.	BC	HP	AP	NP	RP	RC	BA	FA	TE	Year
Stanton and Booth	41			X				X			3/1910
Seuter	127			X				X			9/1910
Anon.(N.P.L.)	128			X				X	X		10/1910
Anon.	68			X					X		5/1911
Booth and Hyde	42			X				X	X		3/1912
Haas and Dietzius	19		X					X	X	X	12/1912
Upson and DeF.Chandler	178			X				X			1926
Anderson	163			X							1946
Chadwick et al	70						X				1949
Eeg-Olofsson	164							X	X		1955
Mellen et al	167	X			X				X	X	1960
Leonard et al	39			X						X	1960
Zender and Deaton	138			X						X	1961
+ Clark	107				X				X	X	1963
$ MacRory and McNamara	165							X	X		1967
Skelton and Freeston	179			X					X	X	1971
Alley and Faison	180			X					X	X	1972

P.T.O. for rest of Table 6.3

Some Previous Tests Using Cylinderical Specimens

Continued from previous page

Author(s)	Ref.	BC	HP	AP	NP	RP	RC	BA	FA	TE	Year
Yendell	169	X		X					X	X	1972
Horino and Kawanishi	166					X			X		1973
~ Alexandroff	172		X	X					X		1974
Minster and Berka	181		?						X		1977
Paute and Segouin	187		X						X	X	1977
Firt	99		X						X		1983

KEY :-
HP = Hydrostatic Pressure
AP = Air Pressure
NP = Nitrogen Pressure
RC = Roller clamps replacing internal pressure
BA = Specimen mounted at bias angles
FA = Force applied parallel to cylinder axis
TE = Torque applied to cylinder ends
BC = Bladder used inside fabric cylinder to prevent pressure leak
RP = Teflon rod inserted inside cylinder to maintain circumferential strain at zero

+ = Cord-Rubber Laminate Tested
$ = Knitted Fabric Tested
~ = Triaxially Woven Fabric Tested

Table 6.3

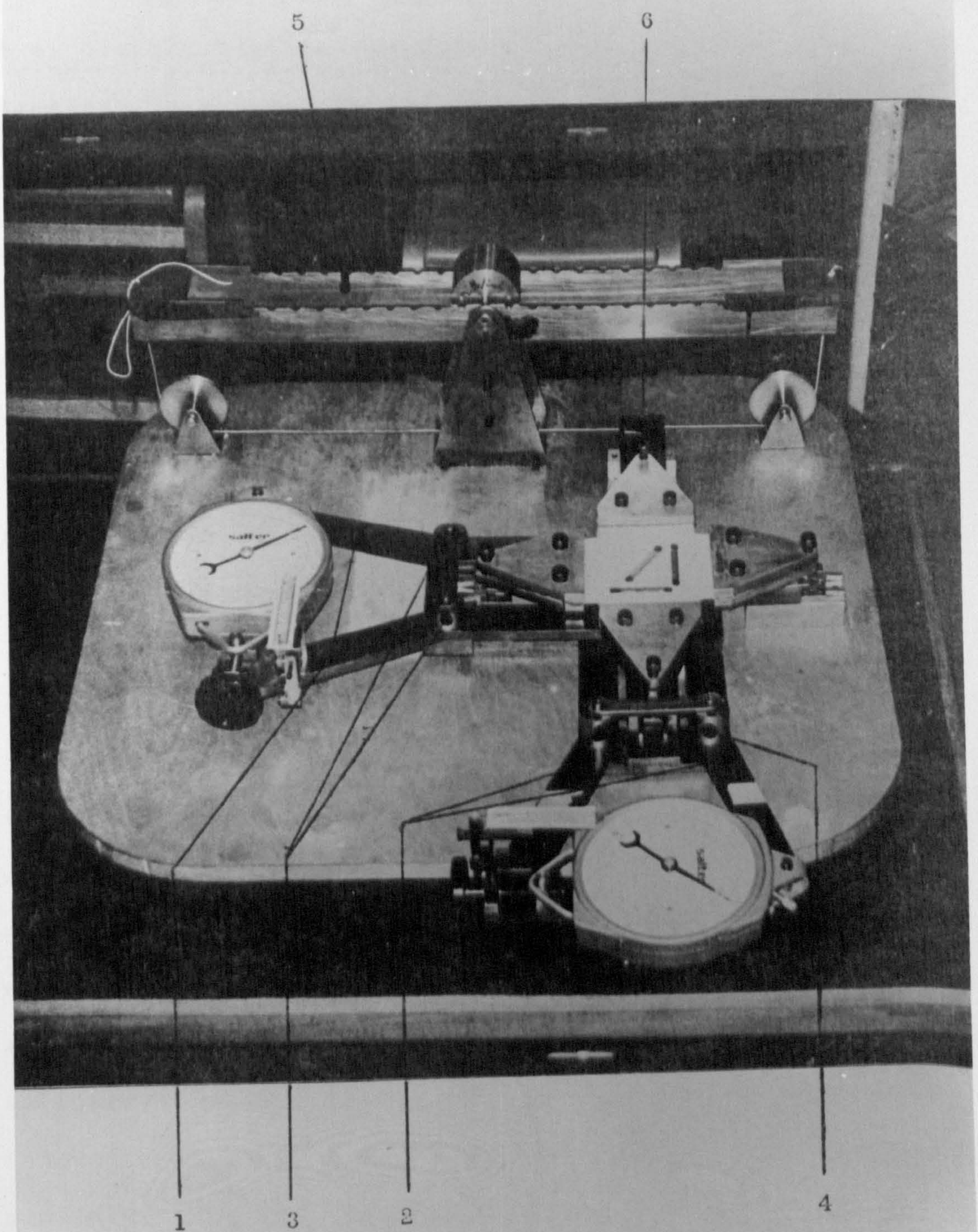


Plate 5 - Yendell's biaxial tensile and shear tester.
(from Yendell(168))

6.4 Biaxial Tensile Testers Which Shear the Fabric Specimen by a Scissor-Like Action

Due to the difficulties with the seam and the time involved in setting up the cylinderical specimen. Relatively recently researchers have attempted to design testers which can take a flat specimen and biaxially load and shear it at the same time. The object is that these testers will produce more realistic results and also be easier to use.

6.4.1 The Yendell Test Rig (168) (169)

The Automate/Yendell fabric testing machine (see Plate 5) was developed as part of the sail research programme at the University of Southampton, and it was intended to be a routine biaxial tensile and shear tester which could be used by sailmakers. Yendell hoped that the tester would be able to discriminate between fabrics sufficiently well to enable sailmakers to evaluate different fabrics, and it still has uses today for both sailmakers and others, such as Scardino and Ko (170), who used it in the evaluation of triaxial fabrics. However there are a number of basic problems with the design of this machine. As in all testers of this type, which use the cruciform specimen in its most basic form with solid clamps, the strain in the central test region is not homogeneous. This may not be a great problem with the low strain levels involved when testing sailcloth, but would make it unsuitable for other more extensible types of fabric. The problems of inhomogeneity in cruciform specimens has been investigated by Minami and Nakahara (141) and Reinhardt (142). They used modified versions of the specimen and special clamping systems.

Another problem with the Automate/Yendell concerns the arrangement of the pivots which enable rotation of the fabric clamps during shear tests. The axes of the pivots pass through the edge of the square test region of the specimen at the points shown in Fig. 6.16, and through the bearings which are underneath the specimen. When the tester is in shear mode, two opposite pivots move in circular paths about the centre of the specimen, under a known applied torque. In turn the clamps rotate about the pivots so that no moments are applied to the sides of the central test region of the specimen, as shown in Fig. 6.17(b).

Basically the Automate/Yendell consists of two arms; one of which rotates about the others centre in a scissor like manner, so that the fabric is sheared. The central pivot point is directly under the centre of the specimen, this symmetry being important in ensuring that the shear strains are homogeneous. On each of the four ends of the two arms are mounted the pivot-clamp systems, as shown in Fig. 6.18. The geometry of two of these systems which are mounted on opposite ends of one of the arms is shown in

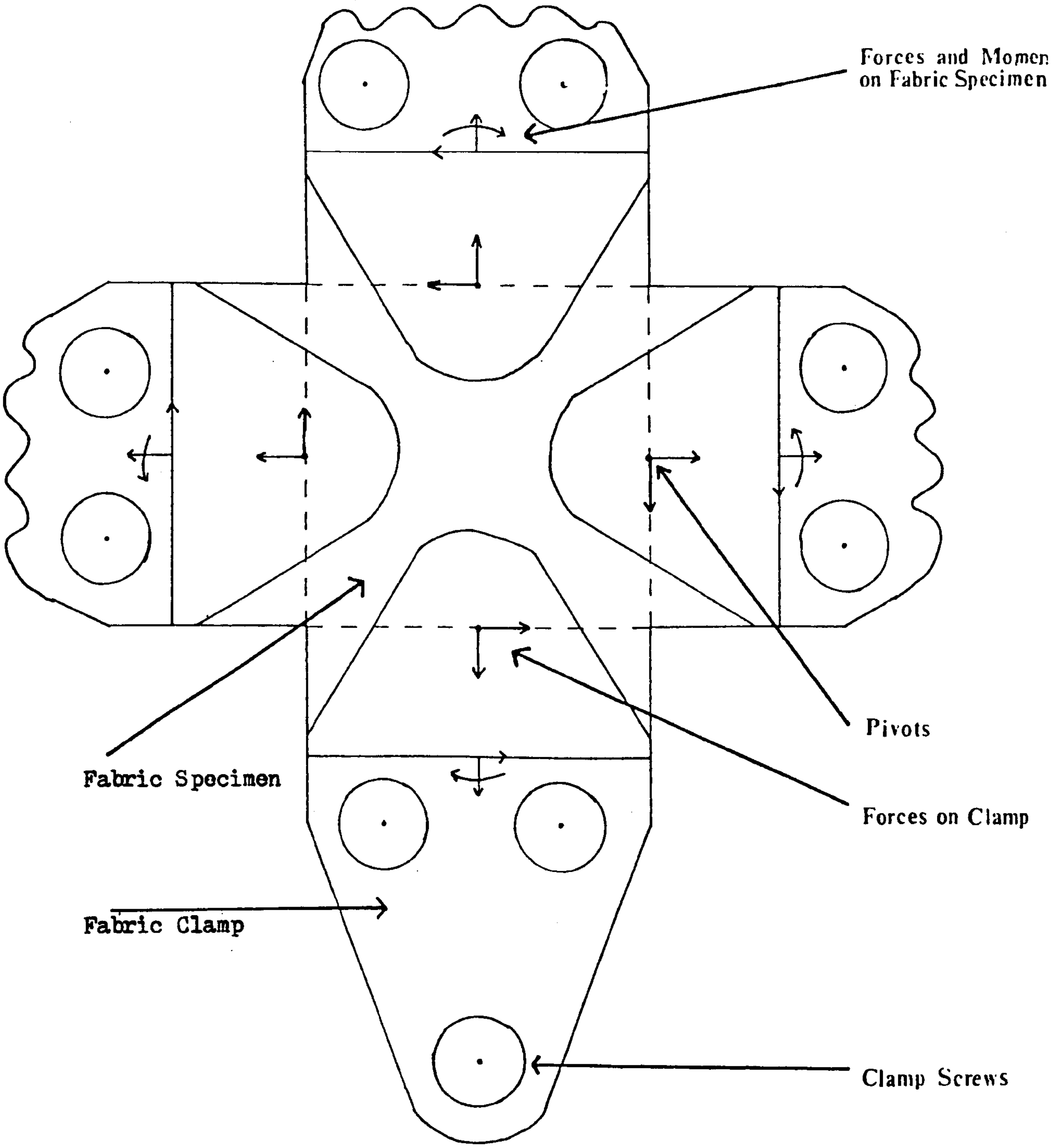
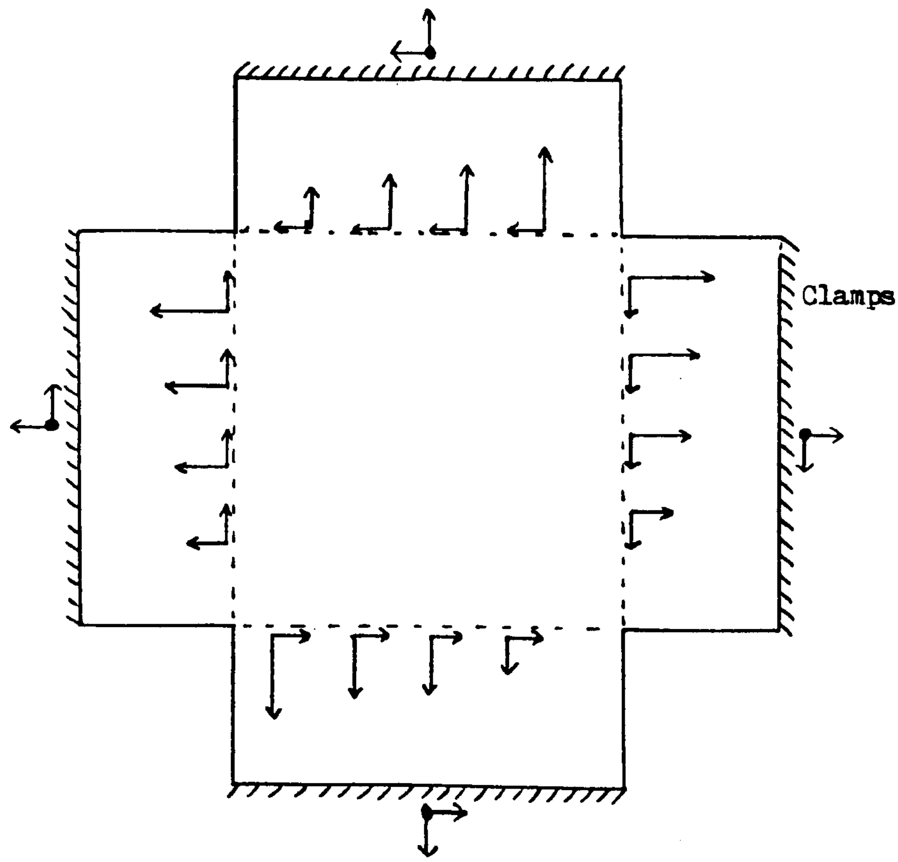
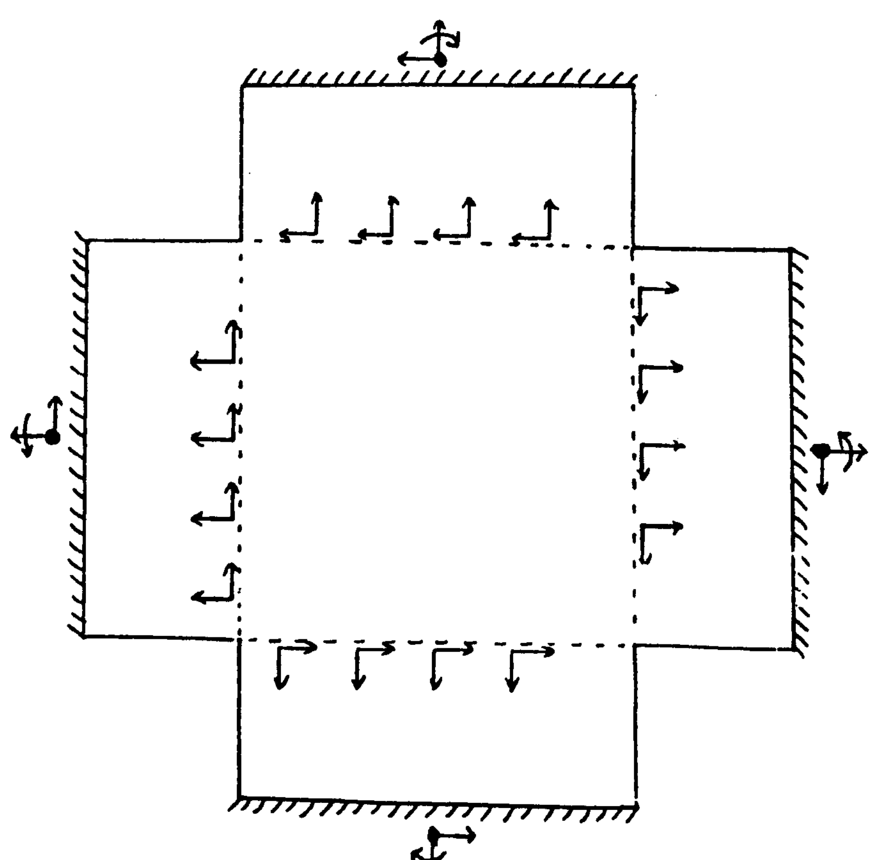


Fig. 6.16 Forces and Moment applied to Fabric Specimen, also showing position of Clamp Pivots.

"from Yendell (169)"



(a) Specimen with Biaxial Tensile and Shear



(b) Specimen with Biaxial Tensile and Shear and Moment Applied to Clamps

Fig. 6.17 Stress Distribution at the Edges of the Square Test Region (from Yendell [168])

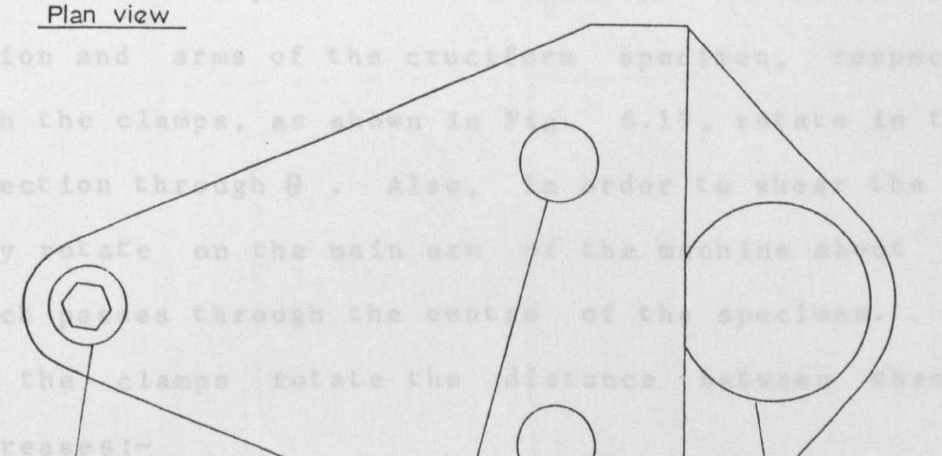


Fig. 6.18 The Automate/Yendell Pivot-Clamp System

"from Yendell (168)"

Fig.6.19. The separation of the pivots is "b" and the distance from the pivots to their clamps is "a". These distances correspond to the dimensions of the central test region and arms of the cruciform specimen, respectively. Both the clamps, as shown in Fig. 6.19, rotate in the same direction through θ . Also, in order to shear the fabric, they rotate on the main arm of the machine about an axis which passes through the centre of the specimen. However as the clamps rotate the distance between them, "t" decreases:-

$$t = \sqrt{(((a\cos\theta)x\ 2)+ b)^2 + ((a\sin\theta)x\ 2)^2}\ .$$

This causes a reduction in the tensile strain energy in the yarns between the two clamps.

This problem will be greatest with large values of the ratio a:b and with fabrics which shear easily, but have a high initial Young modulus. Yendell (169) recognised that this apparatus could only be used with confidence, providing the fabric shear stiffness was greater than a certain minimum. He tested sailcloth, which is generally stiff in shear, and used a small a:b ratio. This could have caused problems with the strain homogeneity as large values of a:b are desirable as they allow strain parallel to the clamps to be ignored.

Despite these problems this apparatus still appears to be one of the only routine biaxial tensile and shear testers in general use. Probably this is due to its low price, simplicity, and ease of use.

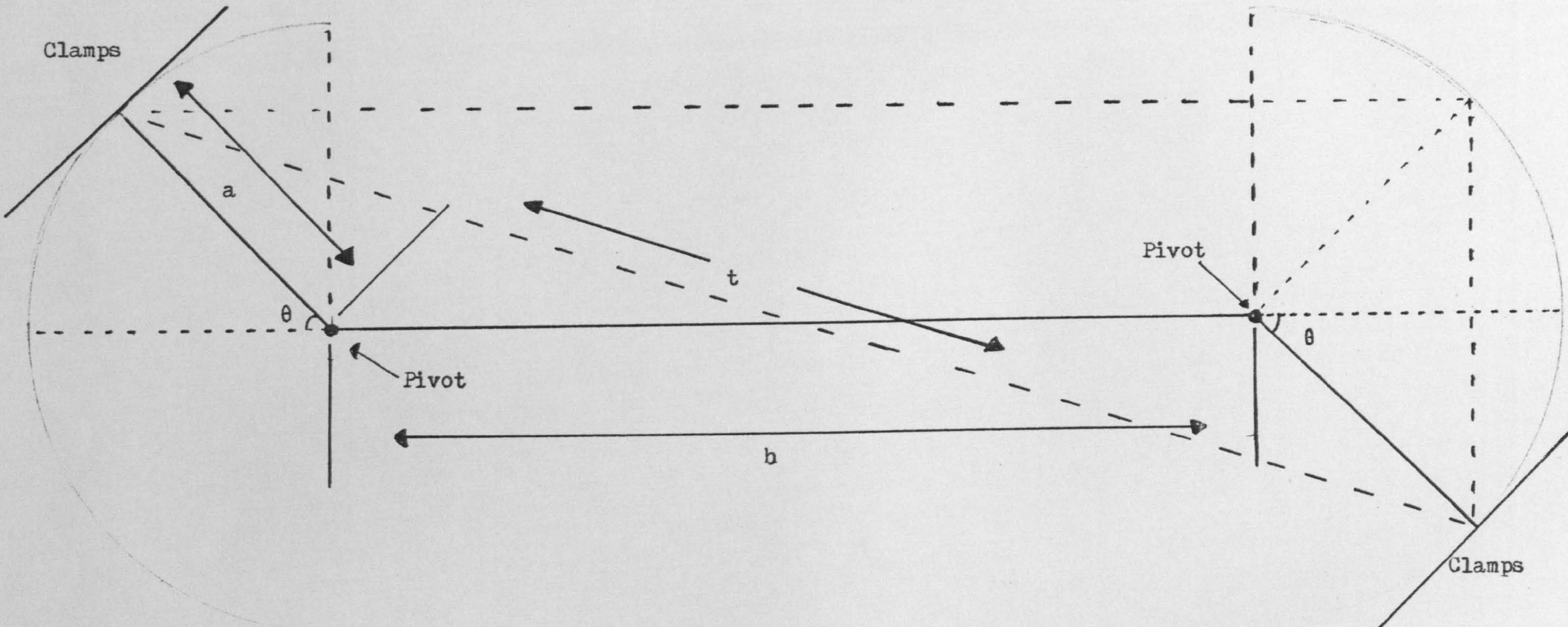
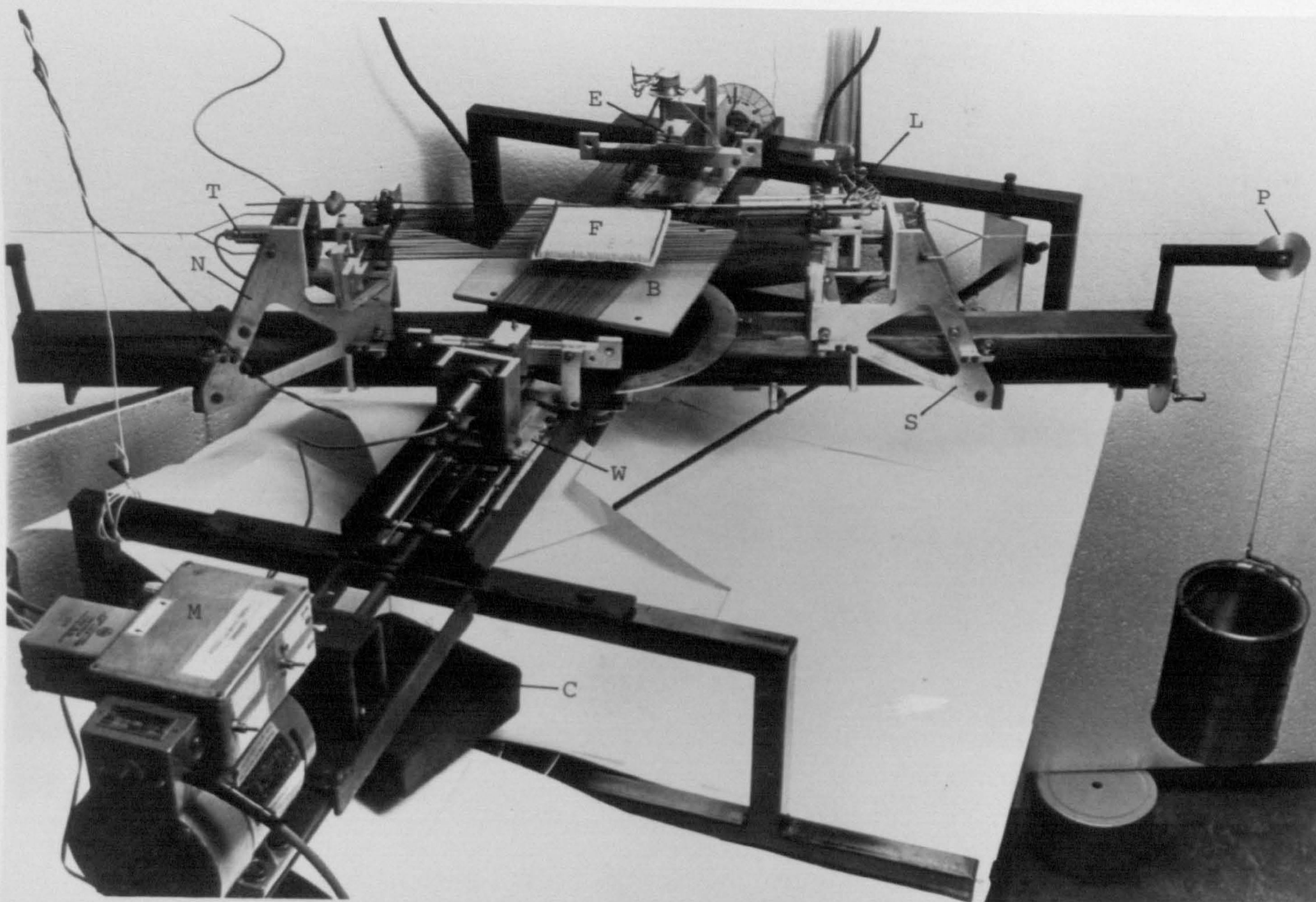


Fig. 6.19 Automate/Yendell- Geometry of the Pivot Action of one Pair of Clamps

(After Bassett (108))



B - Base plate
C - Counterweight
E - East crosshead
F - Specimen
L - LVDT displacement transducer
M - Motor
N - North crosshead
P - Pulley
S - South crosshead
T - Force transducer
W - West crosshead

Plate 6 - Bassett's biaxial tensile and shear tester. (from Bassett[108])

6.4.2 Bassett's (108) Test Rig

This device was built in the School of Textile Technology, U.N.S.W., and was intended for the testing of apparel fabrics. It operates on the same principle as Yendell's (169) apparatus, in that one of the tensile loading systems rotates about the centre of the other in a scissor-like manner (see Plate 6), but Bassett (108) improved on Yendell's (169) system of ensuring that no moments were imposed along the edge of the specimen test region. Bassett's (108) device used an initially square specimen, rather than a cruciform specimen, and the specimen orientation could be varied, providing an extra degree of freedom in stress and strain. Bassett (108) also developed a system of gripping the specimen which attempted to solve the problem of strain restraint parallel to the clamps. This was accomplished by gripping the four edges by a row of bent wires, in the form of hooks, which were pushed through the fabric, and could move freely in the transverse direction. Bassett (108) claimed his instrument was the first to combine grips which allow transverse straining, with the ability to apply shear stress.

Unlike the Automate/Yendell, this instrument was to a certain extent electrically controlled, using an electric motor to apply force or displacement in one (the so-called "E-W") arm, and having electrical means of measurement, with a microprocessor collecting the data obtained when monitoring the necessary five variables. The other ("N-S") arm was manually controlled using weights and pulleys to apply a fixed force, or using a left and right-hand threaded worm to achieve displacement. This arm could be skewed to a fixed angle to allow fabric shear. Bassett (108) pointed out that this had advantages over the Yendell (169) method which applied a torque and measured the shear angle. His method avoided the need to measure a small torque acting on a heavy member, which could be difficult, due to friction and the need to keep the machine level. Control of the skew of the "N-S" arm was also carried out manually.

Although the Bassett (108) device introduced a number of original ideas which will aid the development of biaxial tensile and shear testers, it did suffer from a number of problems. During shear the specimen in this apparatus was free to rotate, and it would do until the condition of moment equilibrium was satisfied. Due to this the edges of the specimen were not parallel to either of the tester arms, and this introduced a complexity to the analysis of the test data, which did not occur in the Automate/Yendell.

Another problem with this device was due to the wires which are pushed through the edge of the specimen in order to grip it during testing. These wires are 0.457mm in diameter and are spaced every 1.27mm across the 10.0cm square specimen. This means that the cross-sectional area of approximately eighty wires must be accommodated across the edge of the 10.0cm specimen. This could cause compressive strains of up to 36%. However, Bassett (108) argues that this can be limited by the wires finding their way into interstices between the yarns, also, in the first version of the tester alternate wires differed in length by 1.6mm so that two rows of wires were used. This problem may not be great in a relatively loosely woven apparel fabric, but, may cause problems in more tightly woven industrial fabrics. The wires also suffered from the problem that during a test when the specimen edges extended or contracted, the wires would diverge or converge respectively. Apart from restricting these deformations to a certain extent, the distance between the clamp faces and the edge of the test region was altering, complicating the analysis of data. Bassett (108), however, recognised this problem and stated that this effect could be ignored.

Specimen preparation time could also be a problem with this instrument. There were over three hundred wires to push through the fabric, and although there were aids to speed this process up, it must still have been laborious. Mounting the specimen, and making sure it is correctly aligned, could also be difficult; and there may be a settling in of the wires after the test begins. Bassett (108) was aware of this and allowed a dummy-run so that some settling in of the wires could take place, but this appears dubious as results would not be taken from the first test, and this dummy-test may affect the fabric properties to some extent. Another problem with the wires is the difficulty ensuring that during their manufacture they are all the same length, and that after use they do not become bent or twisted. Bassett (108) also stated that the maximum stresses which could be applied with this system was determined by the elastic flexure of the grip wires, and the small vertical distance between the fabric plane and the horizontal part of the wire (see Fig.6.20), causes a bending moment to arise in that part of the wire, when tension is applied to the fabric. This results in rotation of the wire hook which passes through the edge of the specimen, so that the fabric may slip off.

Another important requirement in a tester of this nature is that the centre of the specimen is maintained over the axis of the pivot, in the centre of the two main arms. This ensures that shear strains are symmetrical about a point of zero strain, and that they are uniformly distributed over the test region of the specimen. This problem remained unaddressed in Bassett's tester.

Therefore, this device although basically sound in its concept has a number of potential difficulties. It would not be practical for routine industrial use as the time required for setting-up and aligning the specimen may be too great. It is only really suitable for apparel fabrics,

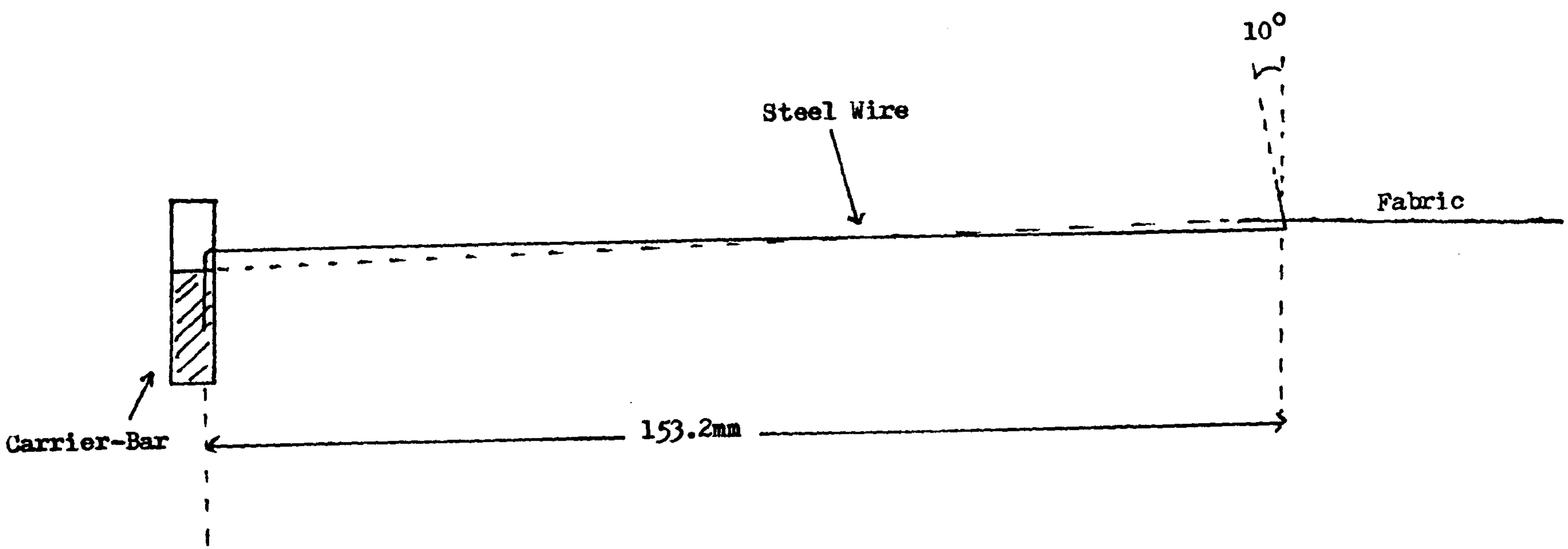


Fig. 6.20 Grip Wire- Bassetts Biaxial Tensile-Shear Tester

"from Bassett[108]"

many industrial fabrics may be too tightly woven or tough to push the grip wires through,(though the method of gripping may be able to be modified), and the device was only designed to apply a maximum force of 50N.

The Automate/Yendell in contrast to this device is more attractive to industry as it is a cheaper, simpler, more compact and tidy design, and is quick and easy to use. Although the results may not be as accurate, the advantages are often more important to industry and the Yendell (169) machine is capable of applying loads of 100kg, which are much more realistic for industrial fabrics. The Bassett (108) apparatus appears to be of little use outside a research laboratory, because its results may be of little value if sufficient time and care is not spent in preparing and mounting the specimen.

6.5 Biaxial Tensile and Shear Testers Which Operate By the Deformation of a Rectangular Test Frame Which is Pivoted at its Four Corners

This type of apparatus takes two basic forms. The first was the type which was described by Skelton (171), Alexandroff (172) and Culpin (173), and involved clamping a rectangular specimen (Culpin used a cruciform specimen) of fabric along the full length of all four edges, while mounted in an initially rectangular test frame, which was pivoted at its four corners.

The second type used a cruciform specimen, which was mounted in clamps, which were fixed to the centre of the four sides of the same type of rectangular test frame. This form of tester was described by Berka and Minster (174) (see Fig.6.21), and was developed as one of a pair of testing machines at the Institute of Theoretical and Applied Mechanics at the Czechoslovak Academy of Sciences, Prague. This device was designed to simulate situations encountered in the skins of air-supported structures and roofing materials of suspended membrane roofs.

6.5.1 The Apparatus

Skelton (171) described the "picture-frame" test, which involved clamping the fabric specimen along the full length of all four sides in a rectangular test frame, as shown in Fig. 6.22. He did not, however, describe any specific testing hardware, but was mainly concerned with the theory of testing triaxial fabrics in this type of apparatus.

Alexandroff (172) briefly described an instrument which was designed and fabricated by I.L.C. Dover, Delaware. This was also for testing triaxially woven fabric, which was to be used as an aerostat material. This instrument was similar in principle to those described by Skelton (171) and later by Culpin (173), and during operation it could be mounted in a standard extensometer and distorted by extending one diagonal, performing a shear

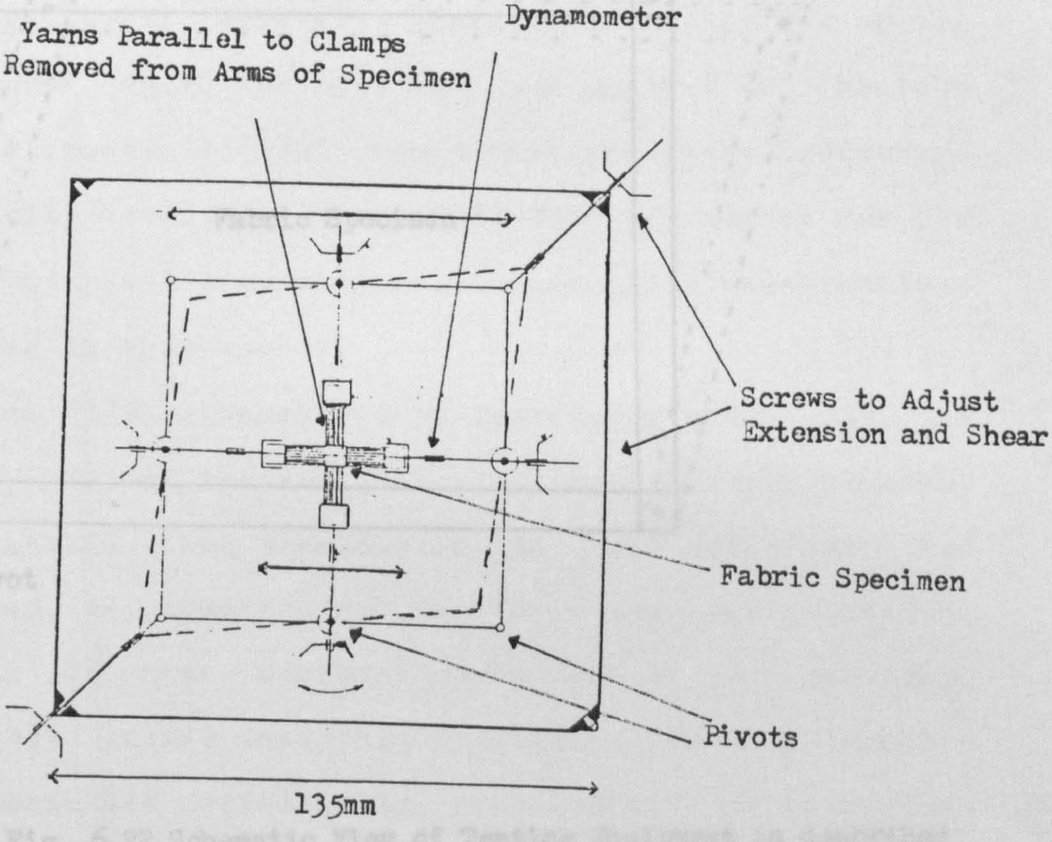


Fig. 6.21 Schematic View of Testing Equipment for the Plane Stress States.

"from Berka and Minster[174]"

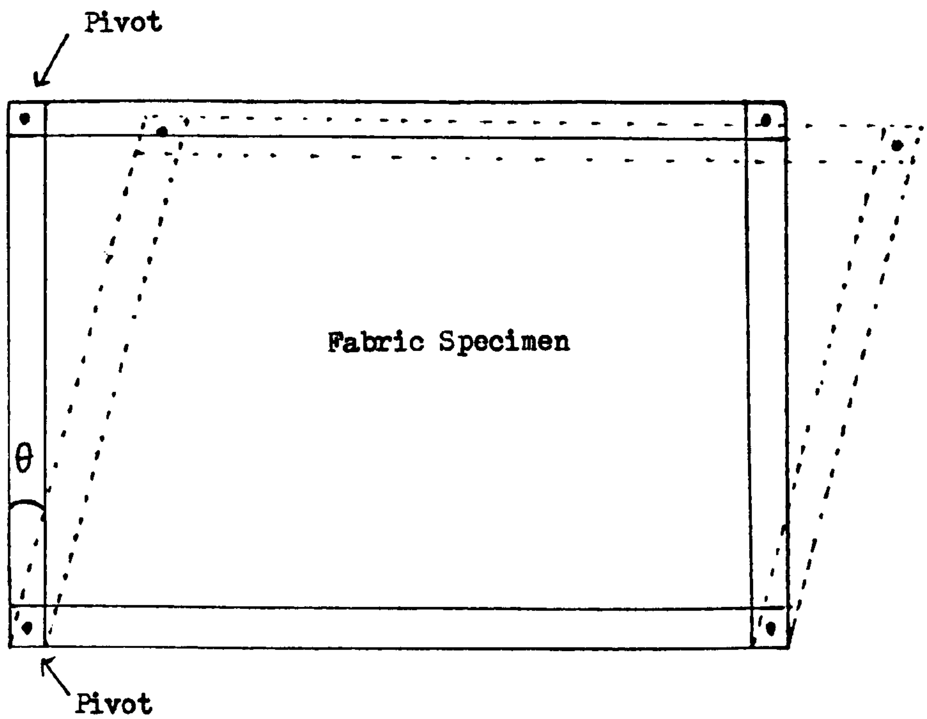


Fig. 6.22 Schematic View of Testing Equipment as described for Skelton's "Picture-Frame" Test.

"after Skelton[171]"

test under predetermined tensile strains. As stated by Alexandroff (172) , the purpose of this test apparatus was to measure the amount of load required to deform a fabric in the bias direction through a given length, 0.5in.(1.27cm) in his particular case. In the description of this instrument, however, there is no indication of the tension under which the specimen was mounted in the test frame. Alexandroff (172) found that the shear resistance in triaxially woven fabric was 250%-300% of that of two-ply biased fabric and biaxially reinforced film construction, when tested in this device.

Culpin (173) described an instrument which was, as mentioned, similar to those described previously. However, he recognised that extension in one diagonal was accompanied by compression in th other and that the shortening of this diagonal could result in buckling. Culpin (173) stated that this buckling could be eliminated if the fabric was sufficiently "pre-stretched". He claimed that this could be done without significantly altering the shear properties of the fabric. Therefore, this apparatus included a pre-stretching jig in which the desired tensile strains could be applied and held, while the specimen was clamped in the test frame.

In general this type of apparatus appears viable. However there are a number of possible sources of error. The test, as described by Skelton (171), is very sensitive to misalignment of the specimen during mounting. Also, there could be undesirable complications due to relaxation of the fabric during the time period between pre-stretching and transfer to the test frame. Bassett (108) states that another problem with Culpin's (173) apparatus is caused by the position of the pivots at the four corners of the test frame. He claims that for homogeneous strain to be achieved, the pivots should be at the inside edge of the clamped corners of the specimen (see Fig.6.23). The position of Culpin's (173) pivots resulted in inhomogeneity of strain at the corners of the specimen, causing buckling, which could only be limited by considerable pre-stretching. Apart from having the pivots at the inside of the corners of the test frame, Bassett (108) also stated that the tester would require that the clamped edges be sharply defined so that there was no fabric slippage near the edges of the clamped region. He suggested that the clamps should incorporate force transducers to enable tensile stresses to be calculated.

Berka and Minster (174) suggested a variation of the devices already mentioned. Their apparatus was capable of adjusting the biaxial tension of the specimen, while mounted in the shear testing frame (see Fig.6.24). The biaxial tension and the fabric shear could both be adjusted by wing-nuts on screws, and the clamps which held the arms of the cruciform specimen incorporated force transducers.

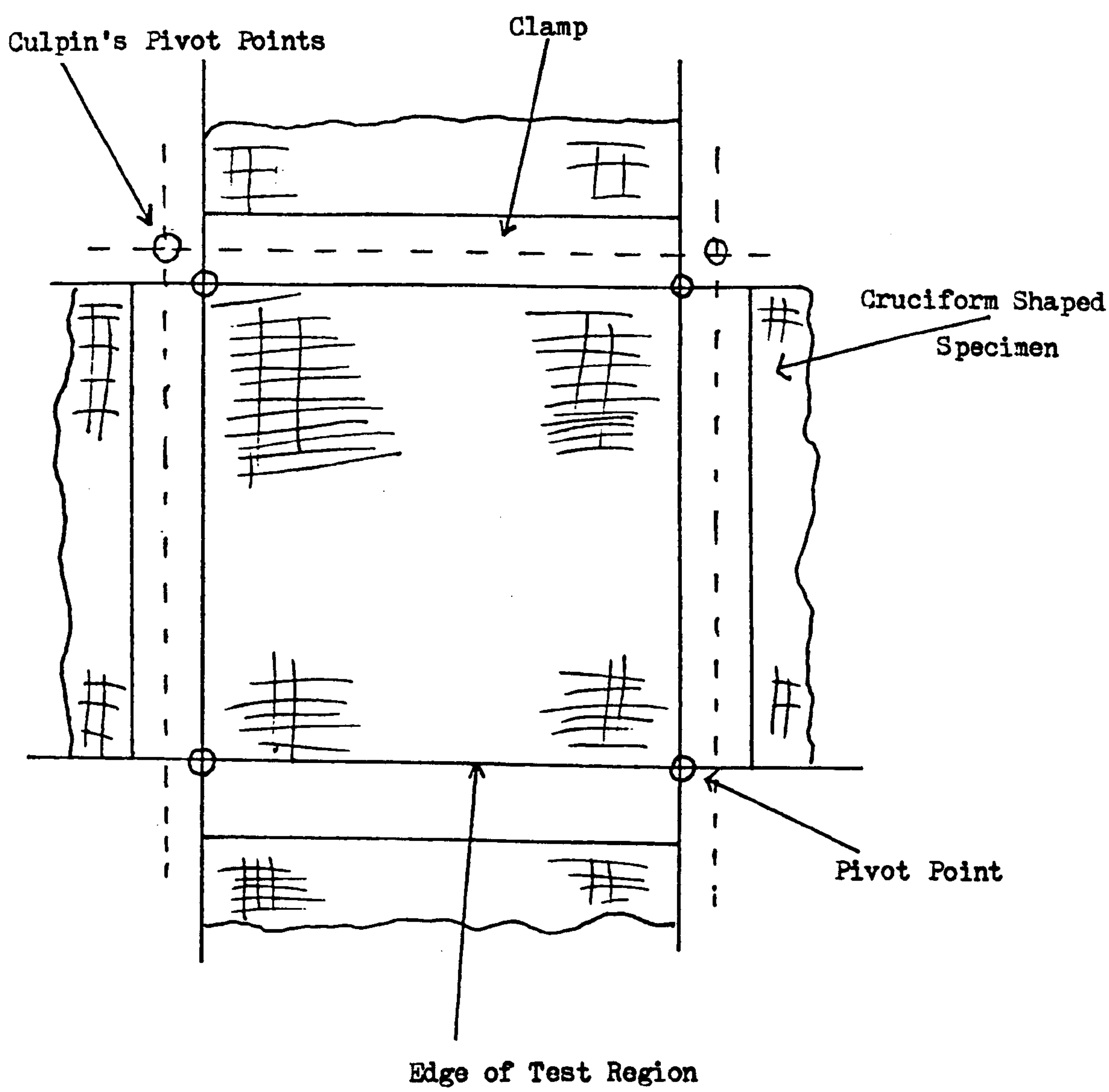


Fig. 6.23 Culpin's Biaxial Tensile and Shear Tester with Bassett's Modification

"from Bassett[108]"

SCHEMATIC VIEW OF BERKA AND MINSTERS APPARATUS

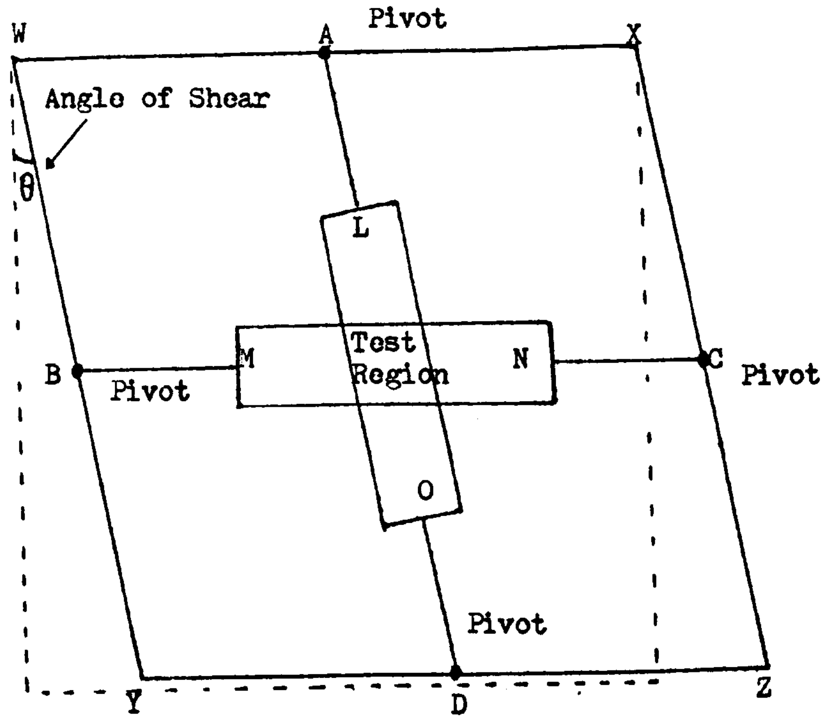


Fig. 6.24 Deformed Biaxial Tensile and Shear Tester with Clamps Free to Rotate.

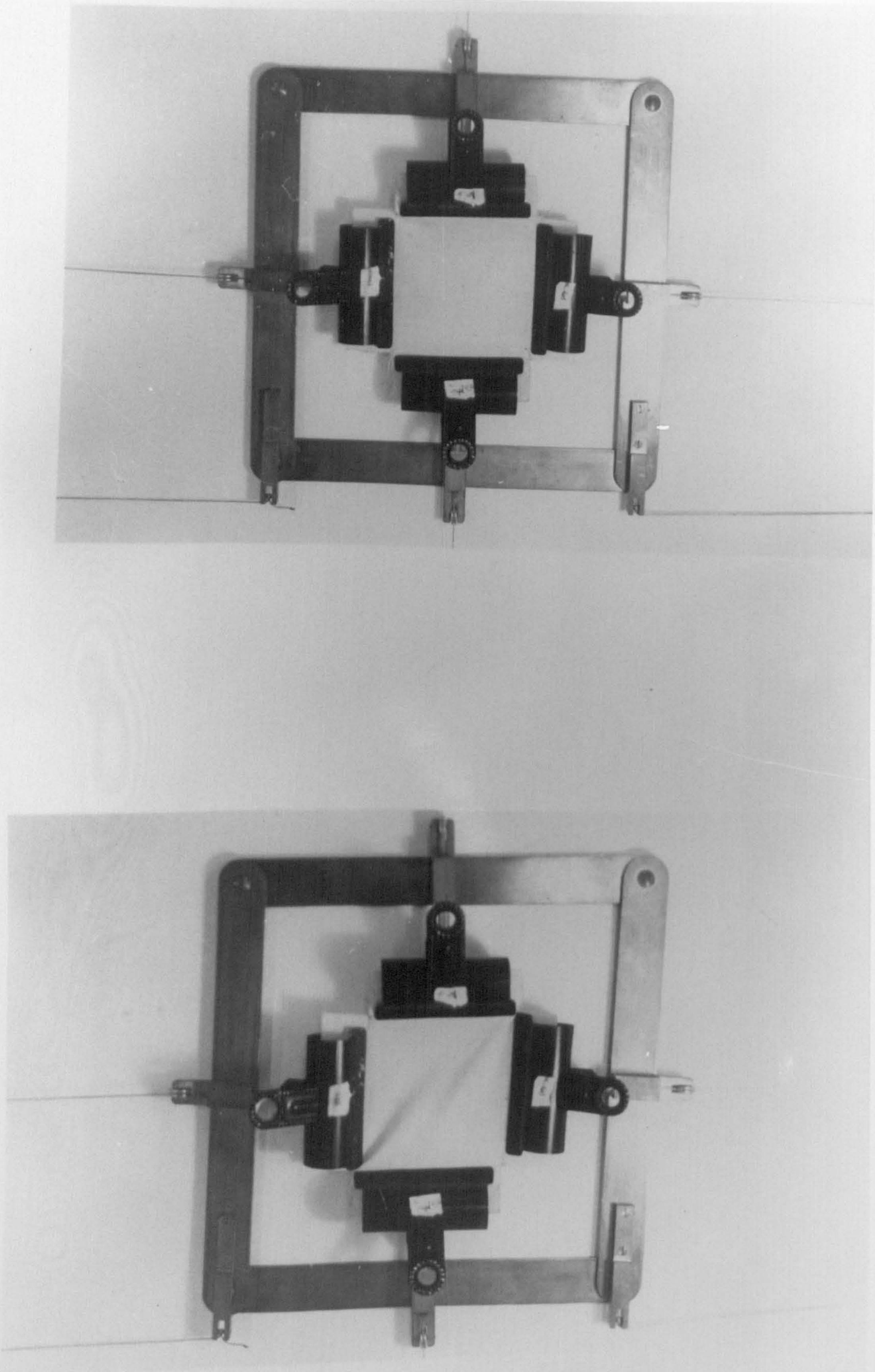


Plate 7 - Prototype biaxial tensile and shear tester designed in Leeds University, Dept. Textile Industries.
(a) Undeformed (above)
(b) Diagonal creases on specimen show inhomogeneity of strains during shear (below).

Deformation in the central test region of the specimen could be measured using photographic methods.

Prior to the discovery of Berka and Minsters (174) apparatus in the literature, the present author worked on the development of a similar tester which was conceived in the Department of Textile Industries, Leeds University (see Plates 7 (a) and (b)). Preliminary work was carried out on a prototype machine, but it was quite soon realised that it would not be satisfactory without a number of modifications (see Fig.6.25). In this type of tester it is very important, if deformations are to remain homogeneous in the central test region, that the centre of the specimen remains in the centre of the test frame. Also the edges of the arms of the cruciform specimen must remain at right-angles to the clamps as shown in Fig.6.24 rather than as shown in Fig.6.25(b). This means that the angle of deformation of the frame gives directly the angle of shear, and it also means that if creep occurs in the two axial directions during a shear test that the shear angle is not altered. Berka and Minster (174) made this possible, by quite simply pivoting the clamps at the point where they were fixed to the testing frame.

This method is more complicated than the previously explained system which operates by a scissor-like action. It requires more pivot points where friction can occur, and more metal, which involves moving more mass during a test.

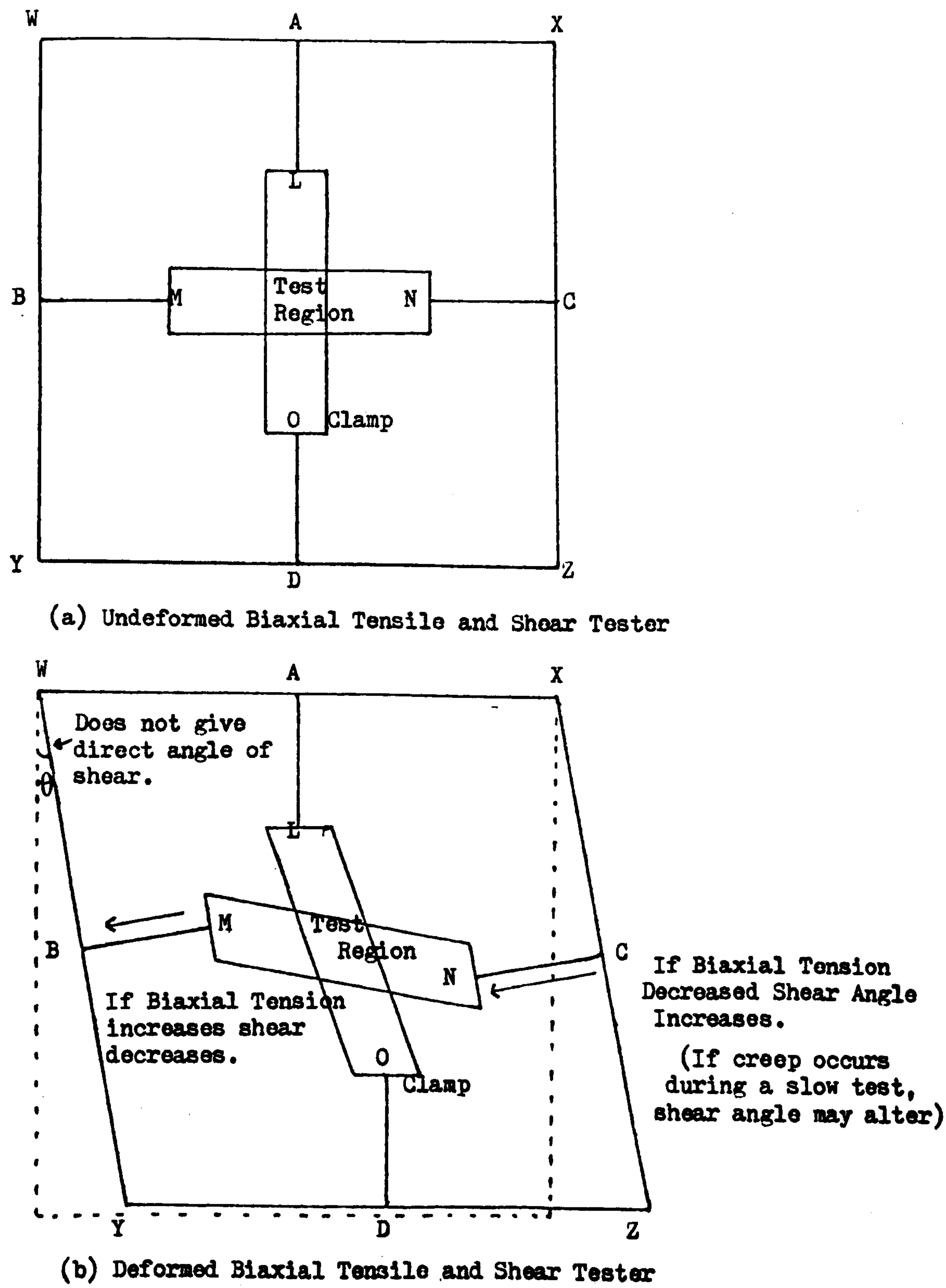


Fig. 6.25 Schematic View of Tester Proposed in L.U., Dept. of Textile Industries.

This system may also be more expensive to build as it would require more parts and labour. There are also no immediately apparent advantages with this system over the scissor-like system.

Conclusions

In general the choice of the most suitable type of testing instrument should be largely governed by the information sought. The uniaxial tensile test suffers from inhomogeneous stress distribution and the information gained may be limited, but the apparatus is relatively cheap and the test is quick and easy to perform. This type of test is still one of the most widely used for many fabrics, as it can easily be used to determine if a fabric meets the required minimum tensile strength. However, this type of simple test only gives the strength in any one direction, and is not very realistic, especially for the structural applications of industrial and engineering fabrics. In fabrics of this type loads are often applied in more than one direction at once, and as fabrics are anisotropic, designers must be aware of how the loads in each direction will interact.

Biaxial tensile tests were a logical progression from the simpler uniaxial test as textile fabrics are, as mentioned, rarely subject to a load in one yarn direction only. This type of test yields quite different results, and introduces complications to the fabric testing and analysis of results, which many manufacturers and designers still do not appear to consider worthwhile.

Relatively few testers are able to apply the three components of stress and strain simultaneously. The majority of those which can use cylinderical specimens, but there are a number of difficulties with this type of specimen, mainly due to problems with the seam and the time involved preparing and mounting. It may also be a consideration that shear in a curved membrane may not be exactly the same as that of a flat specimen in shear, however, there is no real proof of this. Yendell (169) and Berka and Minster (174) have developed devices which are easy to use and can apply three components of stress and strain to flat specimens of industrial fabric. Bassett (108) has also developed an apparatus which is more complicated, but is claimed to be an improvement on these devices as far as accuracy is concerned. It is, however, unsuitable as a routine fabric tester and for industrial fabrics, mainly due to the method used to mount the specimen.

A new tester is required which is as easy to use as the Yendell (169) apparatus, but which possesses many of the improvements of Bassett's (108) apparatus. It was therefore decided to design and fabricate an instrument which would attempt to fulfil these requirements. This instrument will be described later, and it is hoped that it may be used as a routine tester for light industrial fabrics, and that it may be the forerunner of a yet larger device. Ideally progress should be made towards some form of instrument which is useful to manufacturers and designers, and that will also bring a degree of consistency and some form of standard to this type of testing; but it is understood that it must be acceptable to manufacturers, and to those who are likely to use it.

CHAPTER 7

THE DESIGN OF THE LEEDS BIAXIAL TENSILE AND SHEAR TESTER

Introduction

Two basic designs of biaxial tensile and shear tester emerged from the literature survey described in Chapter 6, pin-jointed square frames, and rotating-beam, scissor type testers. The rotating-beam type of instrument was considered to be more suitable for the present work. The tester which was to be constructed had to be a serious laboratory instrument in its own right; it had also to form a small-scale prototype for a much larger machine which was proposed for the Clothworkers' Textile Structures and Mechanics Laboratory. It appeared that no ideal apparatus had previously been built which would meet all the requirements of the new device, however, by combining many of the favourable points from two previous testers (169) (108), and making a number of modifications and refinements, a piece of testing equipment was designed which it was hoped would be suitable for light industrial fabrics, and also form the basis of a yet larger machine.

The work involved in researching and producing the most suitable design, selecting and ordering components, and fabricating the apparatus with the required degree of precision, meant that the research and development of the tester was part of an "on-going" project. The time available was such that the present work had to be limited to producing the basic mechanical design of the tester, and constructing the hardware to the point where the instrument could be used in a simple way, leaving the development of sophisticated control, measurement and analysis techniques to a second research project. As a consequence, the mechanical design had to be capable of easy modification during subsequent development work.

Due to any unforeseen problems which might emerge during the fabrication of the new tester, and modifications which may be required at later stages in its development, it was decided that comprehensive and detailed formal designs would not be produced, for reproduction purposes etc., until the final working model was completed. This would allow greater flexibility during construction and would cause no unforeseen difficulties as the designer would be in close liaison with the engineer building the device. In the time and space available it was considered of greater importance to make future research workers aware of the principles and design features involved, rather than specific engineering details and dimension which may vary in later models due to such factors as workshop constraints, differing end-use requirements, or improved

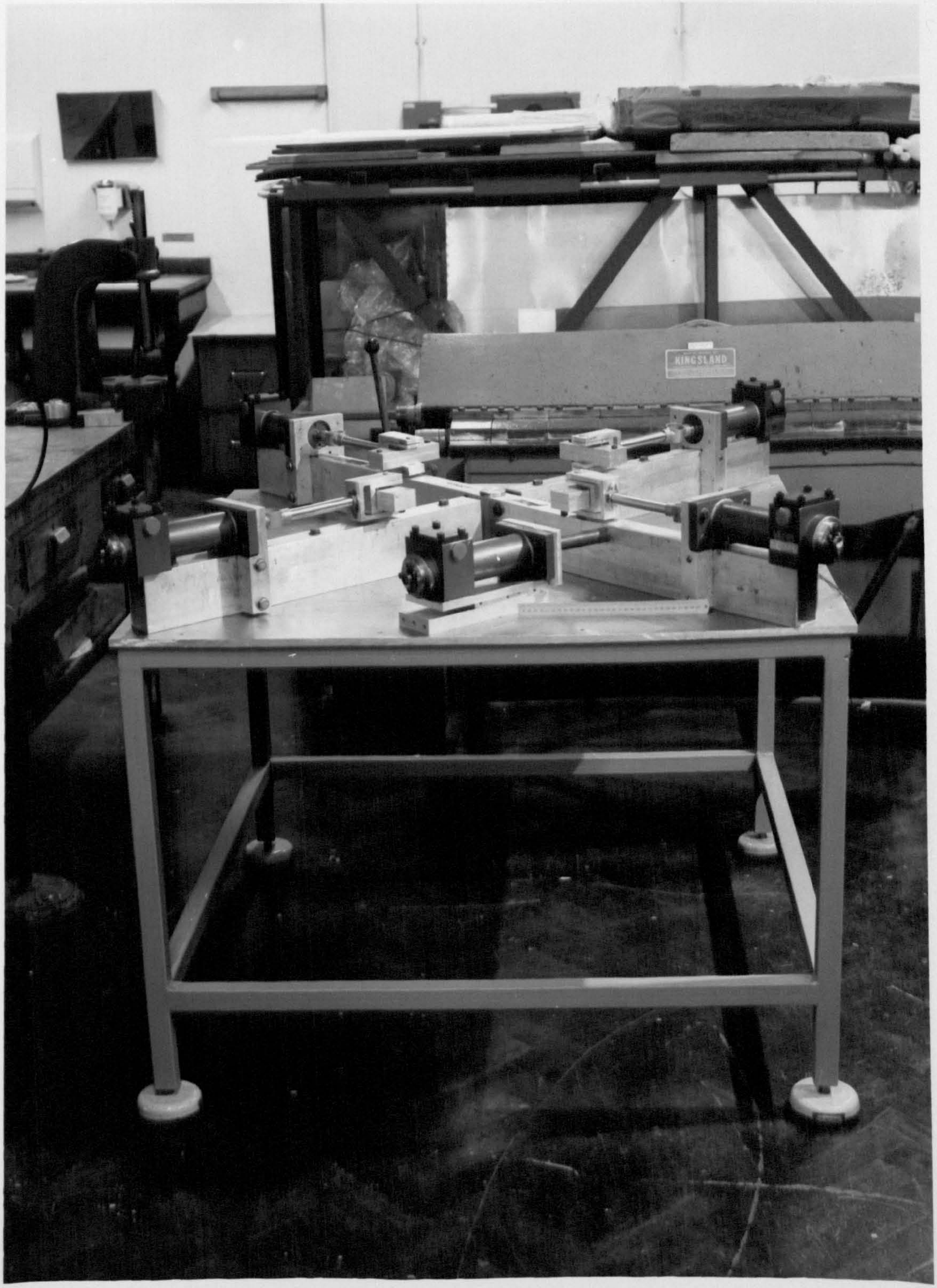


Plate 8 - General side view of new biaxial tensile and shear tester (not fully completed).

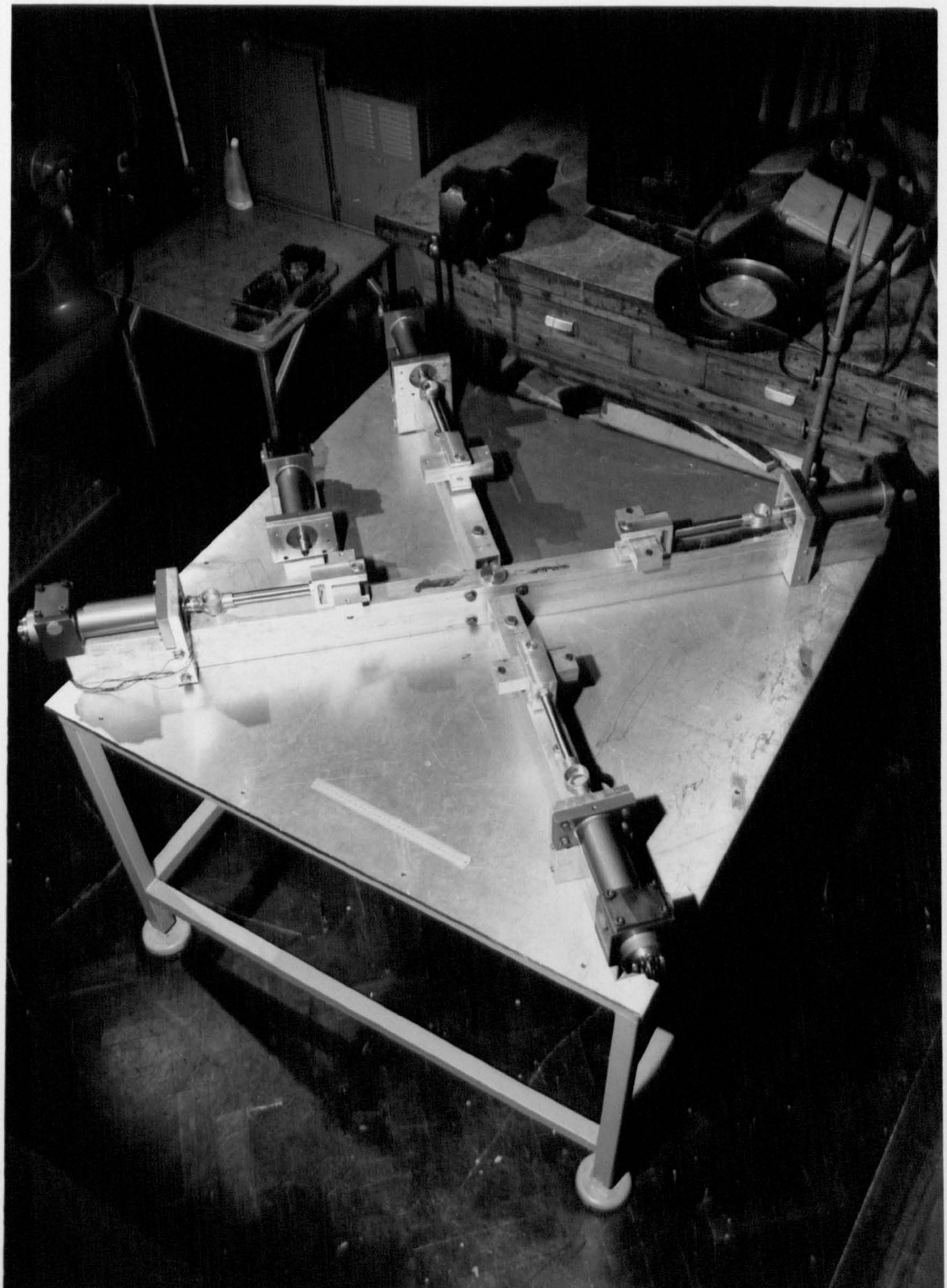


Plate 9 - View from above of new biaxial tensile and shear tester (not fully completed).

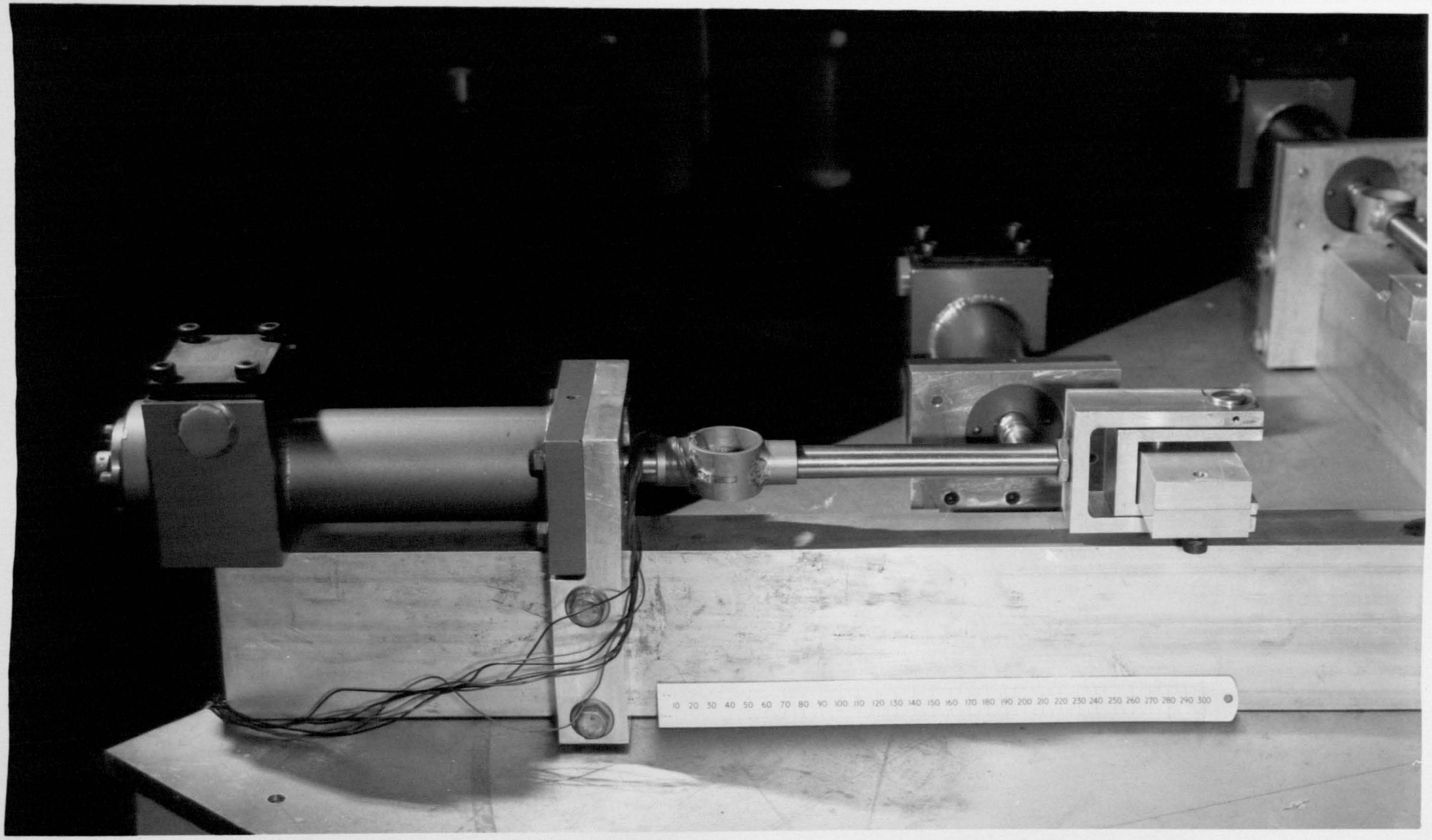


Plate 10 - Side view of one arm of the clamping system of the new tester (side force protection blocks not attached).

modifications. The forces involved in this tester are of a low enough magnitude that design techniques such as detailed stress analysis of individual members could be avoided at this prototype stage, if however, the design principles are considered of a high enough standard to merit the construction of a yet larger testing machine more formal design techniques will be required. At the present stage sketches shall be presented to explain most of the principles, more precise diagrams with measurements will be used to clarify certain of the more intricate features.

7.1 Outline of the Mechanical Design of the Apparatus

The new biaxial tensile and shear testing device consists of two main beams which are pivoted at their centres; one of the beams is free to rotate about the pivot so that shear deformations may be achieved, the other is securely fixed (see Fig.7.1 and Plates 8 and 9). Four actuaters, along with the fabric clamping systems are each mounted on the four ends of the two beams. It has been shown by Yendell (169), and later Bassett (108), that in order to achieve homogeneous stress in the specimen, the tester must not apply any couples to the edges of the fabric specimen (see Chapter 6). A clamping system similar to that used by Bassett (108) was therefore used in the present design; the clamps were pivoted about the centre of their faces (see Fig.7.2, Plate 10 and Appendix 4).

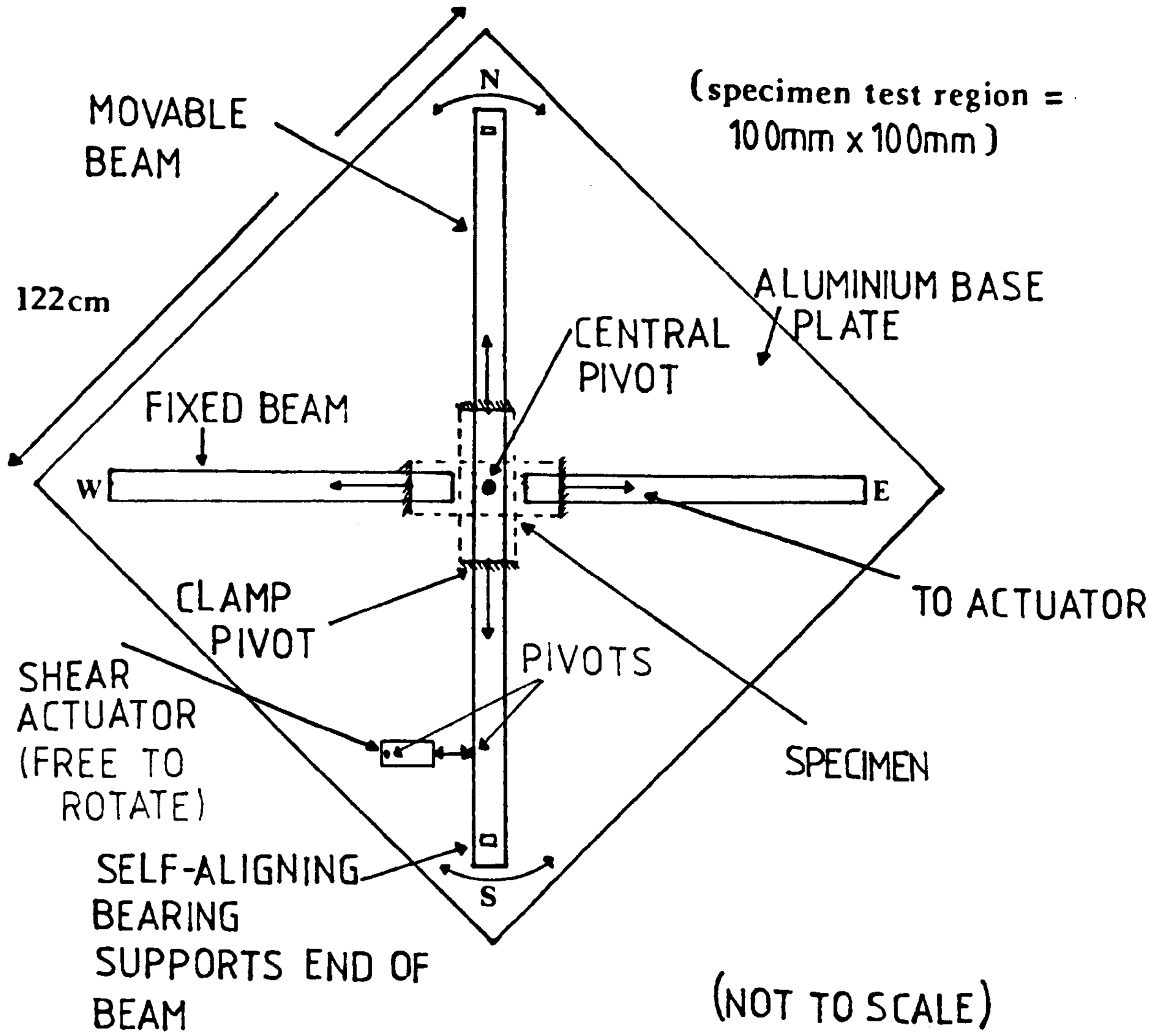


Fig. 7.1 Schematic Diagram of New Biaxial and Shear Tester.

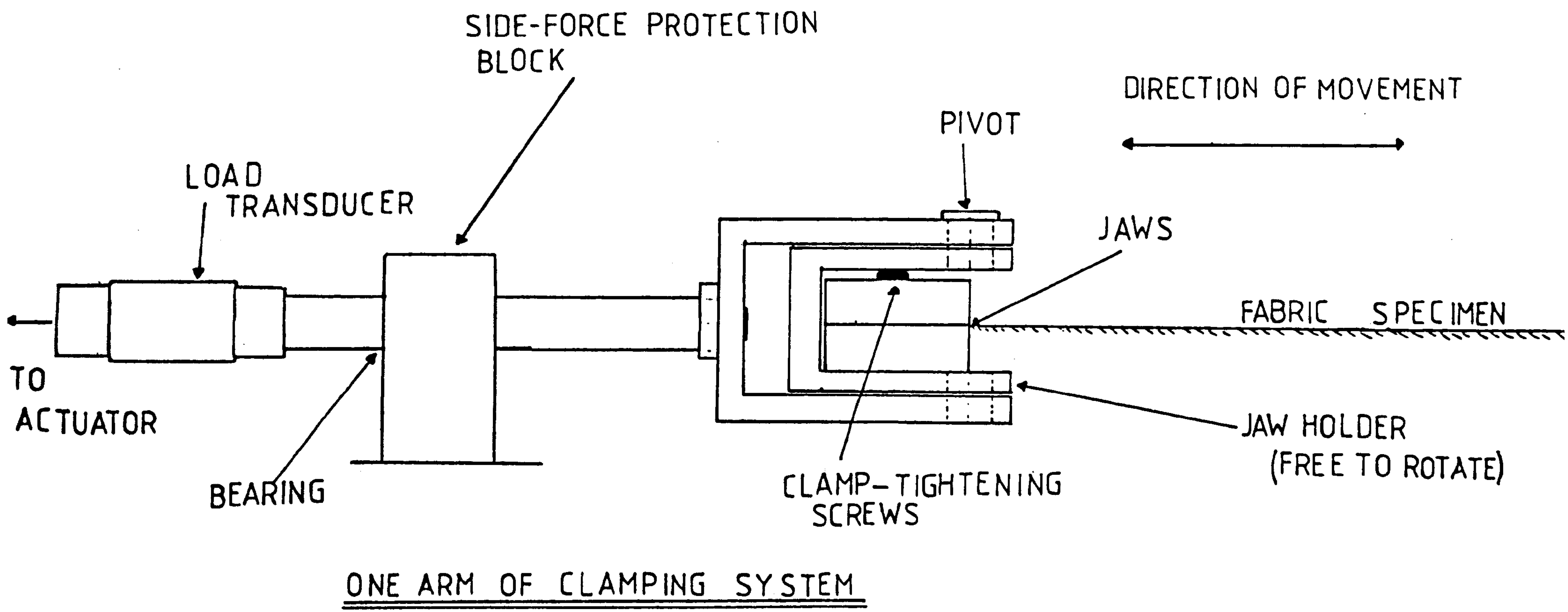


Fig. 7.2 Side View of One Arm of the Clamping System of the New Tester.

It was decided that the maximum tensile loadings which could be applied would be the same as those of Yendell's (169) apparatus, his tester was designed for use with light industrial fabrics, mainly sailcloth, and the loads which could be imposed appeared suitable for use with the new design. Bassett's (108) biaxial tensile and shear tester was designed for testing apparel fabrics, and was only capable of applying forces of 50N (approx. 5kg). On the new tester a maximum load of 100kg could be applied by each actuater, with specimen dimensions of 100mm x 100mm this gives a warp and weft stress of 1kgf/mm. If the specimen test dimensions were increased or decreased this would of course alter the maximum tensile stress levels attainable. Compared with the Bassett (108) tester these loads were relatively high, and therefore they ruled out the use of weights to load the fabric, such as used by Bassett (108) in his "N-S" loading direction.

When investigating fabric shear Yendell (169) applied a torque at the central pivot, about which one of the main loading systems could rotate, and then measured the shear angle. The problem with this method is that it is difficul to measure a small torque acting on a heavy beam, there may also be complications due to friction and the need to keep the apparatus level. Bassett (108) avoided this problem by having a screw and nut system which could control the angle of the movable beam. This allowed the shear angle to be fixed during a test run and the independent variable was normally displacement in the automated "E-W" direction. Load or displacement in the "N-S" beam was fixed during a test.

Bassett (108) was to a certain extent confined to this mode of test due to design restraints, as only one loading system was automated. A similar test facility would be available on the new design, but it was also considered necessary to have an automated shear cycling facility. Tests in this mode would be carried out in a fashion similar to that of Yendell (169), and it was hoped to minimize problems of measuring forces on the heavy beam by reducing friction, and by carrying out the tests at very low speeds to avoid inertia problems.

7.2 Machine Design Constraints

A number of factors had to be taken into consideration when designing the new testing device; the more important of these are as follows:

7.2.1 Maintenance of Symmetry

During fabric deformation it is essential that the centre of the specimen remains directly above the pivot about which the movable loading systems rotate, this is necessary so that symmetry is maintained in the test region. In the previous biaxial tensile and shear testers this situation was achieved by ensuring that the opposite sides of the specimen had tractions applied in reverse symmetry. Bassett (108) accomplished this by constraining the displacements of the "E-W" carrier-bars (clamps on new tester) to be equal, and either symmetrical loads or symmetrical displacements were then imposed upon the "N-S" carrier-bar pair. This procedure is probably sufficient when symmetrical displacements are imposed; however, if symmetrical loads are imposed, slight differences (eg. in friction) between the two sides of the apparatus are likely to cause the specimen position to drift during shear cycling, and symmetry to be lost. As great care is taken with the design and engineering of the clamps and loading systems to ensure the application of homogeneous stresses, it seems sensible to have some means of checking that symmetry is maintained. Symmetry problems may be caused during the fabrication of the tester, and by inhomogeneity in the fabric properties, or by variations between the load or displacement transducers which control the clamp actuaters. It is proposed in the new tester to have an electrical monitoring system to enable the operator to check that the centre of the specimen is over the central pivot axis, this may be achieved using a "joy-stick", as used with radio-controlled models or T.V. games. The joy-stick would have a pin fixed to the end of the control shaft and this would be mounted coaxially with the main pivot, the pin would then be inserted through the centre of the fabric specimen; if symmetry is maintained this pin should not move. It is not intended that this facility should necessarily be used during every test, but as it has not been used before an investigation is required into its usefulness. The information received from the joy-stick, if deviation from the centre occurs, may also be fed to the actuaters to instruct them to return the centre of the specimen to its original position over the axis of the central pivot.

7.2.2 The Fabric Clamping System

In the initial design the fabric clamping system was kept as simple as possible. Solid clamps of the most basic design were used, which could take specimens of up to 100mm wide; the arms of the cruciform specimen are also 100mm in length and it is intended that they should be slit from the edge of the test region to the jaws. The slits will stop before entering the jaws to avoid any clamping difficulties, and it is hoped that this would allow the shear resistance of the specimen arms to be ignored. The advantage of using this system is that it makes specimen preparation and mounting simple and quick.

Bassett (108) used a more complicated system to hold the fabric, this allowed transverse straining parallel to the specimen edges. His system involved the use of a square fabric specimen with a number of wires forming the arms of what will be considered as a modified cruciform specimen. These wires had the advantage that there was no shear resistance or extension in the arms, and this to a certain extent made analysis of the data less complicated than in the new tester, which uses a cruciform specimen consisting entirely of fabric (though the PVDF gauges allow further simplification of analysis). With the new tester it is possible to limit shear resistance in the arms by the method described, but extension of the yarns in the fabric arms cannot be so easily ignored.

Bassett (108) allowed each carrier-bar to rotate about a pivot which had its axis directly over the front edge of the carrier-bar. This system is also used on the new tester, which has the pivot axis over the clamp face, this causes further complications with the analysis of the data as the central test region of the specimen is free to rotate, so that edges of the test region are no longer parallel to the tester axes. The Yendell (169) tester did not suffer from this problem. Bassett (108) pointed out that specimen orientation allowed an extra, fourth degree of freedom, however, as only three are required, the extra degree of freedom could be used to extend the test domain, or to check consistency of the test results.

If friction at the pivots is ignored, the pivoting of the clamp-carriers means that the forces F1 and F2, which are the resultants of all the forces in the fabric strips which make up the arms of the cruciform specimen, can be considered to act along the central strip of each arm (see

Fig.7.3). It can be shown that it is possible to find the angles $\theta 1$ and $\theta 2$ from the values of measurable angles and displacements in the instrument. As this device is based on very much the same principle as the Bassett (108) apparatus, much of his work on the geometry of the specimen and the loading systems applies to the new tester. However, some modifications will be required, as in the new tester extension can occur outside the test region, in the specimen arms. In the Bassett (108) machine this distance was fixed by the wires.

7.3 Force and Displacement Application

Perhaps one of the most laborious tasks in the development of the new tester was the selection of the actuaters which would apply force or displacement to the fabric specimen. This was caused by certain of the unique features which were required in the new design; each clamp had to move independently to provide loads of up to 100kg. This particular feature fulfilled a requirement which was reported as a result of a learned discussion at Kilini.

Initially attempts were made to design actuaters which could be built in the engineering unit of the Textile Industries Department, however, apart from the time involved in constructing five actuaters, there were problems minimizing bulk and still achieving the load requirements, as the approach taken involved the use of

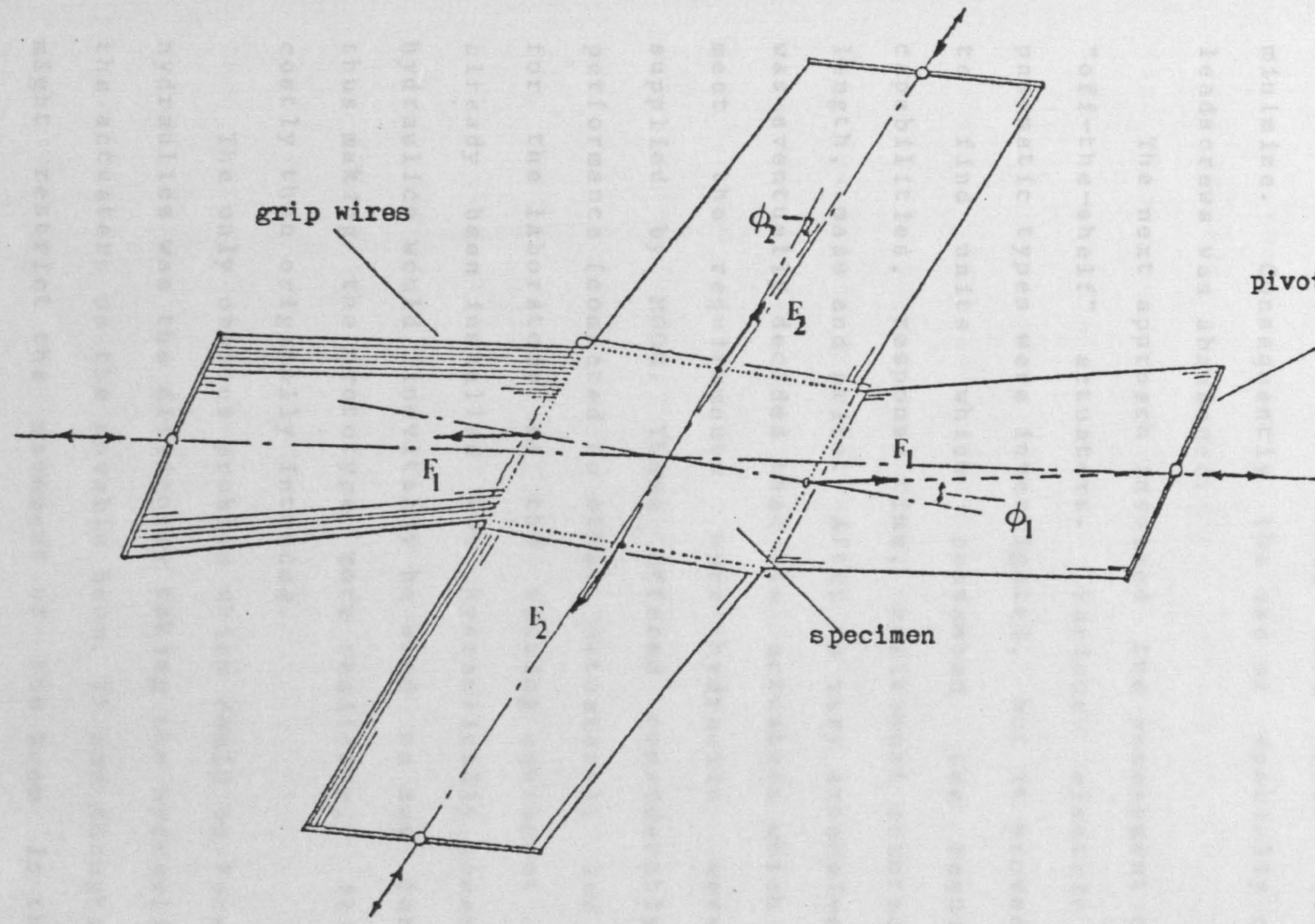


Fig.7.3 Schematic Diagram of the New Tester in Operation with the Specimen Mounted.
(from "Bassett(108)")

electric motors driving leadscrews. Backlash problems were also foreseen, which could have proved difficult to minimize. Consequently the use of specially constructed leadscrews was abandoned.

The next approach involved the assessment of numerous "off-the-shelf" actuaters. Various electric and even pneumatic types were investigated, but it proved difficult to find units which possessed the required load capabilities, response time, positional accuracy, stroke length, mass and price. After a very extensive search it was eventually decided that the actuaters which would best meet the requirements were hydraulic servoactuaters supplied by MOOG. These offered considerably improved performance (compared to other actuators), and were ideal for the laboratory as the testing equipment which had already been installed was hydraulically powered. Also hydraulics would inevitably be used on any larger model, thus making the prototype more realistic, if much more costly than originally intended.

The only obvious problem which could be foreseen using hydraulics was the difficulty taking the hydraulic pipes to the actuaters on the movable beam. It was thought that they might restrict the movement of the beam in the cycling mode, interfering with any force measurements which may be taken from this beam. Interference with the free movement of the beam will be minimized by the use of "rotating manifolds" (supplied by Weatherhead Manufacturing Co. Ltd., Hemel Hempstead), which include one pipe which is free to rotate. Two manifolds are required, one for the supply of hydraulic oil under pressure, the other for the return line. These manifolds will be mounted as close to the pivot axis as possible (to avoid any interference with the specimen they will be mounted on a framework above the centre of the specimen), and will be connected to the fixed part of the load frame by flexible hoses.

The method of applying shear force to the movable beam is quite simple. The fifth actuator is mounted as shown in Fig.7.1 and it is free to rotate about a pivot attached beneath its back end. A spherical bearing is fixed to the end of the actuator shaft and this can rotate on a vertical pin mounted on side of the movable beam. This system ensures that when the actuator shaft moves only tangential forces can be applied to the movable, "N-S", beam.

Forces in all the actuator shafts are determined by load transducers, which are fitted on the shafts between the actuators and the clamps (in four cases), and the movable beam. These transducers were constructed in the Departments workshops, and are essentially based on the "proving-ring" principle. The five transducers were constructed from sections of steel tube, and were each fitted with a full Wheatstone bridge of strain gauges.

7.4 Determination of the Strains with Respect to the Edges of the Specimen Test Region

7.4.1 Determination of the Extension Ratios of the Specimen Edges

The basic geometry of the new Leeds University biaxial tensile and shear tester is very similar to that of Bassett's (108) tester, however, there are certain important differences which have to be taken into consideration when determining the extension ratios of the specimen edges. Bassett used a square specimen which was gripped on each side by a number of rigid hooked wires. The new tester uses a cruciform specimen with arms of extensible fabric which is cut into a number of strips, and is subjected essentially to uniaxial extensions only. On the Bassett tester the wires could be considered inextensible, so that when operating in the biaxial mode, extension in the specimen could be measured directly by the displacement between the opposite carrier bars. In the new tester this is not possible, as the extensible arms are under uniaxial extension while the central test region is under biaxial extensions. It is therefore important to have a selective extension measuring device which can separate out the extension which takes place in the test region. It was for this reason that it was so important to have an extension measuring device which could be used in the central test region of the fabric specimen, and the availability a suitable device was paramount when considering the design of new tester.

In the new tester the newly developed PVDF extension sensor (see Chapters 5 and 6) is to play an important part. This new gauge allows extension measurement in the biaxial mode to be made easily, as the specimen edges remain parallel with the main beams of the tester. Two long thin strips (eg. 35mm x 2mm) of PVDF can readily be attached to the central test region of the specimen in the two yarn directions, and can be used to determine extension in this area.

7.4.2 Determination of Shear Strain with Respect to the Specimen Edges

The measurement of specimen shear strain is not so simple as that of the extension ratios when the tester is in biaxial mode. When the fabric specimen is subjected to shear deformations there can be difficulties as the central test region of the specimen is free to rotate, this means that the edges of the specimen are no longer parallel to the tester arms. Therefore shear strain cannot be measured directly from the angle of the skew of the movable beam, the PVDF gauges can also not be used as they are to stiff to measure shear strain directly (by being mounted in the bias direction, for example).

Bassett showed that specimen shear strain in this type of tester is given by:-

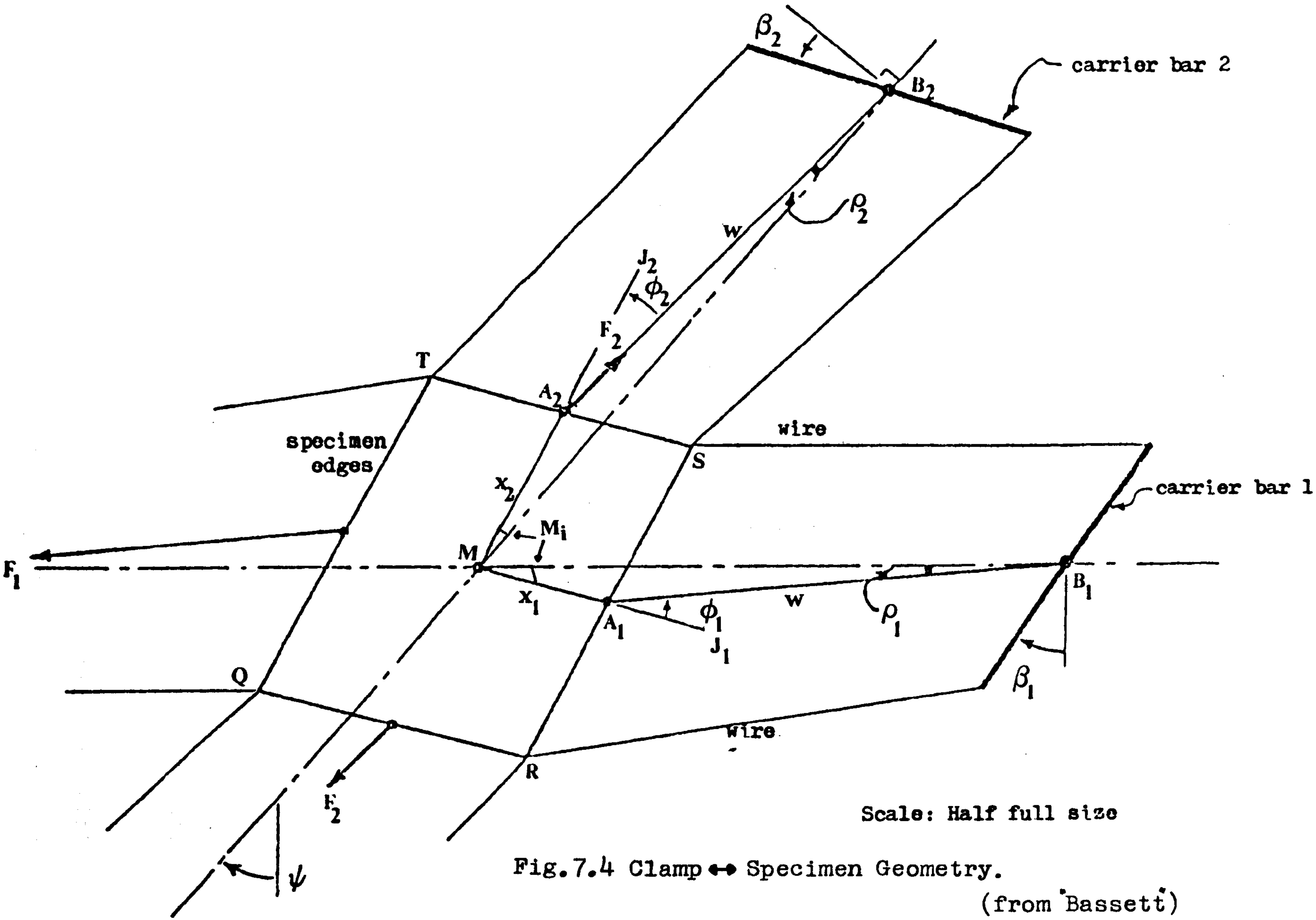
7.1..... $$\varepsilon_{12} = \frac{\pi}{2} - \left(M_2 + \left(\frac{\pi}{2} - \psi\right) + M_1 \right) = \psi - M_1 - M_2$$

This equation requires angles M1 and M2 to be known (see Fig.7.4). If, for convenience, the symbols used by Bassett are maintained, the known parameters of the triangles $A_i M_i B_i$ are:

- MB_i are known from the displacement of the jaws as determined by the position transducer in the actuaters.
- MA_i are known from the PVDF gauge mounted in the fabric test region.
- s is the initial length of the specimen edges over which the strains are to be calculated.
- a is the initial length of the specimen arms.
- ψ can be measured directly, or transmitted directly from a rotary displacement measuring device.
- $A_i B_i$ are known from the extension sensor mounted on the arm of the cruciform specimen.

  $(i = 1;2)$

These known parameters provide us with the lengths of three of the sides of the triangles $A_i M_i B_i$. Angles M_i can then be found quite easily using the cosine rule; the other angles which include ρ_i can be found also. Knowing these angles the specimen shear strain can then be found using equation 7.1. This method allows specimen shear strain to be measured using the PVDF gauges mounted in the yarn directions only.



Scale: Half full size

Fig.7.4 Clamp ↔ Specimen Geometry.
(from "Bassett")

Bassett did not have a suitable direct strain measuring device, although he does describe a prototype model of one which he attempted to design, this meant that some quite laborious mathematics had to be performed to extract the required dimensions and angles from the deformed specimen using the known parameters. The parameters which Bassett (108) knew were as follows:-

- β_1, β_2 and Ψ , transmitted directly from the transducers
- MB_1 was calculated from the displacement of carrier bar pair 1 (E-W), the independent variable
- MB_2 was calculated from the displacement of carrier bar pair 2 (N-S), output of the LVDT transducer
- A_iB_i = w(i=1,2), (w was the length of the grip wires)
- s was the initial length of the specimen edges over which the strains were to be calculated

(because of the "edge-effect reduction system" which Bassett used the strains were calculated over a longer edge length than the forces. Forces were only measured over the central part of each edge)

As can be seen Bassett needed to know the angles β_i , he also knew the fixed length, A_iB_i , of the grip wires; using the PVDF extension sensors avoids the need to have transducers to measure the angles β_i . Bassett used potentiometers to measure the carrier bar rotation, β_i, as well as the skew of the movable beam, Ψ . He points out that there were many problems with these transducers as they exhibited small periodic irregularities in the output.

Although the use of the new extension sensors will greatly simplify the calculations required there may be difficulties due to localized stiffening of the fabric. It is hoped, however, that this problem can be minimized by using long thin strips of PVDF, and also by confining tests to stiffer fabrics such as sailcloth or geotextiles. The use of this type of gauge may also increase the test time. This is not desirable, especially for industrial use, but this problem may be overcome to a certain extent by improving the mounting procedure (possibly the PVDF strip could be mounted between two pins which could be more easily attached to the fabric). There may also be problems making some form of switching device so that one charge amplifier can be used to take sample readings from the four sensors which are mounted on the specimen, rather than having to use four costly charge amplifiers to take continuous readings.

7.5 Calculation of the Forces on the Specimen Edges

It can be seen from Fig.7.5 that the only forces assumed to be acting on the specimen are F_1 and F_2, which are equivalents of the sums of the forces on each fabric strip in each arm of the cruciform specimen. They are assumed to act along the central strip, A_iB_i. When the movable beam is skewed the forces measured by force transducers are the components along the axes, MB_i in Fig.7.4. Firstly these must be corrected by dividing by $\cos\beta_i$, giving the magnitudes of the forces F_1 and F_2 acting along A_iB_i.

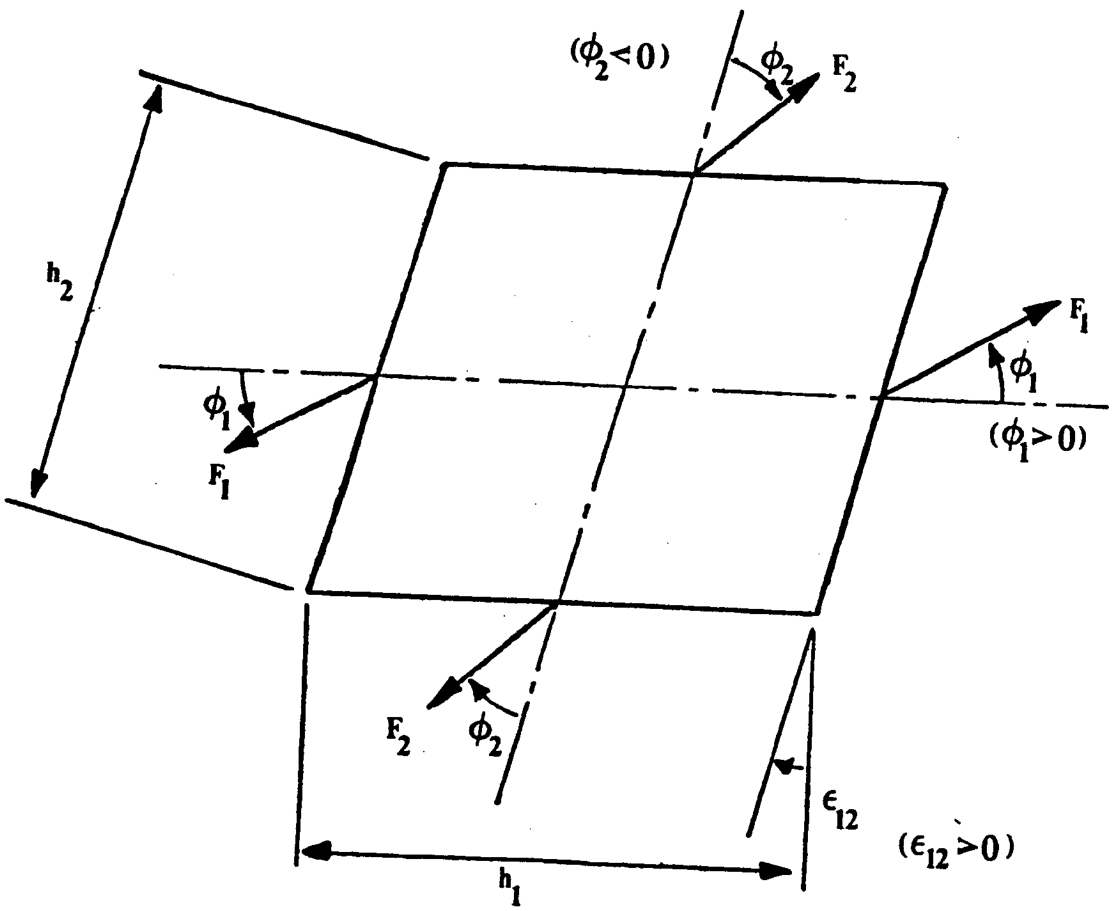


Fig. 7.5 Forces on Edges of the Specimen Test Region (shows sign convention).

(from "Bassett")

The directions $\emptyset_i$ of F_1 and F_2, must also be calculated. Bassett at this stage adopted the sign convention, anticlockwise $\equiv$ positive.

It can be seen in Fig.7.4 that if MA_i is extended to J_i, then, $\emptyset_i$ are the triangles $J_i A_i B_i$. From triangles $A_i M_i B_i$:

$$\emptyset_i = M_i + P_i$$

7.5.1 Stresses with Respect to the Specimen Edges

In the calculations the lengths of the strained sides over which the forces are considered to act are:

$$h_m = s_m \lambda_m \quad (m = 1,2)$$

where s_m are the unstrained lengths over which the forces are considered to act (s is usually 100mm).

As Bassett has shown the tensile stress, σ_m, can be quite easily calculated as follows:

$$\sigma_1 = \frac{F_1 \cos \emptyset}{S_1}$$

$$\sigma_2 = \frac{F_2 \cos \emptyset_2}{S_2}$$

7.5.2 The Calculation of Shear Stress with Respect to the Specimen Edges

Due to the clamp design the tester should in theory impose no couples to the edges of the specimen, however as Bassett has pointed out, when the estimates of the moments on the specimen are summed, there will be a need for the existance of such couples to balance the equation of equilibrium.

The calculation of the shear stresses are on the whole rather more complicated than tensile stresses, but Bassett has shown that this can be determined as follows:

$$\sigma_{12} = \frac{F_1 F_2}{(F_1 + F_2)} \left[\frac{\sin\phi_1 \lambda_1}{S_2} - \frac{\sin\phi_2 \lambda_2}{S_1} \right]$$

(where ϕ_1 and ϕ_2 are positive anticlockwise).

7.6 Simple Control Equipment

Each of the five actuators are controlled independently by individual servoamplifiers, supplied by MOOG for use with their actuators and control valves. Selected position (or load) is compared to position (or load) actually achieved, as measured by position (or load) transducers (see Fig. 7.6(a) and (b)). If these are different, an error signal is generated, which is used to control the servovalve.

Cycling can be achieved, using a signal generator to generate "false" error signals, to drive the servovalve. This signal generator is also supplied by MOOG specifically for this purpose.

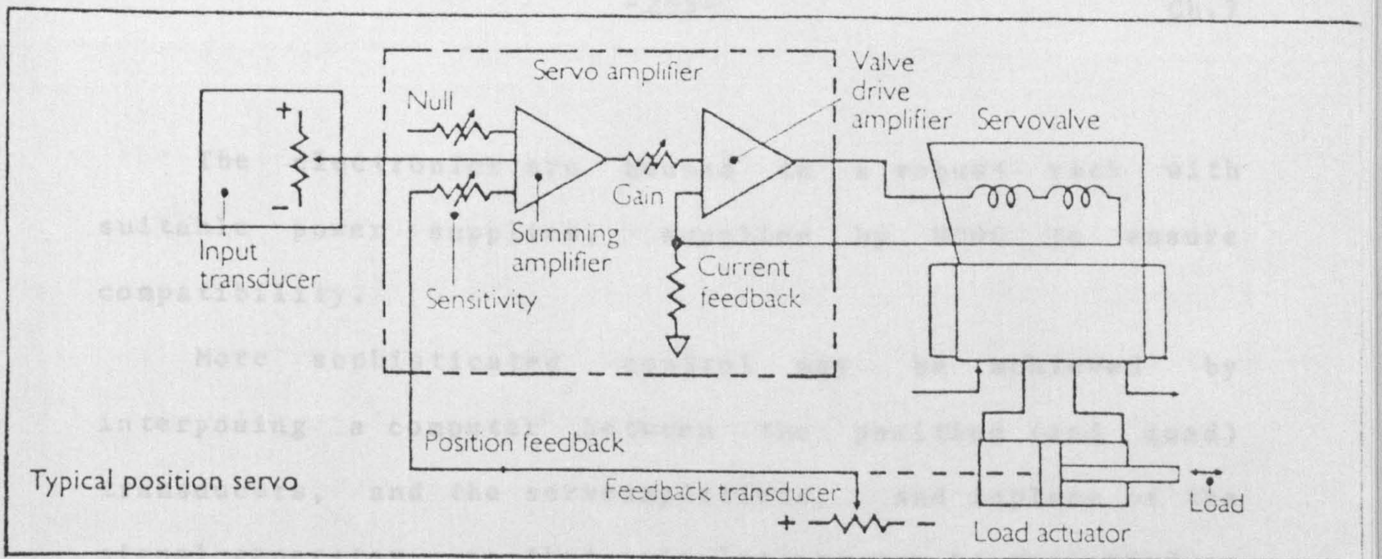


Fig.7.6(a) Position Servo

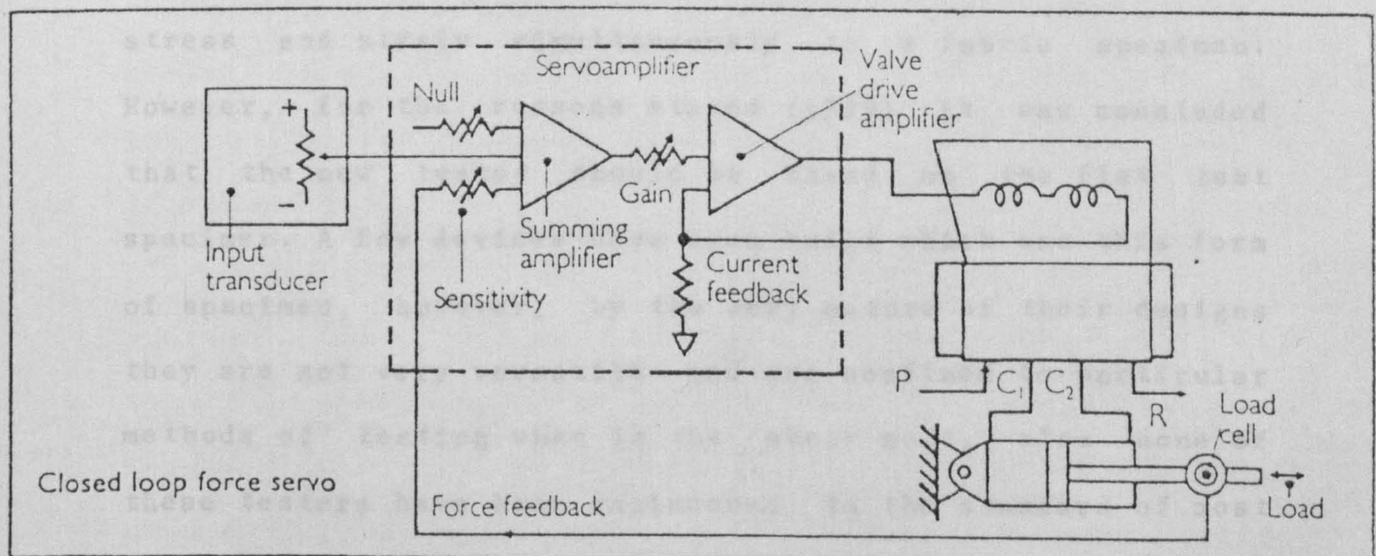


Fig.7.6(b) Force Servo

"from MOOG technical information"

The electronics are housed in a robust rack with suitable power supplies, supplied by MOOG to ensure compatibility.

More sophisticated control may be achieved by interposing a computer between the position (and load) transducers, and the servoamplifiers, and inplace of the signal generator, so that calculations may be performed on transducer signals as necessary, and so that complex control commands may be issued, for example, in response to joystick signals, to restore positional symmetry of the specimen.

Discussion

It can be seen from Chapter 6 that there are a number of methods available to apply the three components of stress and strain simultaneously to a fabric specimen. However, for the reasons stated (p229) it was concluded that the new tester should be based on the flat test specimen. A few devices have been built which use this form of specimen, however, by the very nature of their designs they are not very versatile and are confined to particular methods of testing when in the shear mode, also none of these testers have been engineered to the standard of most modern tensile testers. It was for this reason that it was necessary to build a new automated biaxial tensile and shear testing machine. When fully complete this device will be able to operate in a number of different ways when in the shear mode, for example, it will be able to have the movable beam set to a pre-determined angle, and then perform a biaxial test; or it may slowly increase the angle while performing a biaxial test. There will also be more control over the biaxial tests themselves.

This new apparatus has hydraulically powered clamps which can be independently controlled. The facility which shears the fabric is also hydraulically powered and it can be made to cycle when in this mode. In addition to this it is proposed to have a facility available which will allow the operator to check that the centre of the specimen is kept over the centre of the central pivot of the test frame, this should ensure that symmetry is maintained. It is also proposed that this may be further developed to allow the information which is received from the monitoring system to be fed to the actuators to instruct them to return the centre of the specimen to its original position if required.

Apart from these original facilities the use of hydraulic actuators should allow greater versatility in that they may be supplied with waveforms, of a particular required frequency, so that vibrations due to, for example, wind in fabric structures such as air houses or yacht sails may be simulated. These vibrations may even be superimposed upon a normal biaxial tensile or shear test to investigate if this has any effect on, for example, the internal friction of the fabric.

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GENERAL CONCLUSION AND SUMMARY

Although a particular construction may be essential for any given purpose, it is often the choice of fibre that determines whether the textile will withstand the agents and environmental conditions to which it is exposed. Today the evergrowing number of fibre forming polymers are expanding the range of potential properties and allowing textile fabrics to compete with many of the traditional engineering materials (eg. air houses and tension membrane structures).

Where textile fabrics are used for structural applications a greater knowledge of their properties, both physical and chemical, is required. One major area under investigation in recent years is their structural and mechanical behaviour, this is important when considering the structure's initial design as well as how the fabric will react to high stress, fatigue and shock loads.

Many forms of testing machine have been built which have attempted to quantify these mechanical properties, however, these have been mainly confined to the uniaxial test. This test has a problem in that it suffers from inhomogeneous stress distribution, so the information gained may therefore be limited. The apparatus, however, is relatively cheap and the test quick and easy to perform. This type of test is also restricted in that it only gives the strength in any one direction, and this is often not very realistic. In textile fabrics loads are often applied in more than one direction at once, and as fabrics are anisotropic, engineers must be aware of how the loads in each direction will interact, and how this will effect the fabric in its end-use. This is especially important in many industrial and engineering applications were failure of the fabric may have quite dangerous consequences.

Over the past few decades a number of researchers have attempted to design and fabricate biaxial tensile testers, and shear testers, some of these have even been combined so that the three components of stress and strain could be applied simultaneously. The majority of those which have possessed this facility have used cylinderical specimens; however, there are a number of difficulties with this type of specimen, mainly due to problems with the seam and the time involved preparing and mounting the specimen. Other workers have designed testers which can take flat specimens, these are much easier to use and do not have the problem of a seam to consider. Both methods, however, suffer from clamping problems and difficulties of ensuring that stress is applied homogeneously. It has therefore been necessary to take measurements from small areas in the centre of the specimen using selective strain measuring devices. None of those strain measuring devices used in the past, however, could be considered as ideal and each had a number of shortcomings, some of these include the inability to be automated, bulkiness, excess weight, and tensile stiffness.

A number of workers have tried to avoid the problem of having to use strain measuring devices to take measurements within a small area in the centre of the specimen. They have attempted to design clamping systems which could apply stress and strain more homogeneously, and they hoped that this would make it more acceptable to measure strains by the displacement between the opposite clamps. These clamping systems, however, often proved rather complicated and made mounting of the specimen difficult and much more time consuming. It was also virtually impossible to design perfect clamps, so in practice, selective strain gauges were still required.

One of the main objects of this present work was to design and construct the mechanical hardware for a new biaxial tensile and shear tester, as no ideal machine was at present available for testing light industrial fabrics. It was considered, however, that before this could be done a suitable fabric extension sensor would have to be made available as it was not intended to have a complicated clamping system which might increase the test time, and also make construction more difficult. A literature survey did not reveal a suitable device so it was realised that one would have to be designed.

The present work has achieved both its major objectives, however, the new tester was not, as hoped, completed to the stage were simple tests could be carried out. Some of the the main findings of the work are as follows:

The New Extension Sensor

(1) PVDF piezo polymer film (27μ-52μ) was used as the active element of the new extension sensor. It was shown to be cabable of measuring extensions greater than 10%.

(2) The following circuitry was based on a charge amplifier (Kistler, type 5007).

(3) An installation procedure was established which basically involved:

(i) Long thin narrow strips of film (l:w ratio > 15:1)
(ii) "Araldite Rapid", adhesive secured the film to the fabric. Attached only by two small spots at each end.
(iii) Copper foil with a conducting self-adhesive layer was used to attach the jumper wires to the film.

The New Biaxial Tensile and Shear Tester

(1) It was established that the most suitable method of applying shear was that based on the scissor-like principle, ie., one beam was fixed and the other could rotate about its centre.

(2) Hydraulic actuators are used to apply all the forces. Each of the four clamps can be independently controlled.

(3) Simple solid clamps should be used to ease specimen mounting. Strain measurements should be made in the central test region using the new extension sensors.

(4) An electrical monitoring system will be fitted to ensure that the centre of the specimen remains over the main central

pivot, this will maintain symmetry.

Recommendations for future work include:

(1) Investigate methods of increasing the environmental conditions under which the PVDF extension sensor can operate, ie., by fixing a temperature recording device near the gauge and having it feedback information via a computer which adjusts the calibration to allow for changes in temperature.

(2) Alternative methods of attaching the film strip to the fabric might be investigated. It may be possible to attach the film between two pins which may be pushed through the fabric, this may speed up use.

(3) More general work is required to refine the installation procedure of the gauge.

(4) An investigation of the repeatability of the new gauge when accurately cut with a die requires further work.

(5) A sophisticated computer control system should be developed, to enable the tester to carry out a wide range of test procedures, and to simplify the recording and analysis of results.

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APPENDIX 1

The Bias Extension Test

It can be shown from the expression, first noted by Kilby (91), and later Shanahan et al (189), and Leaf and Sheta (94):-

$$\text{(A1.1)} \ldots \frac{1}{E_\theta} = \left(\frac{1}{E_1}\right)\cos^4\theta + \left(\frac{1}{G} - \frac{2\nu_1}{E_1}\right)\cos^2\theta\sin^2\theta + \left(\frac{1}{E_2}\right)\sin^4\theta$$

Where E_1, E_2 are the tensile moduli in the warp and weft directions, ν_1, ν_2 are the corresponding Poisson ratios for extension. G is the shear modulus, and θ an arbitrary angle to the warp axis.

That the tensile rigidity in the bias direction, E_{45}, is not the same as the shear rigidity, G.

$$\text{if } \theta = 45^\circ,\ \cos\theta = \sin\theta = 1/\sqrt{2}$$

$$\text{(A1.2)} \ldots \frac{1}{E_{45}} = \frac{1}{4E_1} + \frac{1}{4}\left(\frac{1}{G} - \frac{2\nu_1}{E_1}\right) + \frac{1}{4E_2}$$

If E_1, E_2, and V_1 have been measured previously the measurement of E_{45} will make the calculation of the shear modulus, G, possible.

$$\frac{4}{E_{45}} = \frac{1}{E_1} + \frac{1}{E_2} + \left(\frac{1}{G} - \frac{2\nu_1}{E_1}\right)$$

$$\frac{4}{E_{45}} - \left(\frac{1}{E_1} + \frac{1}{E_2}\right) = \frac{1}{G} - \frac{2\nu_1}{E_2}$$

$$\frac{1}{G} = \frac{4}{E_{45}} - \left(\frac{1}{E_1} + \frac{1}{E_2}\right) + \frac{2\nu_1}{E_1}$$

For E the calculation should be made with true finite strain definitions. As Lloyd (190) has pointed out the calculation of Poisson ratio using extension ratios :-

$$\nu_1 = \frac{\varepsilon_2}{\varepsilon_1} \qquad \text{where } \varepsilon = \frac{\text{change in length}}{\text{original length}}$$

is not the same as:-

$$\nu_{\omega 1} = \frac{e^2}{e^1}$$

where e^i is a true finite (Green or Euler) strain.

The Green's strains are defined as:-

$$\varepsilon_x = \frac{du}{dx} + \frac{1}{2}\left\{\left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2\right\}$$

$$\varepsilon_y = \frac{dv}{dy} + \frac{1}{2}\left\{\left(\frac{du}{dy}\right)^2 + \left(\frac{dv}{dy}\right)^2\right\}$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{du}{dy} + \frac{dv}{dx} + \left\{\frac{du}{dx}\cdot\frac{du}{dy} + \frac{dv}{dx}\cdot\frac{dv}{dy}\right\}\right)$$

for the two dimensional case, where ε_x and ε_y are tensile strains and ε_{xy} is a shear strain.

For small strains:-

$$\varepsilon_x = \frac{du}{dx}, \quad \varepsilon_y = \frac{dv}{dy}, \quad \varepsilon_{xy} \frac{1}{2}\left(\frac{du}{dy} + \frac{dv}{dx}\right)$$

can be used, but calculations can only be made for the initial modulus using equation (A1.1) if these definitions are used. If larger strains are used (greater than 2-3%) it is more acceptable to use Green's strains in calculations. However, Lloyd (190) has pointed out that the definitions of such strains is more complicated than a simple extension ratio, and a more sophisticated method of strain determination is required than calculations based on crosshead displacement. These techniques have been discussed by Lloyd (190), and experimentally they involve the use of still photography or real-time video image analysis.

Kilby (91) has pointed out that it should be possible to determine the shear modulus, G, from the measurements of the free Young's modulus provided that the principal Young's moduli and the corresponding Poisson ratios are known. He stated that he was not aware of this having been attempted (Leaf and Sheta (94) used this method), but he did say that the process would appear to involve a lengthy experiment in comparison with the direct method of Morner and Eeg-Olofsson (150). He does, however, suggest that a considerable simplification can be made when, as is usually the case,

$$E_1,\ E_2 \gg G$$

In this event, the expression for $(E_\theta)_{free}$ becomes

$$\frac{1}{(E)_{\theta_{free}}} \triangleq \frac{1}{G} \sin^2\theta \cos\theta$$

when $\theta = 45^\circ$ this reduces to $E_{45} \triangleq 4G$. He draws attention to the fact that the fabric modulus in the bias direction is determined predominantly by the shear modulus.

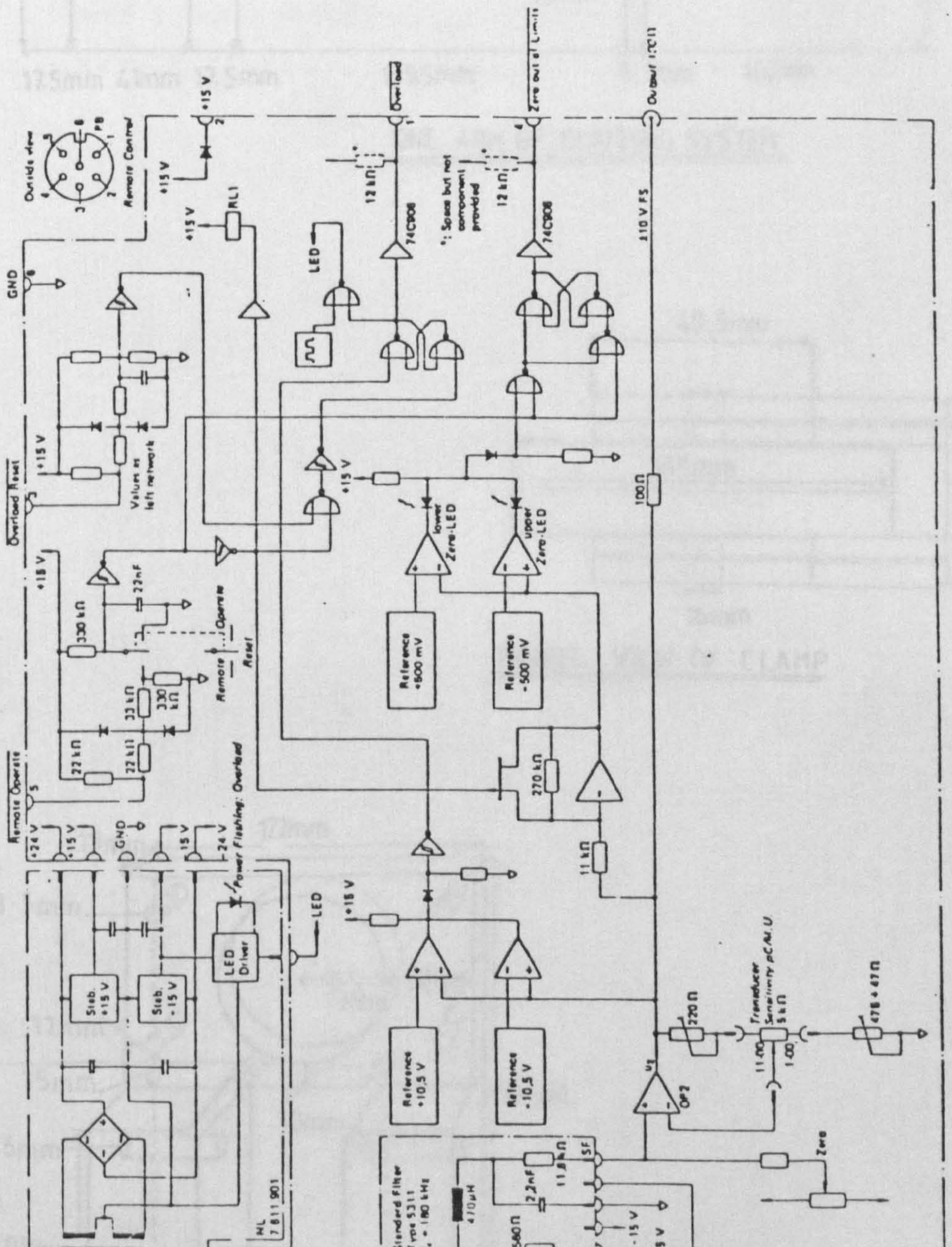
APPENDIX 2

Low Temperature Soldering

The low temperature solder used in this particular case was a eutectic mixture of Sn/Pb/Si prepared with 362 or 366 flux. This solder has a melting point of 97 degrees centigrade and is supplied by Multicore Solders Ltd. in a syringe form. This type of solder can be used directly onto copper or silver coated PVDF. For other metalizations silver ink or conductive paint can be applied first to give contact areas. At this temperature the Kynar Film undergoes a degree of "relaxation", ie., slight warping or wrinkling occurs. However if the specimen is clamped during soldering this deformation can be kept to a minimum.

A suitable iron for use with low melting point solder can be purchased, but for this present application it was considered too expensive as only a relatively small amount of work was to be carried out. It was therefore decided to modify a 240V, 15W Antex CSCN soldering iron, so that it could be used for low temperature work. This could be done simply by using an adjustable transformer, which could be used to regulate the voltage; therefore giving control over the temperature of the iron. The transformer used was a Type V-5HMP Zenith Variac adjustable transformer with Duratrak, input 240V, 50 cycles: output 0<270V, 2A. We of course had to have some means of measuring the dependence of the temperature on the transformer voltage adjustment. This was achieved using a temperature recorder as described by Woodman(191). The recorder was relatively cheap and was made by converting a BBC microcomputer, it was available as it had been recently constructed for other work. The resistance thermometer was attached to the soldering iron and the voltage increased from 100V until the solder melted. The temperature was measured after each voltage adjustment, and time was allowed for the temperature to steady. A graph was produced of soldering iron temperature against transformer voltage, and from this the transformer voltage which supplied the suitable soldering iron temperature was easily determined.

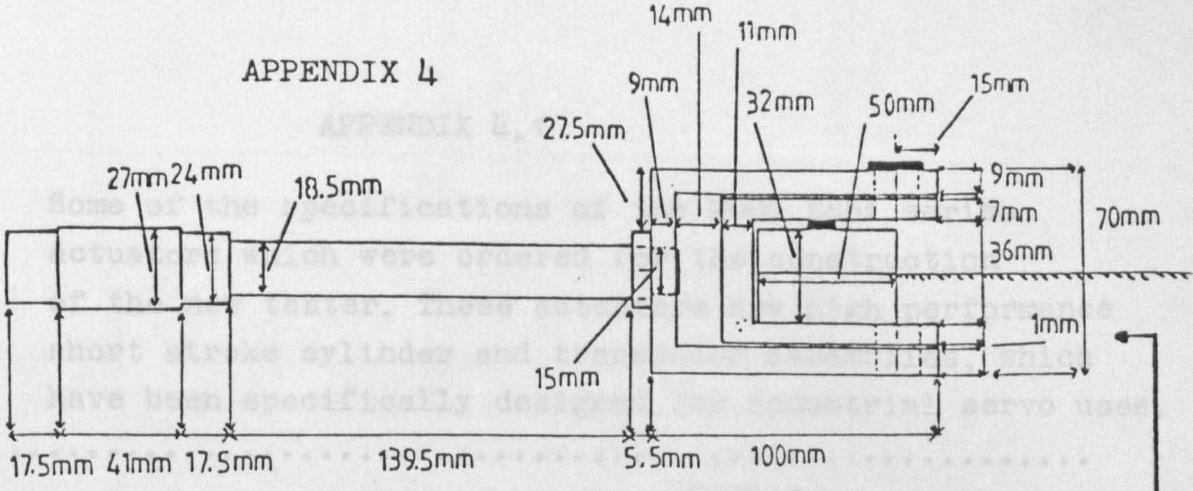
APPENDIX 3



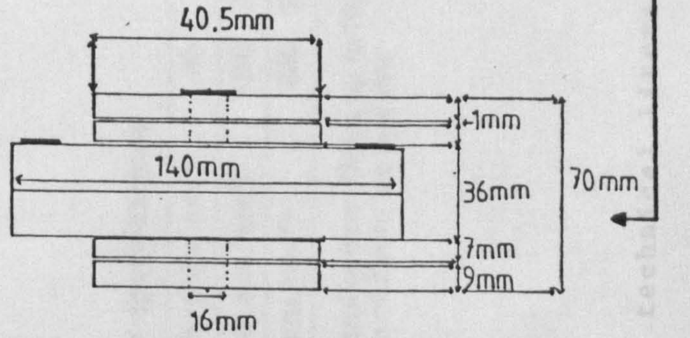
Circuit Diagram of Kistler, type 5007, Charge Amplifier

(From Kistler literature (121))

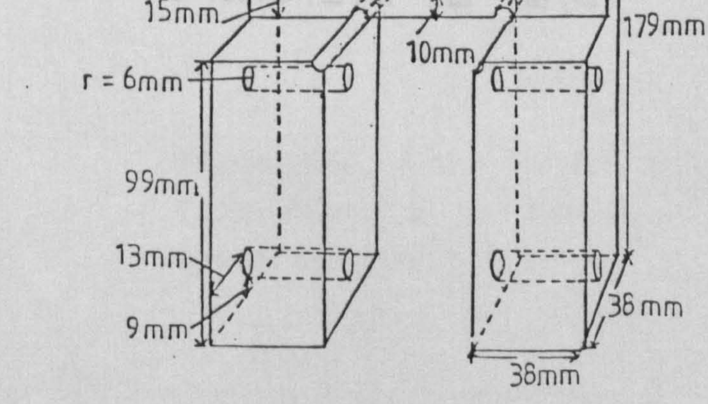
APPENDIX 4



ONE ARM OF CLAMPING SYSTEM



FRONT VIEW OF CLAMP



ACTUATOR MOUNTING FLANGE

APPENDIX 4.1

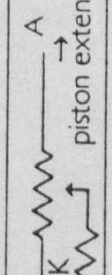
Some of the specifications of the MOOG E851 series actuators which were ordered for the construction of the new tester. These actuators are high performance short stroke cylinder and transducer assemblies, which have been specifically designed for industrial servo uses.

Specifications

General specifications

Supply pressure	3000 p.s.i. maximum
Operating temperature range	—40°C to 85°C
Fluid	petroleum base, hydraulic fluid
Supply filtration required	25 μm absolute or better
External leakage	typically 1 drop/5000 cycles at 100 bar
Breakout force	typically 14N (3 lbf)
Actuator orientation	any

Electrical specifications

Linearity	±0.2%
Resolution	virtually infinite
Resistance	4KΩ/100 mm
Wiper load impedance	minimum of 100 × total element resistance
Life	typically > 50 × 10⁶ cycles at 25 mm stroke
Electrical connections	 piston extension
Temperature coefficient	.013% per°C (max)

Cylinder specifications

Cylinder bore size mm	40	63	80	100
Piston head area (mm^2)	1260	3120	5000	7850
Annulus area (mm^2)	880	2100	3440	5400

Cylinder strokes from 25mm up to 150mm in increments of 25mm are available.

(From MOOG technical literature)

APPENDIX 4.2

QUANTITY	DESCRIPTION
5	Moog E851 servoactuator, 100 mm stroke, 40 mm bore, mid trunion or front flange mounting.
4	Moog E760 servovalves, rated flow 2.5 L/min @ 70 bar drop, 40 mA/80 ohm coils.
1	Moog E760 servovalve, rated flow 5 L/min @ 70 bar drop, 40 mA/80 ohm coils
5	Moog Servo-amplifier Modules without Dither. Model E122-602
1	Moog Power Supply Module E128-601
1	Moog Signal Generator Module. E123-606.
1	Moog Rack Model E127. Unwired for customer to configure.
5	Mating Electrical Connector P/No. 061-49054E/C-14S-2S for use with Items 2 and 3.
5	Mating Electrical Connector P/No. A56257-1 for use with Item 1.
1	25 g.p.m. Filter Assembly. Collapse Pressure 3000 psi, 25 micron rating absolute.
1	25 g.p.m. Filter Assembly. Collapse pressure 100 psi, 3 micron rating absolute.

Inventory of the hydraulic equipment ordered from MOOG for the new biaxial tensile and shear tester.

APPENDIX 5.1

Correlation Coefficients

The degree of correlation coefficient was measured using the formula:

$$r = \frac{\Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}}{\sqrt{\left[\Sigma x^2 - \frac{(\Sigma x)^2}{n}\right]\left[\Sigma y^2 - \frac{(\Sigma y)^2}{n}\right]}}$$

This is a convenient form for computing.

The full set of results of the tests shown in Fig.5.4 are as follows:

Relationship Between Instron Extension and PVDF Signal

	(Instron Extension Measurement(mm))	(PVDF Peak Height(mm))			
	x	y	x^2	y^2	xy
	5.50	108.5	30.25	11772.25	596.75
	5.25	104.5	27.56	10816.00	546.00
	4.25	084.5	18.06	07140.25	359.13
	5.25	103.0	27.56	10609.00	540.75
	4.50	089.0	20.25	08010.25	402.75
	5.00	098.5	25.00	09702.25	492.50
	5.50	109.0	30.25	11881.00	599.50
	4.75	093.0	22.56	08649.00	441.80
	4.50	089.0	20.25	07921.00	400.50
	4.00	079.5	16.00	06320.00	318.00
	4.75	093.0	22.56	08649.00	441.80
	5.75	113.5	33.06	12882.25	652.60
Σ	59.00	1165.0	293.40	114352.5	5792.10

r = +0.997

As stated by Moroney (192) the correlation coefficient, r, cannot exceed +1 or be less than -1 in value. A value of +1 denotes a perfect functional relationship between y and x, an increasing x being associated with an increasing y. When r is equal to -1, again there is a perfect functional relationship, but this time an increasing x is associated with a decreasing y. When r=0 there is no relation at all between x and y. They are not correlated. Other intermediate values of r indicate that, while there is not a strictly functional relationship between the variables there is a trend.

It can be seen in the present case were r=+0.997 that there is almost a perfect functional relationship, this can also be seen from the graph Fig.5.4(b). However, there is a question of the significance of the correlation coefficient. It is important to ascertain whether or not a high value of the correlation coefficient could have arisen by chance in a sample of the size dealt with. This may be tested using tables of the distribution of Student's-t which is named after its discoverer Gosset, who published under the pseudonym of "Student". A calculation is performed using:-

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}}$$

and the tables are read with N-2 degrees of freedom. In this particular case:

$$t = 40.7$$

with N = 12-2 = 10. The tables show that at the 5% level t = 2.228, and at the 1% level t = 3.169. We can therefore conclude that the observed value of the correlation coefficient is significant at the 1% level.

APPENDIX 5.2.1

Dependence of Response on Surface Area of PVDF

The procedure is the same as that for A5.1.

(Area of PVDF Gauge(mm)) x	(Peak Height of PVDF(mm) For 4.5% Extension) y	x^2	y^2	xy
090.70	23.30	08226.5	0542.9	2113.3
124.70	35.00	15550.1	1225.0	4364.5
130.80	30.90	17108.6	0954.8	4041.7
080.60	18.80	06496.4	0353.4	1515.3
056.60	14.00	03203.6	0196.0	0792.4
067.00	15.50	04489.0	0240.3	1038.5
092.30	23.60	08519.3	0557.0	2178.3
094.10	27.50	08854.8	0756.3	2587.8
050.40	15.70	02540.2	0246.5	0791.3
088.50	23.00	07832.3	0529.0	2035.5
139.80	32.50	19544.0	1056.3	4543.5
133.00	28.80	17689.0	0829.4	3830.4
170.40	42.90	29036.2	1840.4	7310.2
139.80	36.00	19544.0	1296.0	5032.8
102.30	26.00	10465.3	0676.0	2659.8
Σ 1561.0	393.5	179099.3	11299.3	44835.3

r =+0.963

t = 12.88

At 5% level t = 2.160, and at the 1% level t = 3.012. We conclude therefore that the observed value of the correlation coefficient is significant at the 1% level.

APPENDIX 5.2.2

Dependence of Response on Surface Area of PVDF

The procedure is the same as that for A5.1.

(Area of PVDF Gauge (mm)) x	(Peak Height of PVDF(mm) For 4.5% Extension) y	x^2	y^2	xy
054.0	05.5	02916.0	030.3	0297.00
213.8	20.0	45710.4	400.0	4276.00
120.1	14.8	14424.0	219.0	1777.48
117.8	11.9	13876.8	141.6	1401.82
159.6	14.9	25472.2	222.0	2378.04
122.5	10.3	15006.3	106.1	1261.75
155.6	14.3	24211.4	204.5	2225.08
134.4	14.4	18063.4	207.4	1935.36
258.4	22.5	66770.6	506.3	5814.00
157.0	14.0	24649.0	196.0	2198.00
188.1	15.0	35381.6	225.0	2821.50
070.0	09.0	04900.0	081.0	0630.00
081.6	09.4	06658.6	088.4	0767.04
Σ 1832.9	176.0	298039.5	2627.6	27783.07

$r = +0.953$

$t = 10.46$

At 5% level $t = 2.201$, and at 1% level $t = 3.106$. It can therefore be concluded, that the observed value of the correlation is significant at the 1% level.

APPENDIX 5.3

Dependence of Response on Surface Area of PVDF:

The Gauge is Mounted on Three Different Fabrics

The procedure is the same as that for A5.1.

	(Area of PVDF Gauge(mm)) x	(Peak Height of PVDF(mm) For 4.5% Extension) y	x^2	y^2	xy
	025.5	05.00	00650.3	0025.0	00127.0
	029.3	04.75	00858.5	0022.6	00139.2
	094.5	18.00	08930.3	0324.0	01701.0
	110.0	19.75	12232.4	0390.0	02184.0
	272.0	46.00	73984.0	2116.0	12512.0
	185.0	38.00	34225.0	1436.4	07030.0
	207.0	40.00	42849.0	1600.0	08280.0
	057.8	10.00	03340.8	0100.0	00578.0
	059.9	11.00	03588.0	0121.0	00658.9
	120.0	22.50	14400.0	0506.0	02700.0
Σ	1161.6	215.0	195058.3	6641.4	35911.0

$r = +0.991$

$t = 20.94$

The tables show that at the 5% level $t = 2.306$, and at the 1% level $t = 3.355$. We can therefore conclude that the observed value of the correlation coefficient is significant at the 1% level.

APPENDIX 6

Repeatability During Repeated Strain Cycles

Full set of results from Fig.5.5

Peak Height from PVDF as Shown on Chart-Recorder(mm)	Extension of Specimen
54.75	5%
54.50	5%
55.00	5%
54.50	5%
54.75	5%
55.25	5%
54.75	5%
54.50	5%
54.50	5%
54.25	5%

$\bar{x} = 54.68$

S.D. = 0.2899