THE ELEVATED TEMPERATURE PROPERTIES

OF

REINFORCED CONCRETE

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SUMMARY

The effect of elevated temperatures upon the strength properties of four reinforcing and three prestressing steels of varying size, manufactured to British Standards, is investigated. To simulate the temperatures likely to be experienced during a fire for the steels, a range of 20 - 700°C is used.

After outlining the aims of the research, previous work on structural concrete is reviewed. To test the steels in their as rolled condition, a tensile testing machine with tube furnaces and associated instrumentation is designed and built. A testing programme is developed to provide the essential data on the strength properties of the steels under various loading conditions.

The three strength parameters of yield stress, ultimate strength and elastic modulus obtained are normalised by using the corresponding room temperature value. The use of non-destructive testing to obtain the residual strength is investigated together with the results of some chemical tests.

After normalising the results it is shown that the size of material has no effect. The three prestressing steels behaved identically although a difference between hot-rolled and cold-worked reinforcing steel is observed, the latter showing reduced strength when tested after cooling to ambient temperature. When tested at elevated temperature all three strength parameters reduced significantly. On application of a working load during heating, failure is obtained between 500 and 600°C for the reinforcing steel and at 300°C for the prestressing steel, with the minimal reduction in strength for those specimens that did not fail during heating.

Apart from the prestressing steels heated to 400°C and above, the non-destructive tests proved inconclusive.

The design curves currently available for use at elevated temperatures on the steel by designers are shown to fall within the general spread of results. They do not, however, form the lower bound limit.

Robert Neil Crook, Doctor of Philosophy, 1980

Key Words:- Tensile properties, reinforcement, fire, concrete

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CHAPTER 1

Introduction

In the early days when reinforced concrete was first used, well laid down processes were applied to this new construction material. A structure built in this mode would be resistant to most types of external damage with a collapse being absolutely unthinkable. This was mainly due to careful detailing and workmanship of very high standards resulting from an abundance of skilled craftsmen. The last quarter of a century has seen the use of new and higher strength materials, ie, concrete and steel, and the use of computers in analysis. The initial processes used could not change with the advent of these new materials and saw the disappearance of the craftsman and good detailer. It would be expected that the new materials available would result in better and safer structures. However, because of the format of the industry at present, the lack of knowledge of production techniques by some designers, and the decisions made by all the interested bodies concerned with the production of a structure, can sometimes result in disjointed elements and badly detailed drawings.

Fire is one of the phenomenons that can expose the weaknesses of a structure not evident from the surface. Fire tests on sections subjected to standard procedures (BS 476[1], ASTME[2] and ISO 834[3]) have shown that well designed, detailed and constructed concrete structures rarely give any fire problems for a fire resistance of two hours. The minimum cover approach seems to give a satisfactory fire resistance. However, because of mass production, the use of many new and high strength materials, the different possible modes of failure on similar sections at different positions in a structure and the inherent weaknesses at joints, whether due to construction or prefabrication, makes it necessary to develop a design that will compliment the empirical rules from fire tests with the performance of individual materials at high temperatures. This would allow structures that could not conceivably have a fire test performed on them to have some form of fire assessment.

When a fire does occur in a building it can have disastrous effects on human life and more often than not on the building itself. Figures produced in the joint report[(4)] by the Concrete Society and Institution of Structural Engineers based on fire statistics for 1973 in the UK give the following data:

Total number of fires	331164
Fires in buildings	132044
Fatal casualties	1041
Non-fatal casualties	6700
Direct fire losses	£194m

Structural damage results in only one sixth of the direct fire losses with most of the fatalities occurring in domestic dwellings. However, indirect costs based on the direct fire losses results in a total fire bill of £1069 million for the same year, and made up as follows:

Costs and Expenditure	Value £ million
Direct losses	194
Consequential losses	388
Insurance administration	128
Fire brigades	194
Fire protection to buildings	103
Personal injuries	1
Fire research	1
Total	£1069 million

These consequential losses could well be cut if a quick decision could be made as to the suitability of the fire damaged section for rebuilding or demolition. Even a reduced loading criterion upon this damaged section could well result in a company remaining in business rather than going bankrupt due to lost production. It has been estimated that one third of all businesses that suffer a major fire do not continue to trade but how many could have continued if accurate information regarding residual strength properties were known?

This therefore leads to the conclusion that any sound design process should include the effects of fire on the constituents of a building. The fixtures and fittings have well laid down fire precautions in the relevant British Standards but it has only been recently that a code of practice CP110[5] has dealt with the problems of designing the structure itself for fire resistance.

If a reinforced concrete structure is considered, the performance against elevated temperatures on the steel and concrete are of prime importance. These two constituents, being inert materials, are not combustable but are susceptible to elevated temperatures with the effect of a reduction in the strength properties.

Concrete has and always will be a source of continual investigation into the effects of temperature on its structural properties. The many variables that can be applied to a single section are large enough to keep any researcher interested for quite some time. Some of these variables include type and size of aggregate, type of cement, water/cement ratio, design strength, applied loading conditions, size of section etc.

Steel however is not the major constituent of a reinforced concrete section, sometimes having as little as 0.15% of the gross cross-sectional area (to CP110:1972 design[5]), and therefore not being the prime element when considering a fire. But without the steel there would be no structure, so the effect of the fire on the steel is equally important as that on the concrete. The small amount of information available on the elevated temperature properties of reinforcement, which is covered fully in Chapter 3, and with the basic assumptions subsequently made, makes an investigation of prime importance before any complete and up to date analysis can be made.

Chapter 2 deals more fully with the reasons and aims of such an investigation.

The structure itself also derives some of its strength from the bond between the concrete and steel. Although this aspect is not the basis of the research, it is another area of importance and will be dealt with, where appropriate, in later chapters.

CHAPTER 2

Scope of Investigation

2.1 Aims of Investigation

The joint report by the Concrete Society and the Institution of Structural Engineers[(4)] lays down design procedures based on present knowledge and indicates areas where further research is required to enable current design procedures to be improved. One of these concerns the effect of high temperature on reinforcement steels used in concrete structures.

When considering the effect of high temperature on reinforcement steels two main considerations must be borne in mind. Firstly that when subjected to fire a concrete structure should not collapse before a specified time has elapsed, this provision provides an acceptable level of safety for the occupants. The second consideration, which is concerned with economy rather than safety, arises after the fire, when a decision must be made on whether to demolish or reinstate the fire damaged building. As far as a reinforced concrete structure is concerned it must be decided whether or not the high temperature to which it has been subjected has left the structure with a sufficient factor of safety to continue in use.

Current design procedures are based on schedules in the Building Regulations which generally specify minimum thickness of concrete cover and minimum member sizes according to the period of fire resistance required. The schedules in the Building Regulations have been assembled over a considerable time from data derived from tests at the Fire Research Station and elsewhere. These tests are carried out on complete structural members.

The Joint Report suggests that design procedures could be rationalised by adopting a direct method of calculating the fire resistance of a structural member. In order to prepare such a calculation, basic information is required about the temperature/

strength/strain properties of reinforcing steels.

Various experiments have been carried out abroad and in this country but there are no comprehensive up to date data available. Work by Bannister[6] & Corson[7] is cited in the Joint Report[4], but is not complete and is contradictory in part.

There is considerable scatter of the results, and it is unclear whether yield strength or ultimate strength has been used as the criterion. If the recommendations of the Joint Report[4] are to be adopted, it is therefore necessary to prepare authentic and comprehensive data based on tests on bar reinforcement.

Designs based on the fresh data would show economy over the methods of design now in use as it would be possible to calculate the effects of varying cover, stress, continuity and other parameters.

The research programme outlined in Chapter 5 has been designed to provide essential experimental data on the effects of high temperature on the strength and stiffness properties of reinforcement steel. In designing the programme, attention has been paid to both aspects mentioned above, ie, the deterioration in strength of a structure during a fire and its residual strength at ambient temperature after a fire.

2.2 Types of Steel to be Investigated

The principle types of reinforcing material available in Britain are described by Anchor[8,9] and Bannister[6]. The reinforcement available and made to British Standards is:

Mild steel bars (BS4449)[10]
Hot-rolled high-yield deformed bars (BS4449)[10]
Cold-worked high-yield deformed bars (BS4461)[11]

In most structures mild steel is generally not used for primary reinforcement but more often for secondary reinforcement. Both the hot-rolled and cold-worked steels are now available with a yield stress of 460 N/mm^2 for the 6 to 16 mm diameter range or 425 N/mm^2 for the larger sizes up to 50 mm diameter.

Prestressing steel is available in the form of wire or strand, the quality being related to the size and condition in which it is supplied.

For this investigation four types of reinforcement and three types of prestressing steel were decided upon to give a wide spectrum of the steels currently available to the construction industry. As well as the types of reinforcement, three nominal diameters were chosen ie, 8 mm, 12 mm and 25 mm. This would then enable a correlation, if any, to be made as to the effect of size on the strength properties. The prestressing wire was chosen in 5 mm diameter form and the strand as 9.3 mm 7 wire strand.

Table 2.1 gives the type of steel to be used, its trade name and supplier, to whom the writer extends his thanks in supplying the material in the required condition necessary for testing.

At the onset of the research, materials were available in all the sizes required, except the 8 mm unisteel. However, near the end of the testing programme this size became available and a full set of tests were perfomed on it. The recent introduction of the TorBar type of cold-worked high yield steel, with much improved bond characteristics, had led to the stopping of production of the square twisted type of cold-worked steel. However, since this type of steel had been used for some time, the information from the tests was still necessary so that the aim of being able to assess the residual properties of existing fire damaged buildings could be made. The original consignment of steel needed to be supplimented with a further

Type of steel	Trade name	Supplier/Manufacturer
Mild steel	Mild steel	BRC Engineering Co, Stafford
Hot-rolled high yield	Unisteel	Reinforcement Steel Services, Sheffield
Cold-worked high yield	GK TorBar	GKN (South Wales) Ltd, Cardiff
	Square Twisted	BRC Engingeering Co, Stafford
Prestressing wire	Mill coil	GKN (Somerset Wire) Ltd, Cardiff
	Stabilised wire	
Prestressing strand	7 wire strand	

TABLE 2.1 Steel Types and Suppliers

amount during the testing programme. All the sizes and types required were still available, except for the 8 mm square twisted type which, due to the stopped production, was completely unavailable. Since some of the tests had already been completed it was decided to continue with the testing programme and obtain the next available size. 10 mm was obtained and used to complete the tests on this nominal size of steel.

The manufacture of the various types of reinforcement was in accordance with BS 4449 (10) and BS 4461 (11) with the prestressing steels covered by BS 2691 (12), BS 3617 (13) and BS 4757 (14). All these standards lay down specific requirements, such as chemical composition, characteristic strength (yield or proof), ultimate tennile strength etc. that have to be obtained from the production of that type of steel. Each manufacturer has produced data sheets giving the advantages of their own product and the results from their own tests. To use either the values from the standards or from the manufacturers literature would not be sensible, as it would not give an accurate value for each individual steel. Therefore values were obtained from actual, as delivered, samples and the results included in the appropriate sections of Chapters 6, 7 and 8.

2.3 Basic Assumptions

When an investigation is being planned, certain assumptions have to be made so that it is feasible for testing to be performed. It is important that these assumptions do not alter the results in such a way that they cannot be related to the ultimate aims of the investigation. The areas where the assumptions have been made can be split into two categories, ie, theoretical and practical. The theoretical assumptions being related to the idealisation of on site condition and the practical ones concerned with the actual testing of the materials. Given below are some of these assumptions.

Theoretical

(i) During an actual fire, spalling of the concrete can occur and result in the reinforcing or prestressing steel being subjected to flame temperatures. The time temperature curve given in BS 476 [1] could not simulate this sudden temperature increase on the steel and the timing of such spalling is totally unpredicatable.

(ii) The thickness of the cover to the steel also affects the rate of heating and maximum temperatures. The heating curve in BS 476 [1] therefore does not apply in the case of the steel and, rather than perform tests with different heating rates, uniformity should prevail throughout the tests with a specific soaking period adopted after the desired temperature has been reached.

(iii) Although compression reinforcement is found in reinforced concrete structures the effects upon the tensile steel is more important when considering the influence of fires. The results and analysis are therefore based on tensile tests performed on the specimens.

Practical

(i) Components of stress, strain and temperature that are recorded are accurate to within the required limits.

(ii) All the tests are performed on 'as rolled' specimens.

(iii) The inclusion of experimental error in the tests results is unavoidable with a large practical test programme but are kept to a minimum by the uniformity of procedures.

These assumptions and specific application to the test programme and results are dealt with at the appropriate stages in the test procedures, Chapter 5, and the conclusions, Chapter 10.

CHAPTER 3

A Review of the Literature on the Properties of Structural Concrete due to the Effect of Elevated Temperatures

3.1 Introduction

There has been a large quantity of published research on the aspects of the behaviour of structural elements in fire. The designer needs to have evidence that the design methods and forms of construction has not led to a lowering of fire resistance standards. The development of a design to compliment the emperical rules devised from the fire test[1] and resulting in improvements in the understanding of the behaviour of concrete structures and the information available on the properties of materials exposed to high temperatures has been associated with the name 'rational design'.

The term 'rational design' was first introduced by A H Gustaferro in his work for the Portland Cement Association (PCA) in the USA. Its basis is a new approach to fire design by the use of engineering and thermal principles supported by the results of fire testing and the evidence of real fires. Although there was a lack of suitable research on many aspects, there was sufficient work to justify a change from the emperical values presented in current codes of practice[5,19]. The interdependence of factors such as load, reinforcement, cover to steel and type of concrete, leads to the idea of limit state philosophy. CP110[5] had adopted limit state principles for normal design but the lack of information at the time of its preparation resulted in similar principles not being used for section 10 of the code. The code gives no consideration to continuous, as opposed to simply supported, elements and the results from some special fire tests [20,21,22] and the experience of real fires has given data which shows that continuity and restraint can be beneficial to the fire resistance of a structure.

The possibility of implementing limit state principles for the design against fire was the basis upon which a joint study group of the Concrete Society and the Institution of Structural Engineers was convened. The symposium[23] held in September 1975 at the University of Aston, discussed the report of the study group, now renamed the Joint Committee, and the papers presented were later reviewed by Anchor[24] in 1977. The papers relating to the report dealt specifically with the problems of using rational design procedures. Examples of this procedure given by Bobrowski and Forrest showed that calculation was possible although more information regarding restraint and continuity was necessary.

The published report[4] surveyed the whole subject of the design of structural concrete for fire resistance including details of the behaviour of the two materials (steel and concrete) at high temperatures and the performance of concrete structures in real fires. The report concludes that designs should be performed in a rational manner so that variations in material properties could be reflected in the estimate of the fire resistance of the whole structure or any single structural member.

It can be seen from the preceeding argument that any design based on the rational procedure needs up to date information on the properties of the materials when they are subjected to elevated temperatures. The next section reviews the major works on the properties of structural concrete (reinforced and prestressed) with particular emphasis placed upon the steel properties at elevated temperature.

3.2 Concrete

Concrete has for some time been the subject of intensive research and eminent researchers such as Dougill, Gustaferro and Malhotra to name but a few, have obtained and published data on the properties of this complex material.

Purkiss[25] in 1972 reviewed the structural properties of concrete at elevated temperatures. He described the properties of concrete in two separate categories. The first being material properties found from tests on concrete as a material and the second technological properties found from structural tests. Under material properties the peak stress was found to increase up to 300°C and then decrease rapidly with increasing temperature[26] (Fig.3.1). Youngs modulus was seen to decrease linearly with temperature to approximately 50% of its original value at 400°C and 25% at 600°C[27] (Fig.3.2). The expansion of concrete will depend on the aggregate type and on whether aggregate or cement paste dominates[28,29] and finally creep strains are exceedingly large at high temperatures when compared with those expected at normal temperature[30] (Fig.3.3). All these factors being affected by preload on the specimen[31] (Figs.3.4 and 3.5).

The technological properties encompass the effects upon the structural element that a change in Young's modulus and the application of restraint would have on the assessment of the fire endurance. These properties can be measured from furnace testing although they are not representative of the total structural behaviour unless the furnace test conditions simulate the original loading and restraint. Very few tests have reproduced these actual structural conditions. Most of this type of testing on beams and slabs has been performed by PCA using the condition of allowed expansion followed by complete restraint. The results from the calculations agree well with experimental values although this is probably due to the beams being under-reinforced, whereby the temperature of concrete is low enough to prevent its strength being reduced and the steel reaching a critical temperature causing it to yield excessively and thereby dominating the concrete behaviour. The opposite would be true in an over-

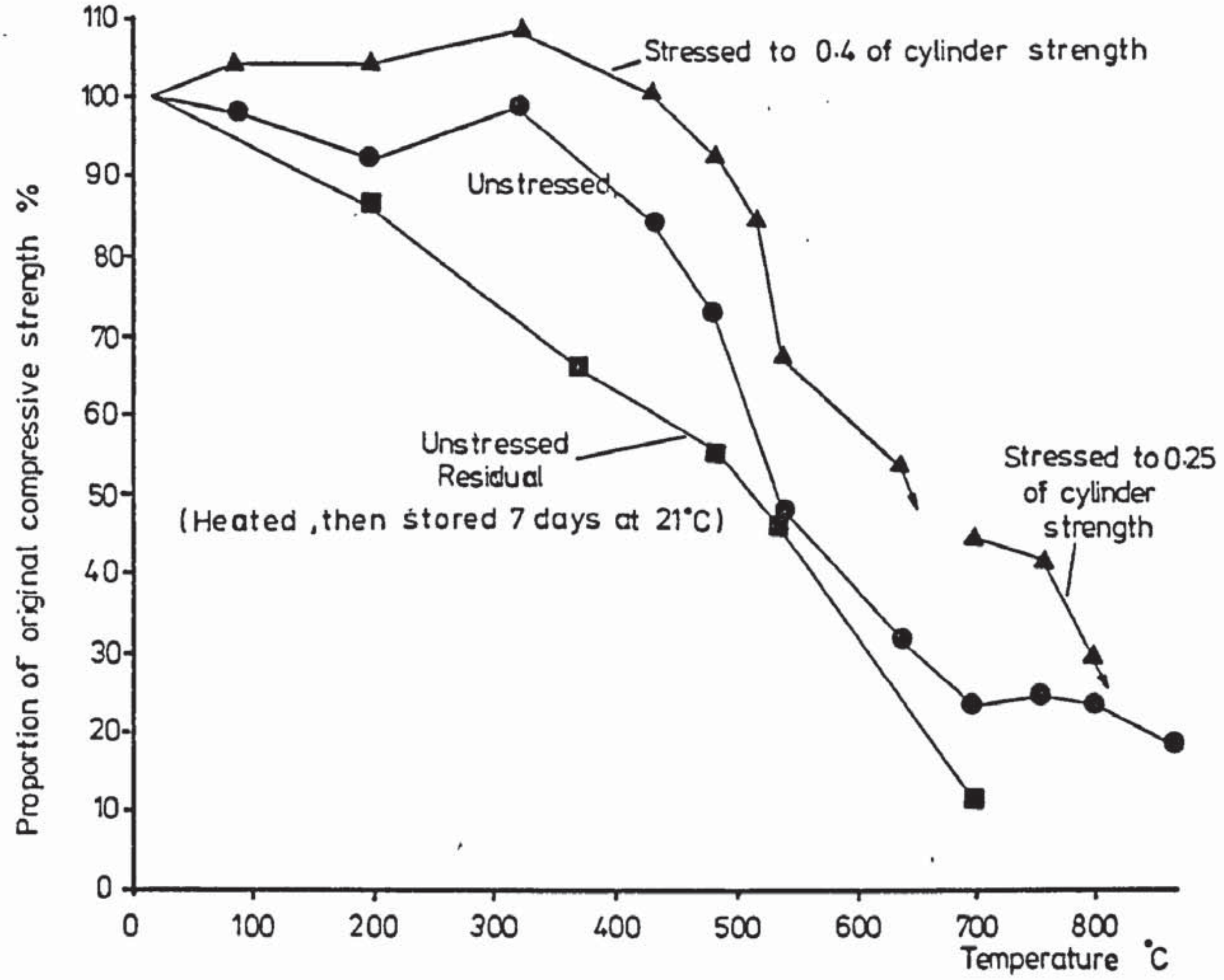


FIGURE 3.1 Effect of temperature on compressive strength of a siliceous aggregate concrete(26)

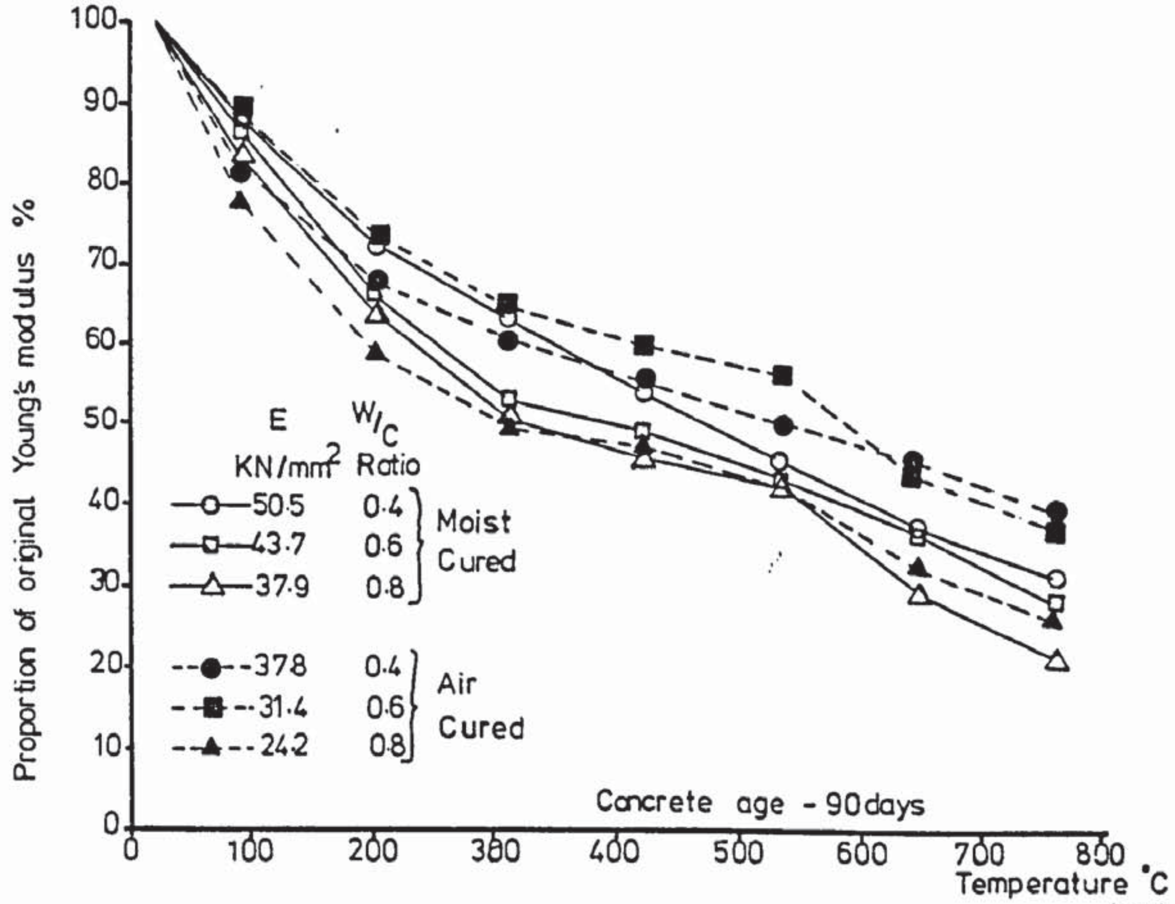


FIGURE 3.2 Effect of temperature on Young's modulus of concrete(27)

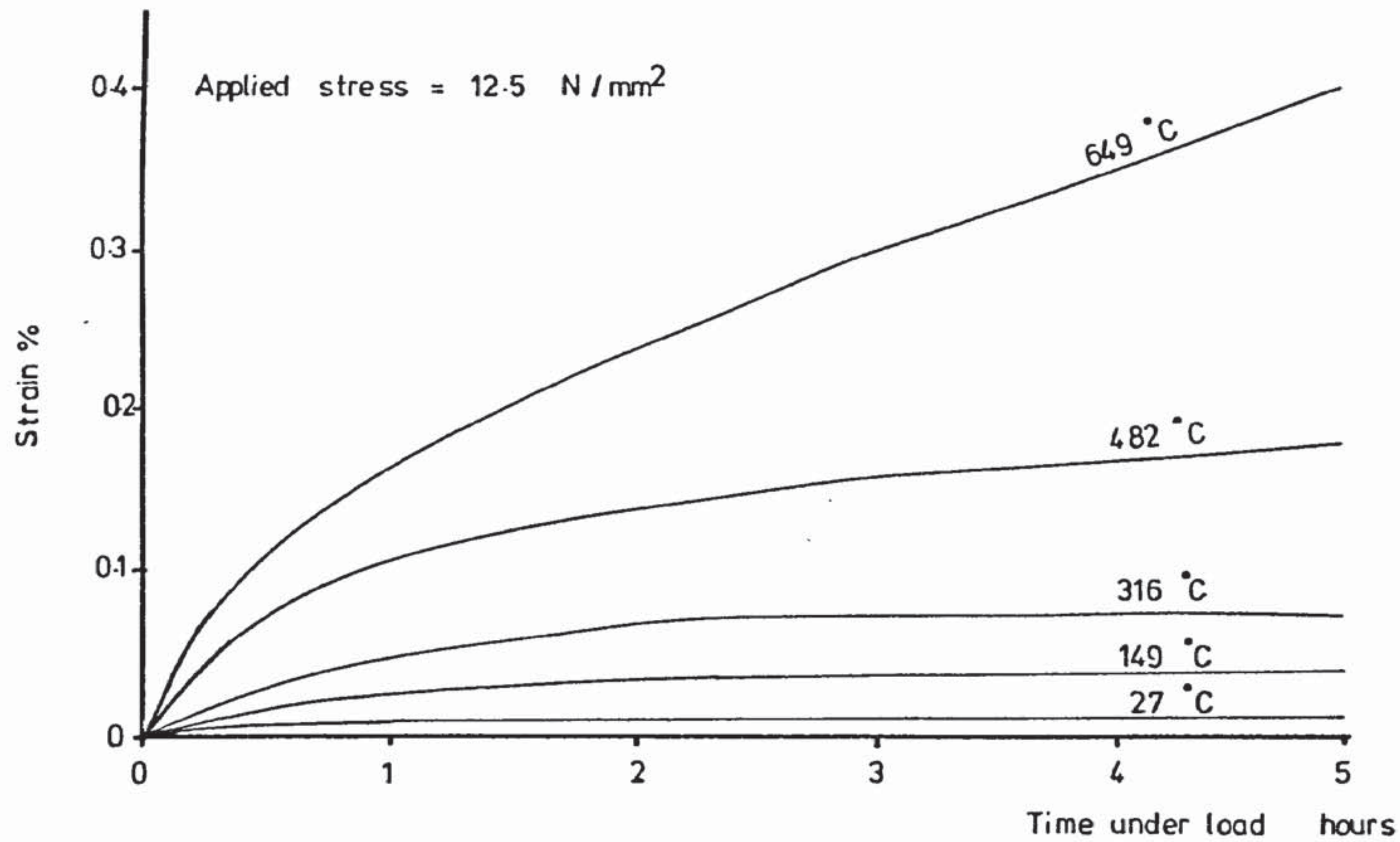


FIGURE 3·3 Time-dependent strains in concrete maintained under load at high temperatures [30]

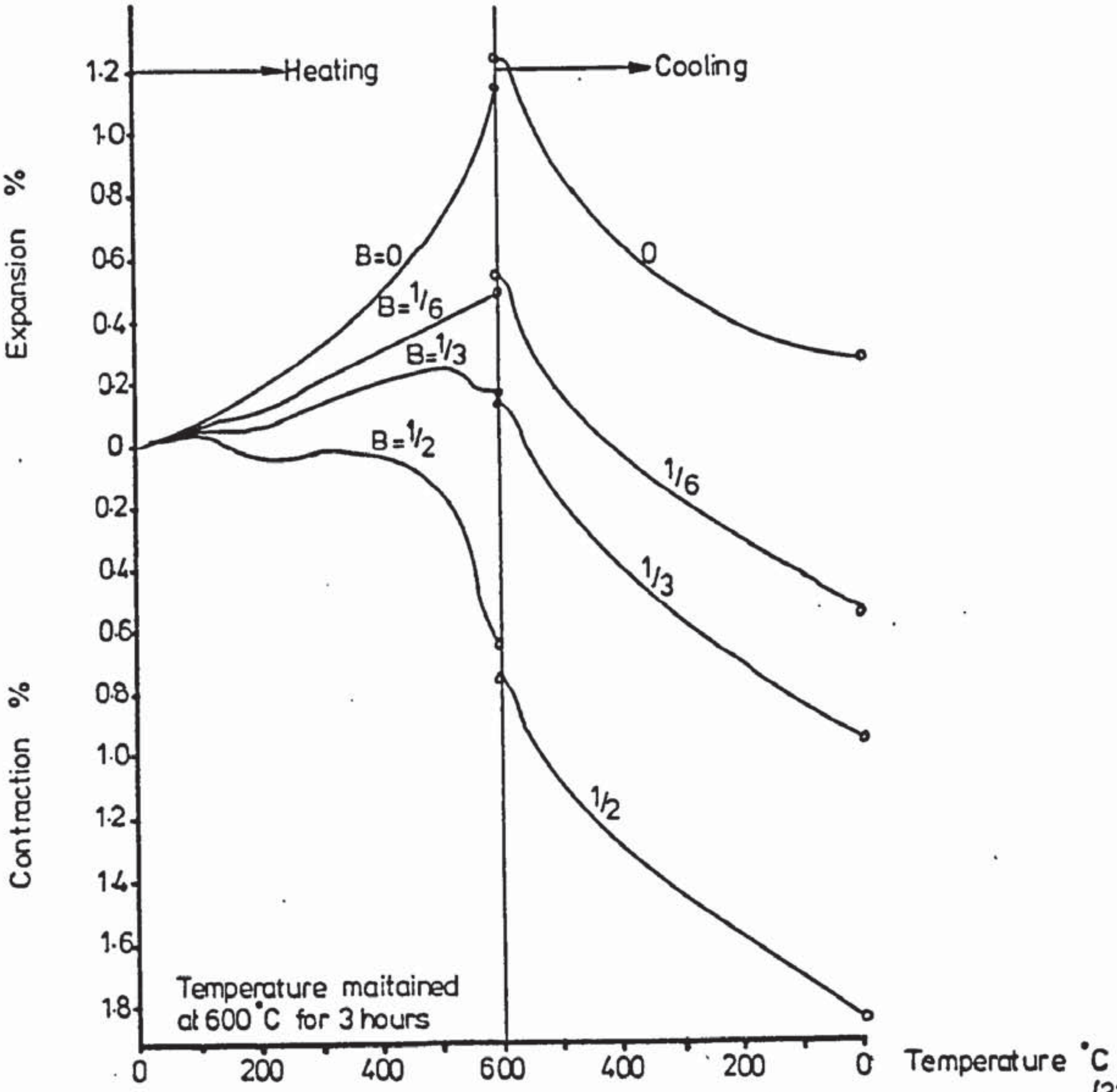


FIGURE 3.4 Strains measured on concrete specimens heated and cooled under load (31)

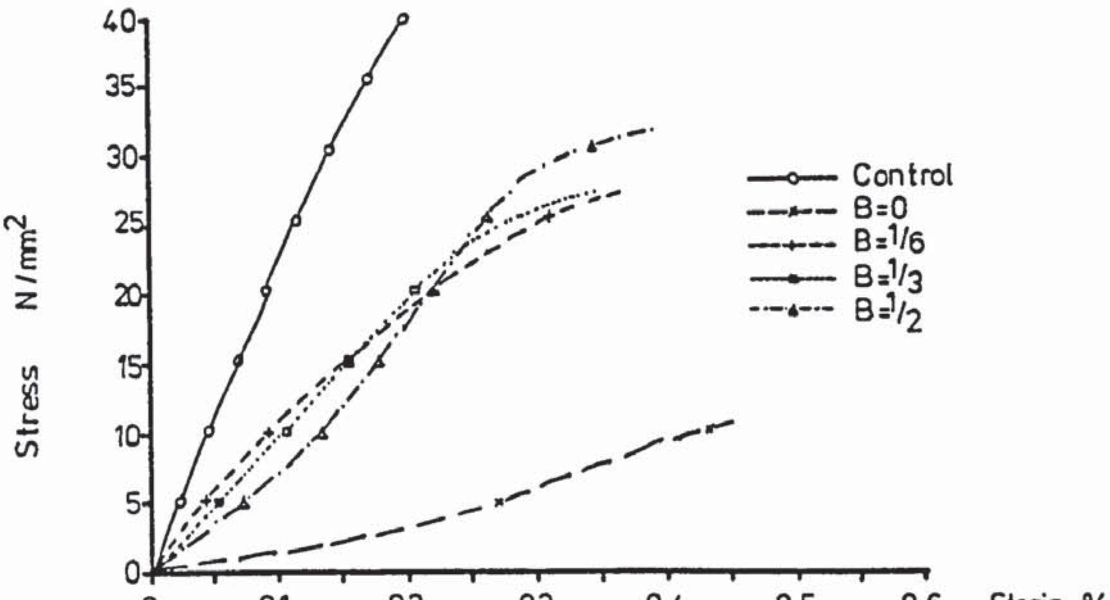


FIGURE 3.5 Variation in Young's modulus for concrete specimens tested under load at 600 °C (31)

B= stress maintained during heating / original strength reinforced beam and agreement between results would probably not be as good. Work by Dougill[32,33,34,35] on walls and columns has shown that restraint may cause premature collapse and indicates a need for more consideration in its effects on concrete properties.

Most of the experimental data obtained has been based upon OPC with little information on the behaviour of lightweight concrete. This may result in behaviour different from the dense concrete. There is no generally acceptable theory that can predict the behaviour of concrete heated to high temperatures under load or restraint, although published work allows the designer to obtain a guide in assessing the susceptability of a structure to fire damage.

3.3 Reinforcing and Prestressing Steel

There has not been a uniform testing procedure applied to reinforcing and prestressing steels when they have been subjected to elevated temperatures. Some of the results on the steels have not been the main objective of a certain test programme but derived from the tests on complete beams. Although the ultimate tensile strength has been consistently reported, some reports do not specify whether it is yield strength (or its equivalent) or the ultimate strength that has been used to obtain the graphs.

3.3.1 Yield Strength

Depending upon whether the steel has been tested at the required temperature or allowed to cool to room temperature before testing influences the results considerably. The temperatures at which the yield strength, as well as the ultimate strength, reduces below the room temperature value, is equivalent to the working stress (usually taken as 0.55 or 0.5 of the original), together with the maximum reduction in strength at the maximum temperature tested are the primary areas of interest.

The effect upon the yield strength with increasing temperature is generally associated with reinforcing steels rather than prestressing steels, although some data [36,37] have given the limit of proportionality for prestressing steel. This, according to Cahill[36] determines the maximum permissible stress in a prestressed wire at elevated temperatures. The reduction in strength has also been obtained for an American prestressing steel[38] with a 50% reduction occurring above 300°C for the British steel and above 400°C for the American steel (Fig.3.6). The yield strength has not been observed after the steels had been allowed to cool before testing.

The performances of hot-rolled and cold-worked reinforcing steels has been investigated separately and together. The general view is that both types behave similarly when tested at temperature. The yield strength only being reduced at temperatures above 300°C and a 50% reduction occurring between 500 and 600°C[4,6,7,40,41]. The exception to this being for an Australian cold-worked steel where a 70% loss at 500°C has been found[42].

The reduction in yield strength for both steels cooled from temperatures below 400°C is negligible but after cooling from between 700 and 800°C the cold worked steels have shown a 30% loss[6,7,41] and the hot rolled steels a 5-10% loss[6,7]. It has also been shown that the size of a cold worked bar has an effect upon the residual yield strengths with the larger bars exhibiting a greater loss after being cooled from temperatures up to 600°C[40].

Some typical results of the yield strengths of both types of reinforcing bar for the two testing situations are shown in Figs.3.6 and 3.7.

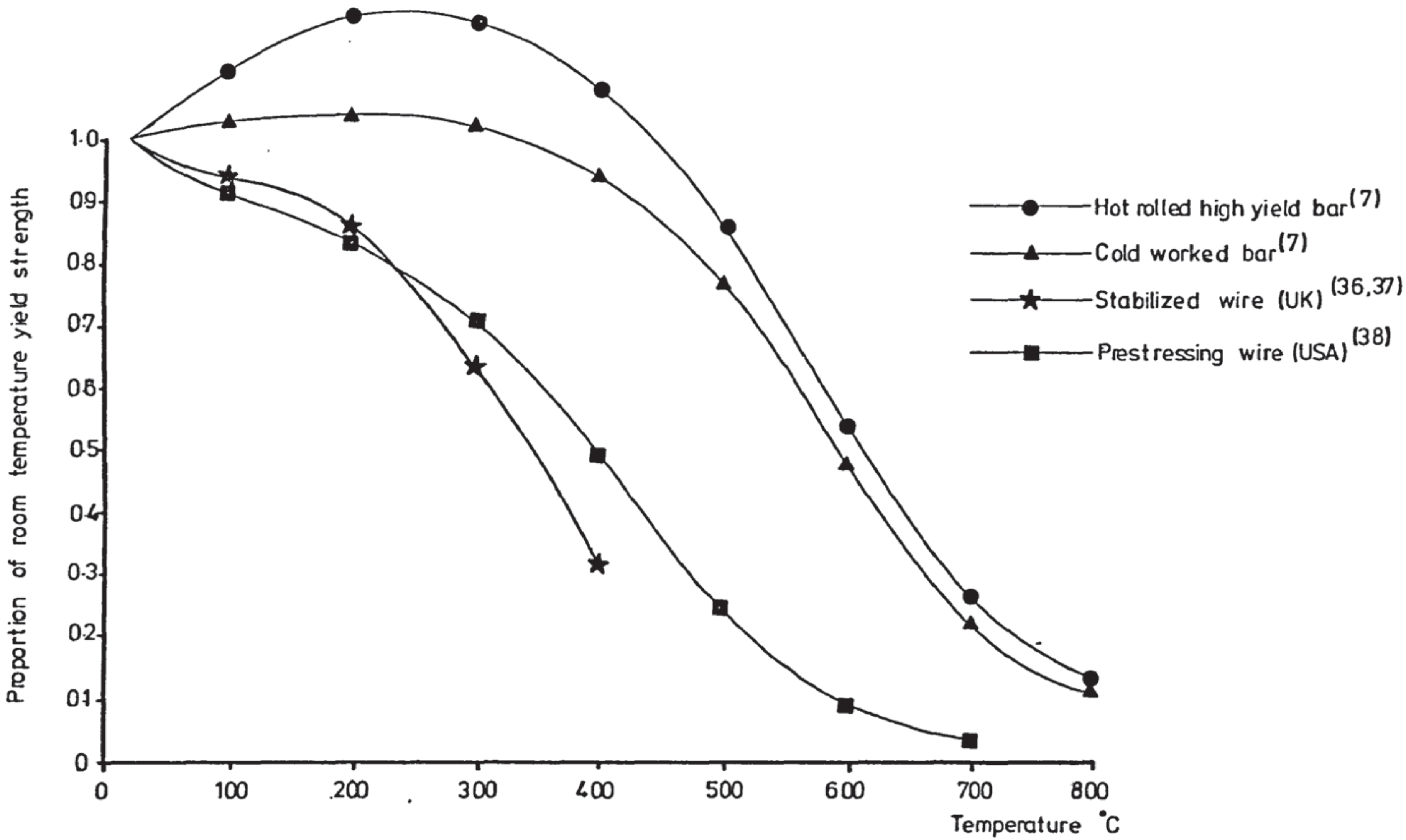


FIGURE 3.6 Typical yield strengths of reinforcing and prestressing steels tested at elevated temperatures

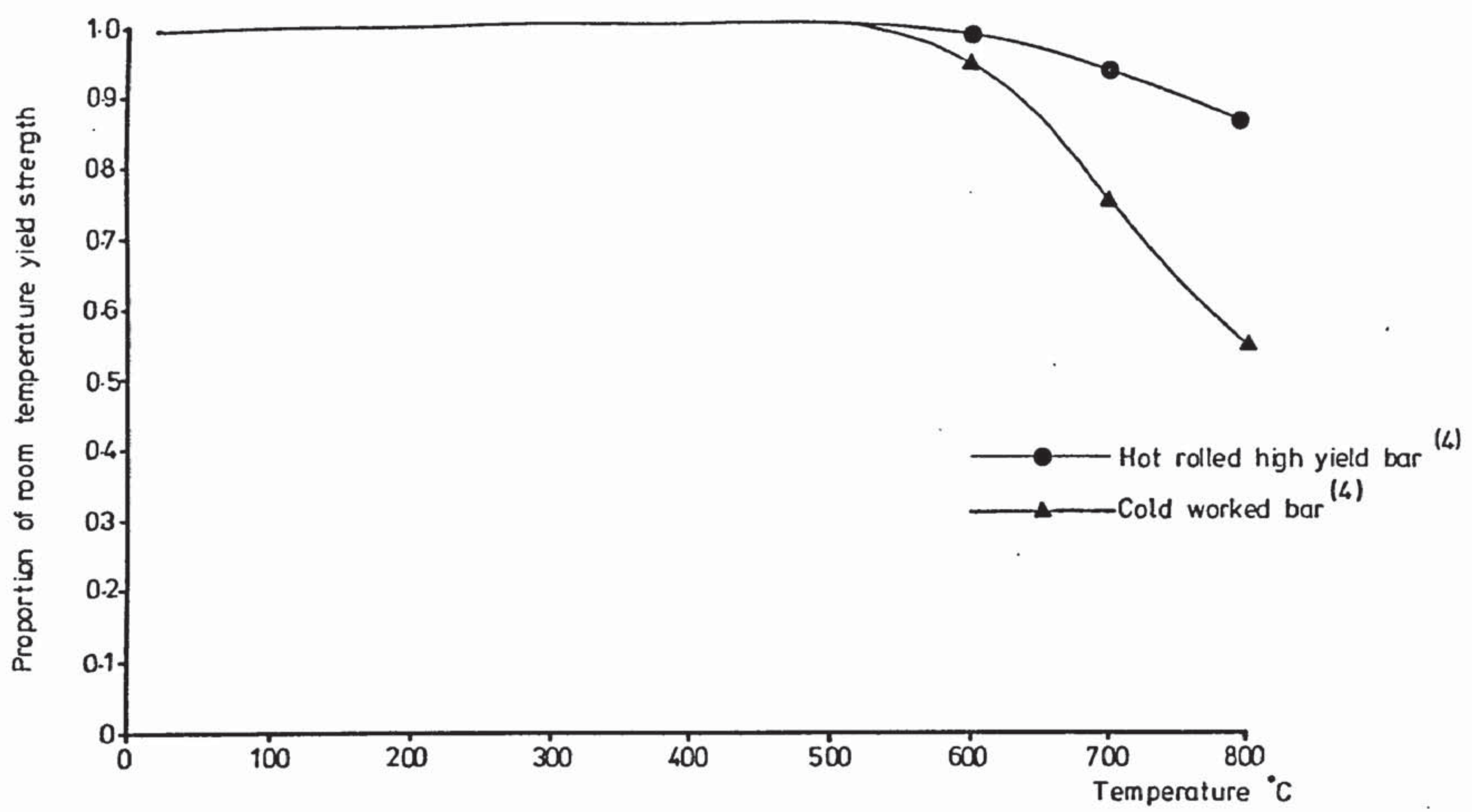


FIGURE 3·7 Typical yield strengths of reinforcing bars tested at room temperature after heating to an elevated temperature

3.3.2 Ultimate Strength

In Germany considerable differences in the ultimate strength have been found between hot rolled and cold worked reinforcing steel of the same original strength when subjected to the same test conditions[43]. Anderberg[44] has found that the strength reduction for cold worked steel is greater due to the fact that the cold working effect is lost at about 400°C. Below this temperature both types of steel do not show a loss in strength[7,45] and an increase of 20% being observed for some hot rolled steels at approximately 200°C[6,7,39,46]. A reduction of 50% from the original strength has been observed when tested between 600 and 650°C[7,45] although Roberts[47] has reported it to occur at 500°C for hot rolled steels.

The residual strength for both steels after cooling from 500°C is similar to its original ultimate strength and above this temperature, as with the yield strength, the cold worked steel displays a greater loss. At 800°C the residual ultimate strength has reduced by 20% for the cold worked steel and 10% for the hot rolled[6,7].

The reduction in ultimate strength for prestressing steels is greater than that for reinforcing steels at similar temperatures[4]. A 10% loss has been observed at 200°C and a 50% loss between 400 and 500°C[36,38,43,46,49]. After cooling from 300°C the strength is unaltered from the original strength[36,48,50] but at 350°C and higher the loss is permanent[4,51]. Typical results for the ultimate strengths are shown in Figs.3.8 and 3.9.

According to one report[43] the point at which the material begins to yield has not yet been defined clearly. Accordingly this yield point should not be compared with the proof stress which is applicable at room temperature and marks the residual elongation of the deloaded steel. To justify this statement the report suggests

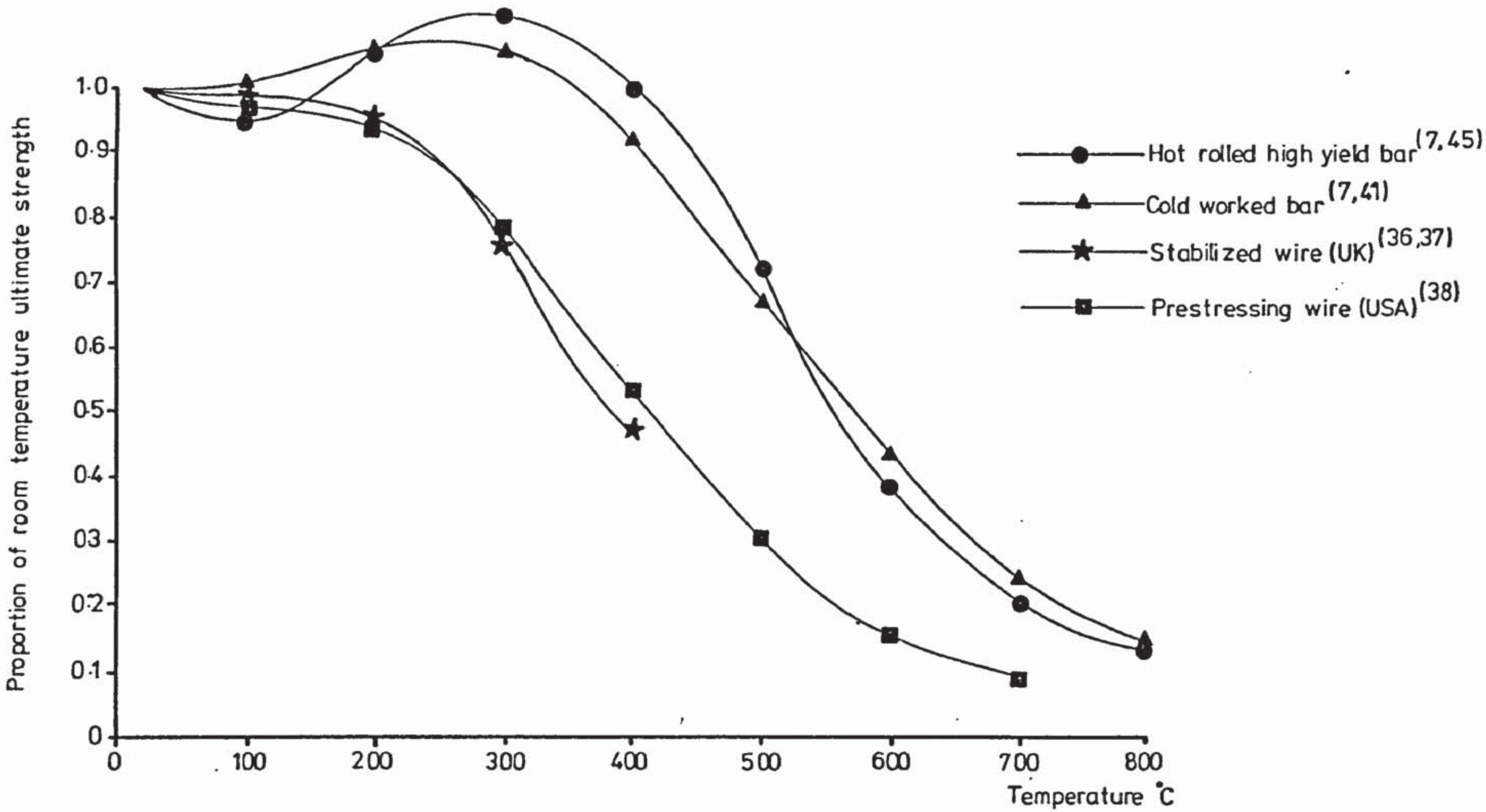


FIGURE 3.8 Typical ultimate strengths of reinforcing and prestressing steels tested at elevated temperature

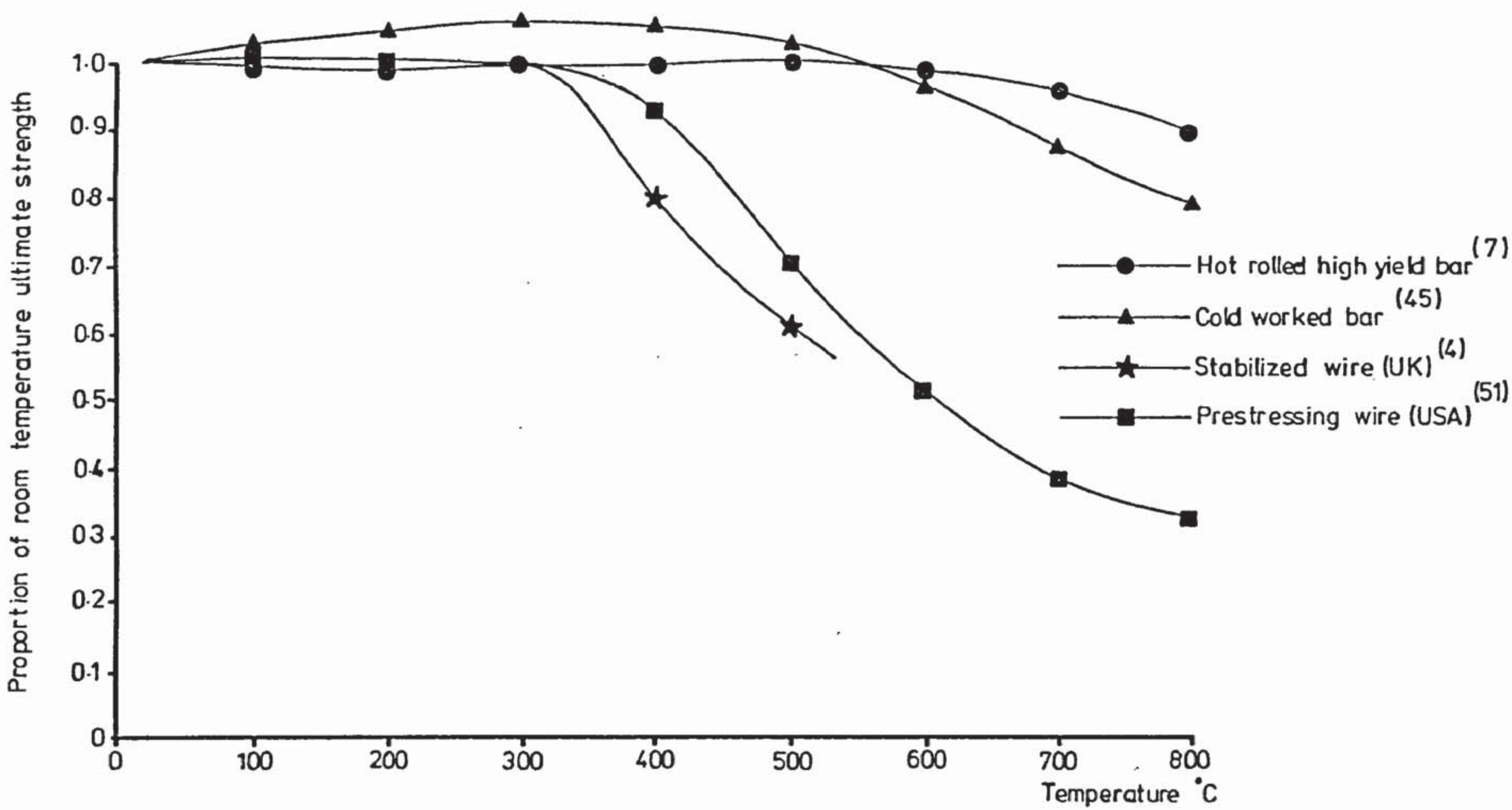


FIGURE 3·9 Typical ultimate strengths of reinforcing and prestressing steels tested at room temperature after heating to an elevated temperature that, when considering fire resistance, the reduced tensile strength be used, since in the high temperatures reached in actual fires the difference between yield and ultimate strengths is small. Although a graph of the reduction in the yield strength with increasing temperature is given (Fig.3.10) a comparison with the ultimate strength is not shown This conclusion has not been expanded further in the report but work by Anderberg(44) on Swedish steels has shown that the strength properties of reinforcing steels are sensitive to temperature increase and the yield stress for hot rolled steels disappears at approximately 300°C. He reports that it is commonly accepted that the 0.2% proof stress is to be used for fire design although a critical stress, based on the real behaviour of a reinforced concrete structure, would influence the characteristic strength value. The concensus from other work is that, although the yield strength is difficult to pin point, a value needs to be obtained to enable it to be used in analysis and design.

3.3.3 Sustained loading

Work on sustained load with increased temperature for reinforcing steels has been limited. Soretz(53), in his work on grade 40 Torsteel bars and smooth round reinforcing steel of Swiss origin, has shown that the cold worked steel when stressed to 80% and 60% of permissible stress at a temperature of 500°C and then allowed to cool, had the same factor of safety as that for the hot rolled steel stressed to the same percentage of the permissible stress.

Work in Russia(54) on two types of 14 mm diameter steel, 20 ГC2 (0.19%C, 1.2% Mn, 2.1% Si, 0.022% S, 0.011% P) and 20 ГC20 (0.2% C, 1.35% Mn, 2.1% Si, 0.027 S, 0.016% P, 0.10% V) which had been tested at 550°C with a stress equivalent to 80% yield stress failed after 4 min and 24 min respectively.

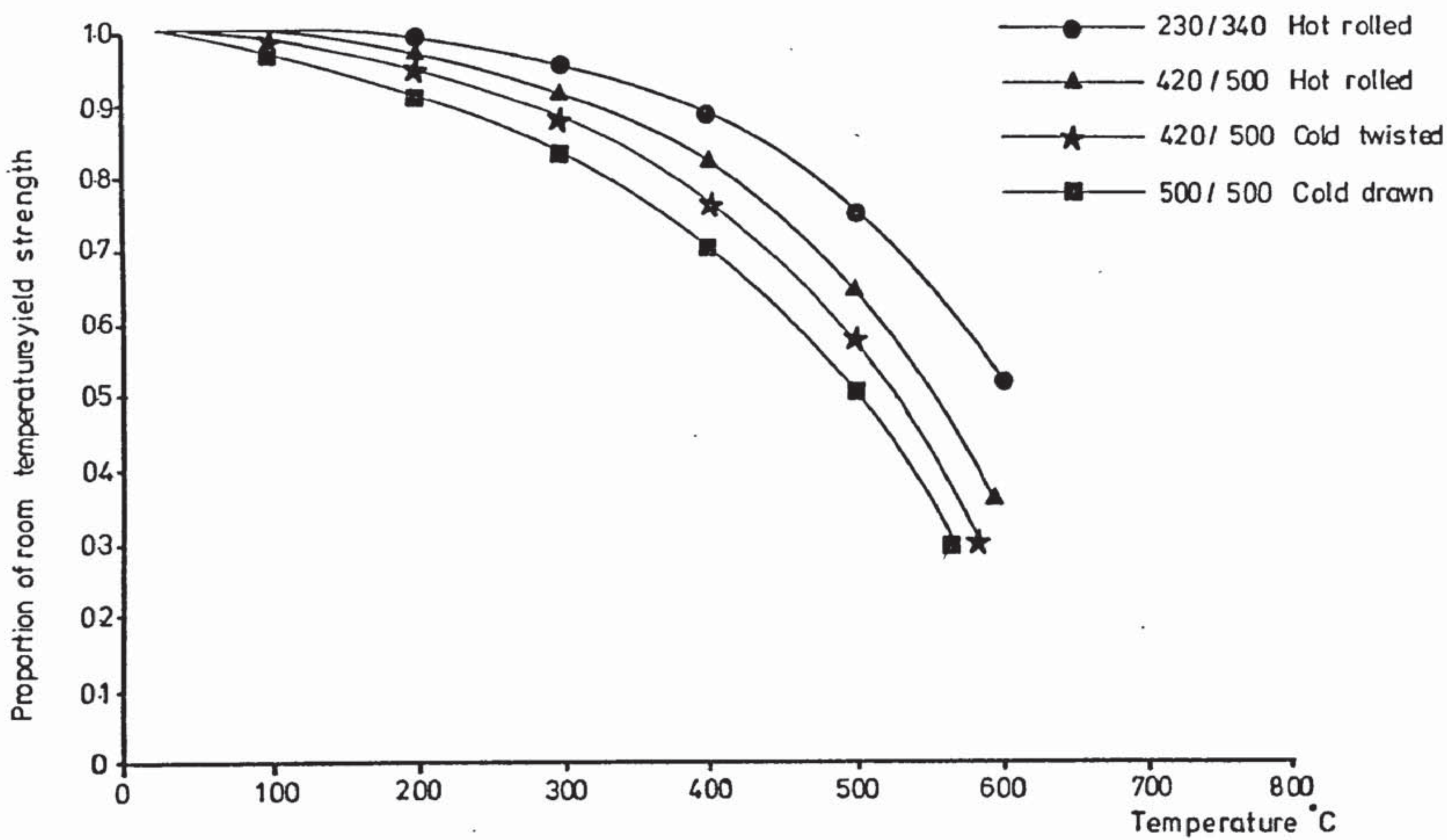


FIGURE 3.10 Decrease in critical strength of reinforcing steels caused by heating (43)

Woodman and Copeland[42] have shown that the results obtained from working load tests on the reinforcing steel show considerable variation with the results from full scale fire tests on structural members. They report that failure would be expected at a temperature in the vicinity of 400°C, whereas, in a fire test, collapse had not occurred at temperatures and times far in excess of those anticipated. Restraint or, because of the differences in the coefficients of thermal expansion of the two materials, the member suffers a redistribution of stresses at elevated temperatures which allows it to survive for longer periods.

The effect of sustained load with increased temperature on prestressing steels was first reported by Bannister[50]. He noted that the most important effect on the prestressing wire contained within a prestressed beam which is subjected simultaneously to temperature and stress, was the effect on the strain in the wire. After cooling a considerable assessment of residual strain was observed from the wire, but this was governed to a great extent by the load on the beam. This permanent 'set' of the wire which results in a loss of prestress due to the reduced tension could be the failure criteria rather than the actual fall in strength of the steel[48]. This is pre-supposing that the prestressed beam remains intact after a fire.

When individual wires and strand have been stressed between 55 and 70% of the ultimate strength, rupture has occurred between 315 and 425°C for the strand[49] and 400°C for the wires[55]. Upon cooling from 350°C the wires had not been weakened and some of the tensile properties had undergone improvement. Cahill[36] also noted that up to 300°C there were no deleterious effects. The wires could therefore be prestressed to the same level and the beams restored to their original load bearing capabilities.

A knowledge of the relaxation of strand and wire at room temperature is a standard requirement when using the material. Cahill[36] has relaxed stabilised and cold worked wires loaded to the limit of proportionality (load at which material deforms plastically) at temperatures up to 400°C for 5 hours. The stabilised wires showed an increased superiority over untreated wires up to 200°C. Over this temperature the results converge until at 400°C there is little difference between the two. The inital losses up to 200°C are severe with the loss becoming more rapid until at 400°C the residual stress is 15% of the room temperature value (Fig.3.11). After relaxation the tensile strengths have improved up to 200°C, decreased slightly at 300°C and progressively decreases as the temperature increases.

A creep model using the Zener Holbman parameter and a dimensionless creep parameter has been applied to an American prestressing steel, ASTM A 421-65, by Harmathy and Stanzak[38]. This gave close agreement between both experimental and theoretical results, and enables a rupture time to be anticipated.

3.3.4 Elastic Modulus

The vast majority of work performed on reinforcing and prestressing steels has, generally, ignored the reduction in elastic modulus due to elevated temperatures. Information concerning elastic modulus can be based on either static or dynamic measurements with the steels being used not normally associated with reinforcing steels.

The dynamic method uses the principle of vibrating a specimen transversely at its reasonant frequency over the temperature range required. This method was based upon that of Forster and Koster[56] with the characteristic frequency depending upon the density and elastic modulus of the material. The results[57,58] for most steels tested under this method show a decrease of about 25% between room

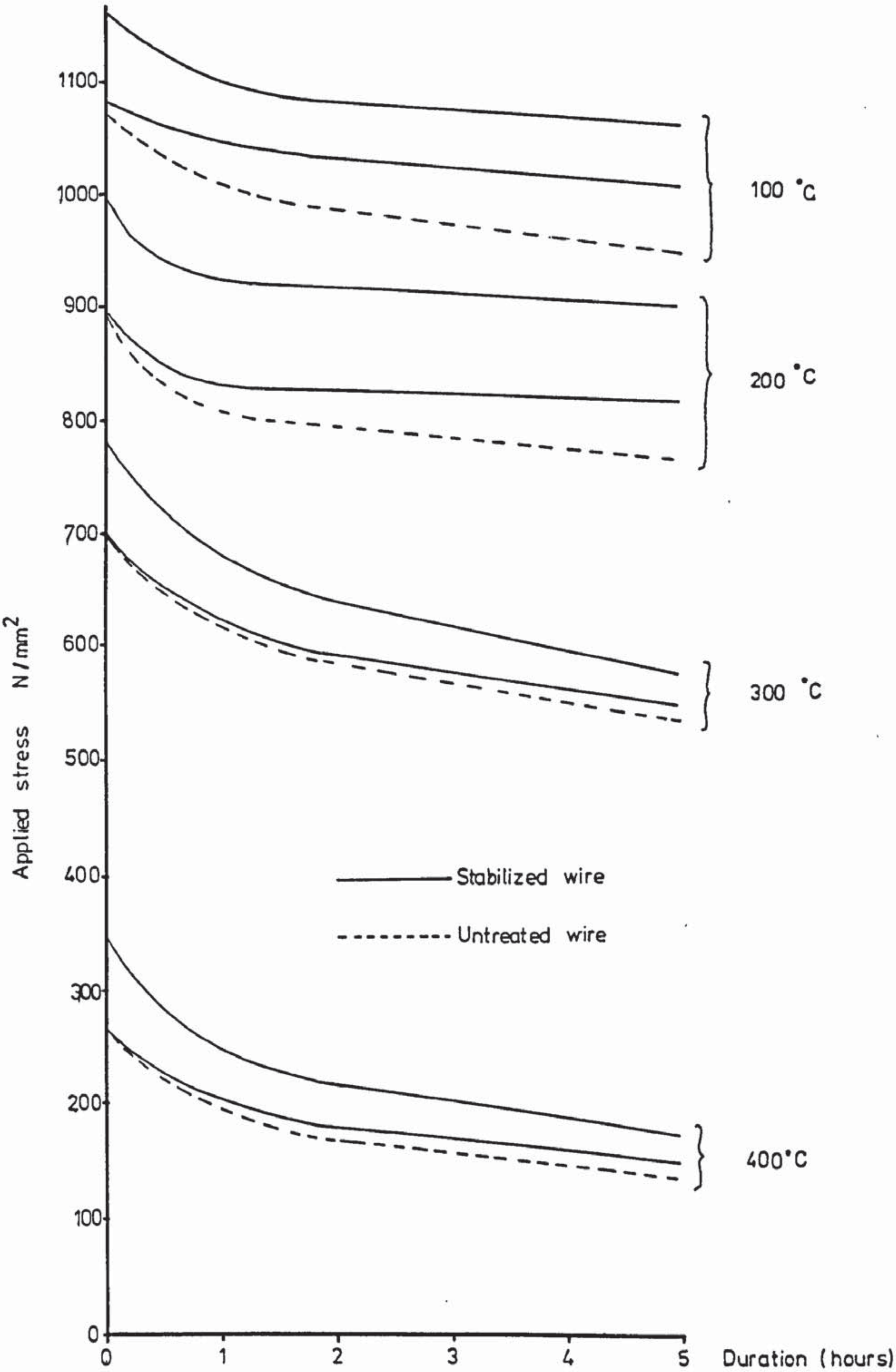


FIGURE 3.11 Relaxation of stabilized and untreated prestressing wires at various temperatures (36)

temperature and 600°C and a 2% variation with the static values.

The static elastic modulus is obtained from tensile tests performed at the required temperature with a stress-strain plot being produced. The linear portion of the plot allows the modulus to be obtained but due to differences in the manufacture and testing of the steels from country to country a close agreement should not be expected. Although the extent of reduction is dictated by the type of steel Australian[42], American[39,59,60] and more recently Swedish[61] results show a noticeable decrease in modulus with increasing temperature (Fig.3.12).

Generally there has been little to suggest any differences in the decrease of modulus between reinforcing and prestressing steels although one report[62] shows a greater decrease in elastic modulus for prestressing steels than given for some American reinforcing steels.

3.3.5 Thermal Expansion

Odeen has reported[63] that the results from three German reinforcing steels show the coefficient of thermal expansion to be quasi-linear (Fig.3.13) whereas Woodman and Copeland[42] have shown it to be constant up to 300°C but with an increase of approximately 20% above this temperature for Australian reinforcing steels. This,as with the elastic modulus values, suggests that type and country of manufacture of the steel influences the property to be measured. However, Soretz[53] fifteen years after his original investigation on 106 samples from 19 steelworks in eight countries, has shown that the change in production of reinforcing steel bars during this fifteen year period had no significant influence on their behaviour in the case of fire. The results showed a scatter which was approximately the same as that for the tensile tests at room temperature. However, the information regarding the residual properties after the loading sequence are sketchy and do not give any conclusive results.

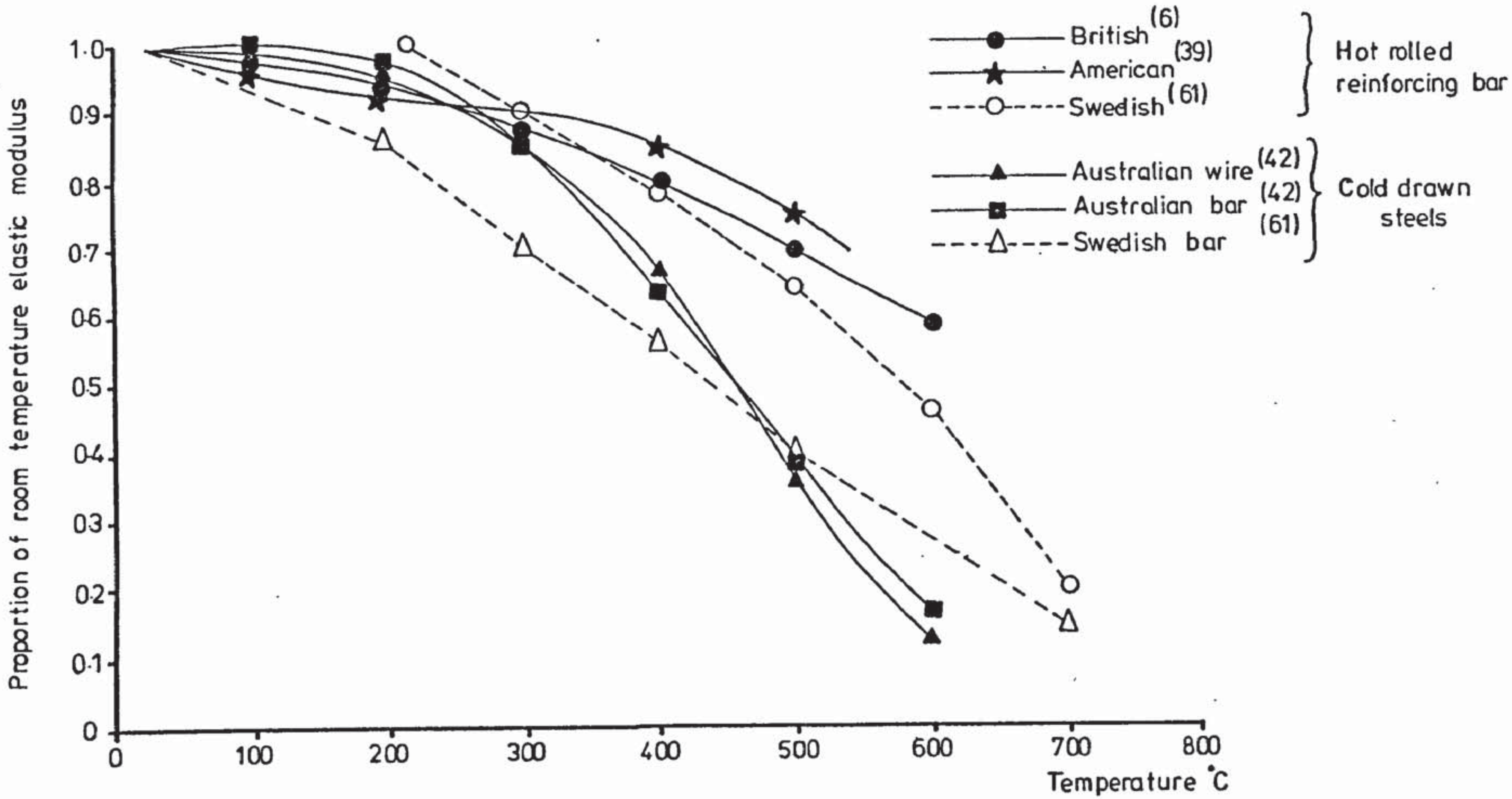


FIGURE 3.12 Effect of temperature on elastic modulus of reinforcing and prestressing steels

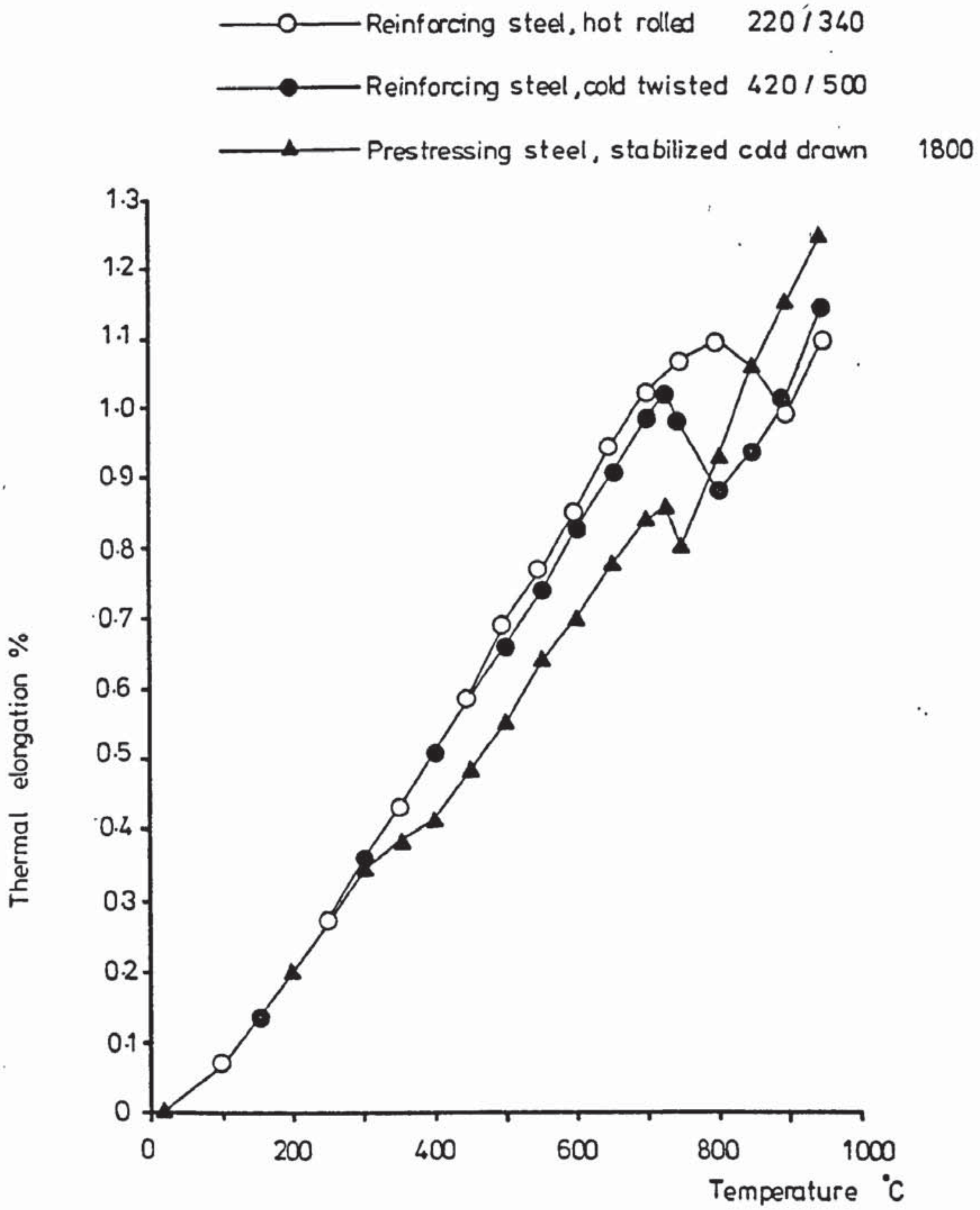


FIGURE 3.13 Thermal expansion of reinforcing and prestressing steel (63)

3.4 Composite Sections

3.4.1 Temperature Distribution

An attempt has been made[64] to obtain a direct and simple comparisons between the time-temperature curve of a furnace and that of a fire. This did not provide a meaningful relationship and subsequent heat transfer calculations show significant differences between the two situations.

However, the standard heating curve[1] has been used to obtain the temperature distribution within any cross-section under non-steady state conditions by using the Fourier equation. The resultant temperature distributions for various cross-sections and times of exposure are given in recent publications by the Institution of Structural Engineers[65] and FIP/CEB[43]. Based on these, the temperature of the steel, whether it is reinforcement or prestressing, can be estimated anywhere within the desired section (Fig.3.14).

3.4.2 Analytical Considerations

Ellingwood and Shaver[66] have investigated the methods for analytically predicting the behaviour of simply supported reinforced concrete beams subjected to fire conditions and have obtained a relationship which makes it possible to form idealised curves for both concrete and steel at elevated temperatures from the idealised stress-strain curves of both materials at room temperature. These idealised curves are assumed to be made up of straight lines with the yield stress, elastic modulus and coefficient of thermal expansion up to 1150^{o}C being obtained.

Anderberg[44] has discussed a rational fire design methodology of reinforced concrete structures based on actual performance of a real fire exposure in which the development of simple design methods

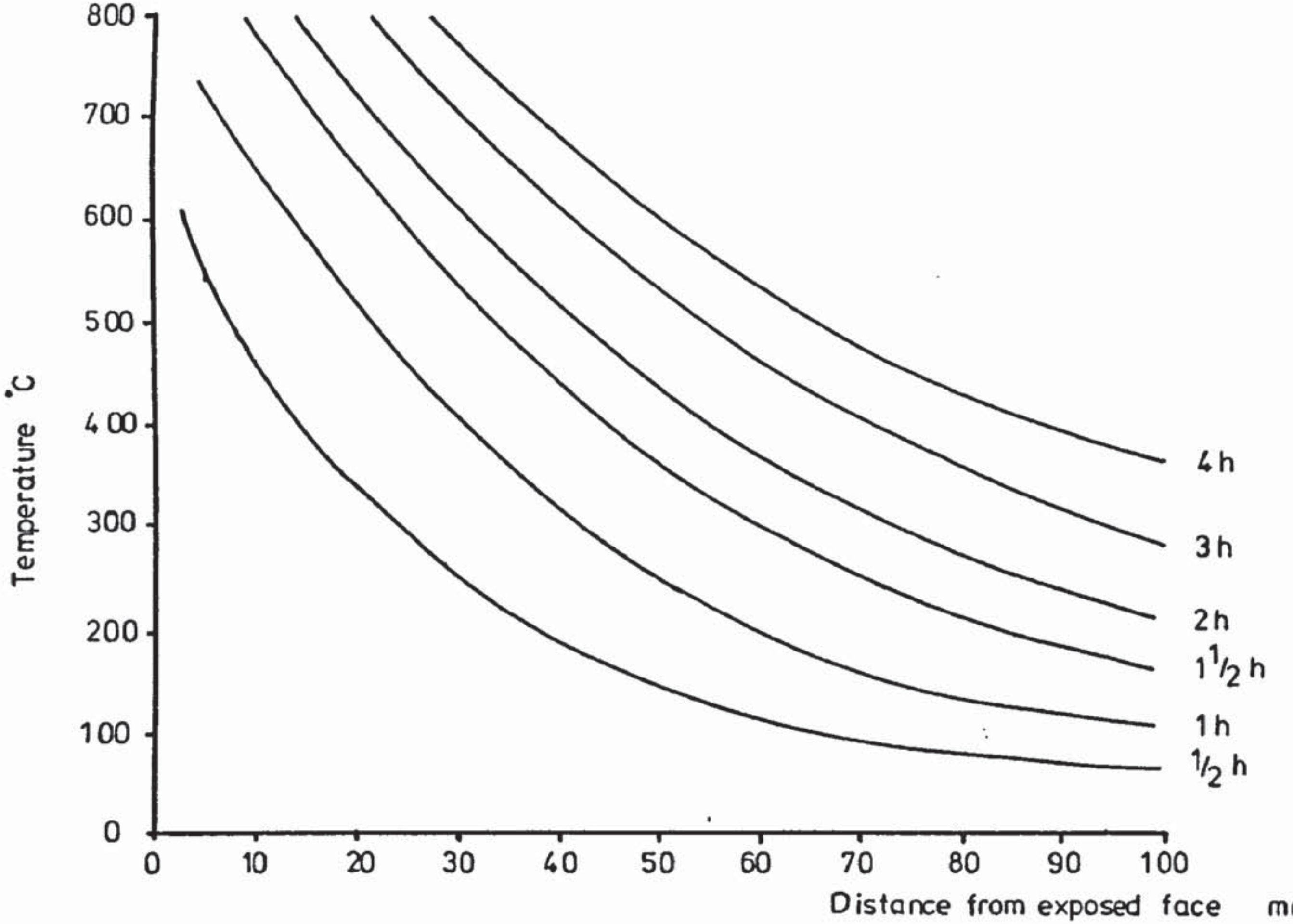


FIGURE 3.14 Temperature distributions in a concrete slab for dense concrete (concrete density - 2300 kg/m^3)

of analysis that concerns reinforced concrete cross-sections is used. These methods are based upon an analytical study of structural behaviour currently in progress in Sweden.

3.4.3 Design Methods

Publications by the Institution of Structural Engineers[65], FIP/CEB[43] and Heron[67] have summarised the information obtained from individual research results so that the Engineer is in position to decide the elevated temperature effected on each component of structure. Design curves for both concrete and steel (Figs.3.15 and 3.16) produced by the Joint Committee[65] are a simplification of the available experimental results. However, they give a basis from which the design and detailing for fire resistance can begin. This data is primarily aimed at the British Engineer since the fire exposure used is based on the standard fire resistance test of BS 476 : Part 8[1] and on the current standards used for the production and design of structural concrete[5]. A similar procedure has been recommended by Heron[67] whereby the material properties at elevated temperature (shown in Fig. 3.15 and 3.16) could be taken and the ultimate load calculations prepared as for normal temperatures. The approach adopted by the FIP Commission[43] is to use selected individual results from worldwide research from which it should be possible to make an assessment of the reduced load-bearing capacity of a structure due to the transfer of heat. A specific approach is not given but the design or checking for fire resistance of a structure based on different approaches is categorised. These are:

i) Fire resistance test data

ii) Tabulated data on minimum sizes derived from fire tests

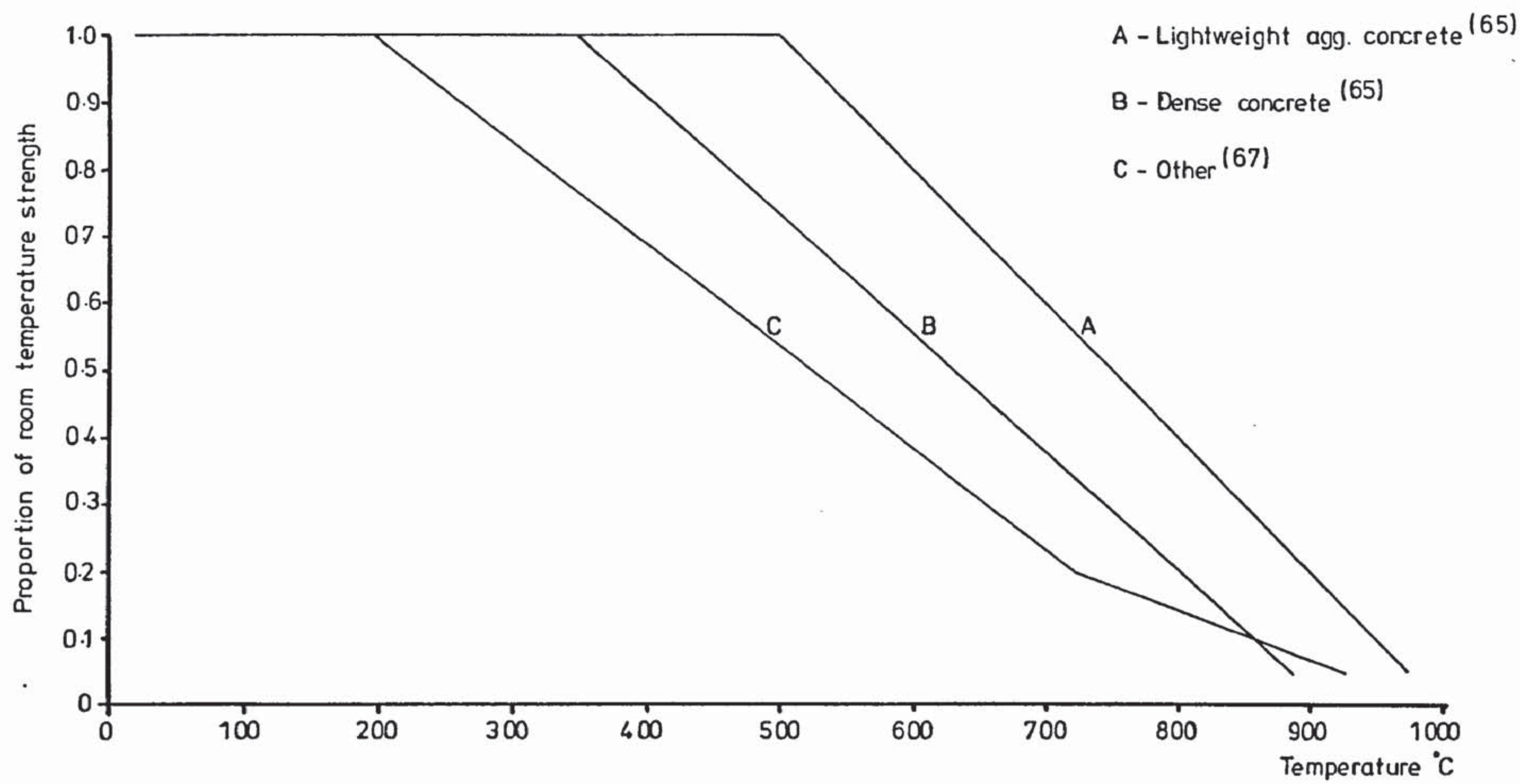


FIGURE 3·15 Design curves for variation of concrete strength with temperature

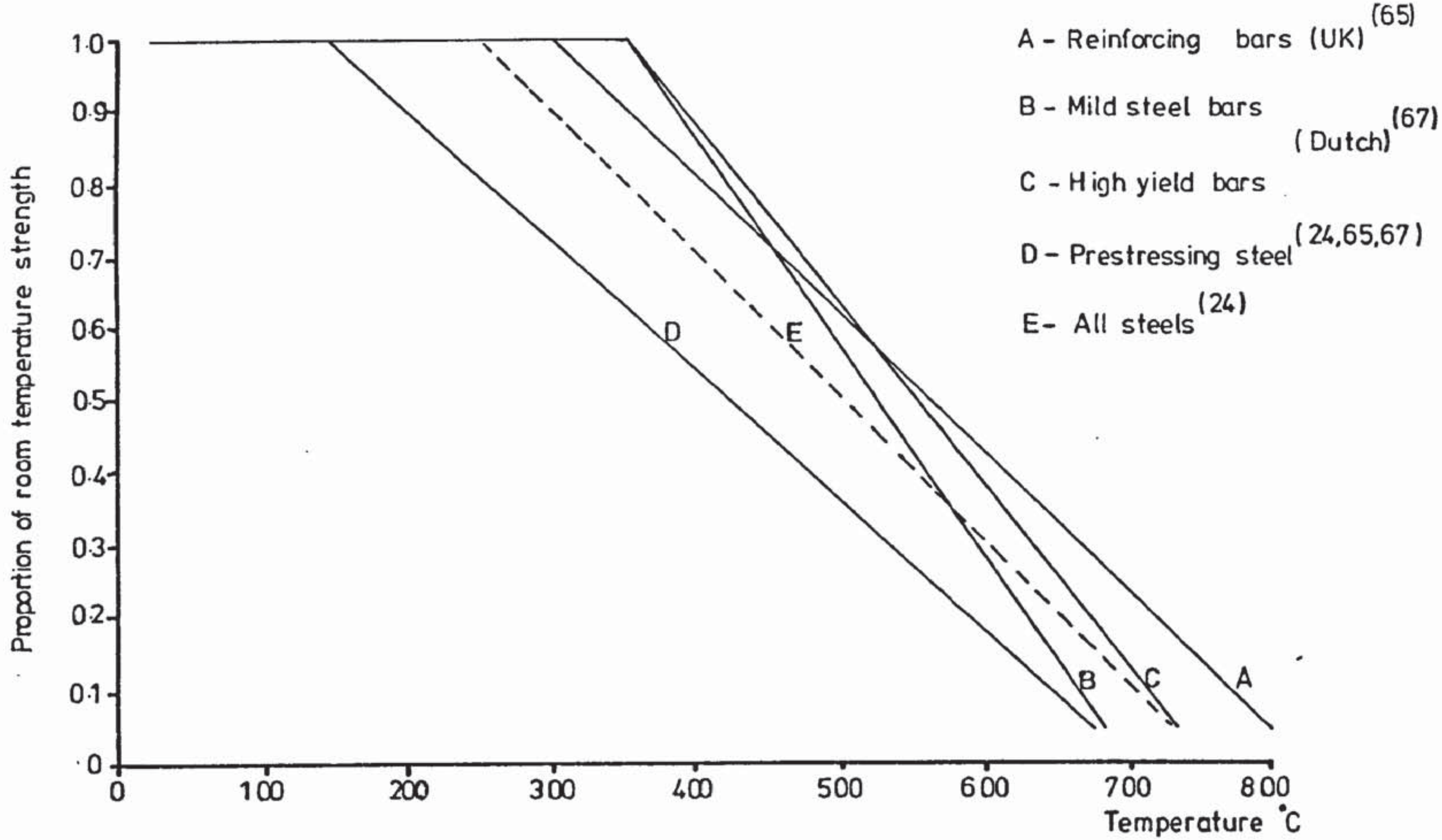


FIGURE 3.16 Design curves for variation of steel strength or yield stress with temperature

iii) Emperical relations based on fire tests

iv) Computational techniques

Anchor[24], in his review of the various documents which provide methods of assessing the fire resistance of structural concrete elements, has noted that the choice of particular grade of reinforcing steel has little effect on the fire resistance if the temperatures are not greater than 500°C. For a rational design the calculation for the fire resistance of simply supported elements assumes, that for all types of steel, the yield/proof stress is assumed to be constant up to 250°C and then vary linearly to zero at 750°C.

One major item absent from the effect of temperature on structural concrete is the effect upon the bond between the concrete and steel. This aspect has not been documented although work is currently being undertaken to fill this gap in the knowledge of the performance of structural concrete at elevated temperature.

CHAPTER 4

Test Rig and Associated Instrumentation

4.1 General Specification of Equipment

At the time when the investigation commenced a suitable piece of equipment was not available to perform the tests. It was therefore necessary to obtain either from a proprietary manufacture or within the department itself, the required test rig and instrumentation that would enable the required experimental data to be collected. Certain specifications to the performance of the testing machine and instrumentation were decided upon before any design was commenced. It was accepted that the first design would not allow for all the tests to be completed without any modifications to either the test machine, or the testing procedures. However, it must be possible to perform most of the tests on the original design which also had to be flexible enough to allow slight changes in the actual test programme.

The main criteria for the test rig was that it should be:

(i) able to perform tensile tests

(ii) machine stiffness many times greater than specimen stiffness

(iii) free from vibration and shock

(iv) friction between moving parts kept to a minimum

(v) allow the specimen to be loaded axially

(vi) no torque applied to the specimen

(vii) safe and easy to use

(viii) allow access for all instrumentation

(ix) able to test the specimens in the 'as rolled condition'

(x) design to comply with BS 449[15]

Certain specifications were needed for the instrumentation and heating equipment, they were:

(xi) uniform heating rate applied to specimen

(xii) furnace large enough to allow for largest specimen and gauges

(xiv) temperature controllable do that a temperature occurred along the full length of the heated zone

(xv) strain measurement to be flexible enough to cope with all sizes of specimen and yet accurate to within the limits given in BS 18[16] and BS 3688[17]

(xvi) data to be recorded continuously throughout the tests

All the above points are discussed fully when each item of equipment is described later. The design calculations for the test rig are given in Appendix A and only the final conclusions given in the following text.

4.2 Test Rig

This was the most important item of equipment in the whole research project as the test rig must be capable of performing all the necessary operations to obtain all the required information. Firstly it was necessary to decide upon what type of test was going to be performed, what was to be measured and the maximum size or loading the equipment would be expected to accommodate.

In Chapter 2 it was decided that all the tests would be of tensile type without any compression tests. A tension machine having the versatility to take the size and length of specimen that had been decided upon, with the required deformation under load and temperature was not commercially available. Therefore, a special purpose machine had to be designed and built.

Working on the basic concept of two load plattens moving apart, a design was formulated which involved the use of two parallel plate frames combined within each other through bushes in one of the plattens and separated by a loading mechanism. Since the only available one was a 1000 kN hydraulic ram, manufactured by Losenhausen, with a mode of operation by the extension of the central core, it resulted in one parallel plate frame being in compression and the other in tension.

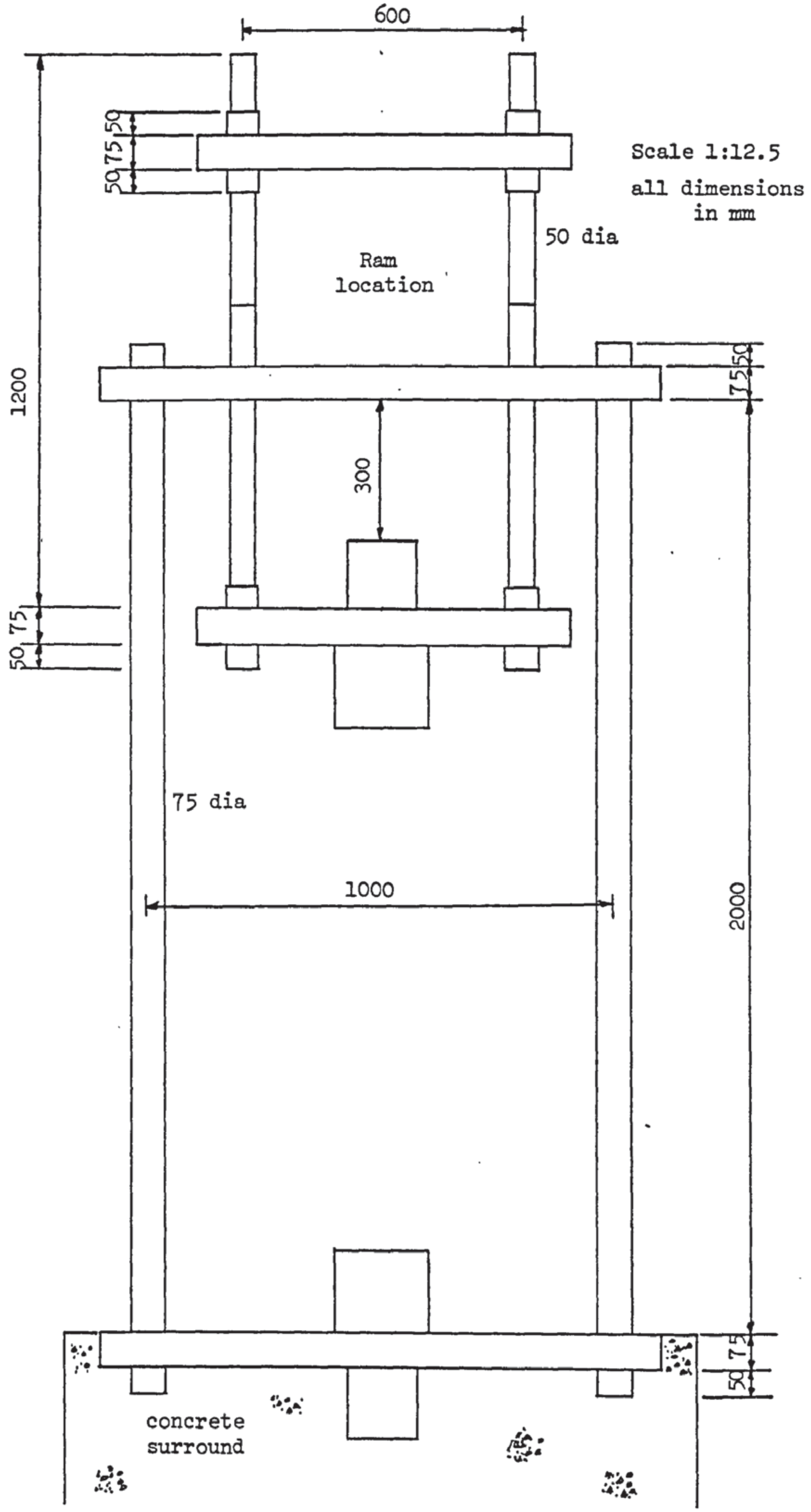
Appendix A gives the design calculations for the main plates and columns and a diagram of the final arrangement is given in Fig. 4.1.

The ram itself had an overall maximum extension of 150 mm, however, the extension expected from the mild steel specimens was approximately 300 mm and a method of obtaining the extra travel was required. This was obtained by placing two jacks under short columns connected to the top plate. When there was an extension of 150 mm the ram was then unloaded and the top plate allowed to rest on the jacks. When the ram had fully retracted a 150 mm spacer could be inserted between the ram and the top plate and then reloaded. This gave the extra 150 mm travel required without taking the specimen out of the test rig. Plate 4.1 shows the jacks and spacer in position.

4.3 Specimen Anchorages

After deciding upon the overall testing frame a method of gripping the specimen was the next requirement. The fact that all the specimens were to be tested in the 'as rolled condition' restricted the possibilities of connection. A method of placing a threaded section

FIGURE 4.1 Test frame arrangement



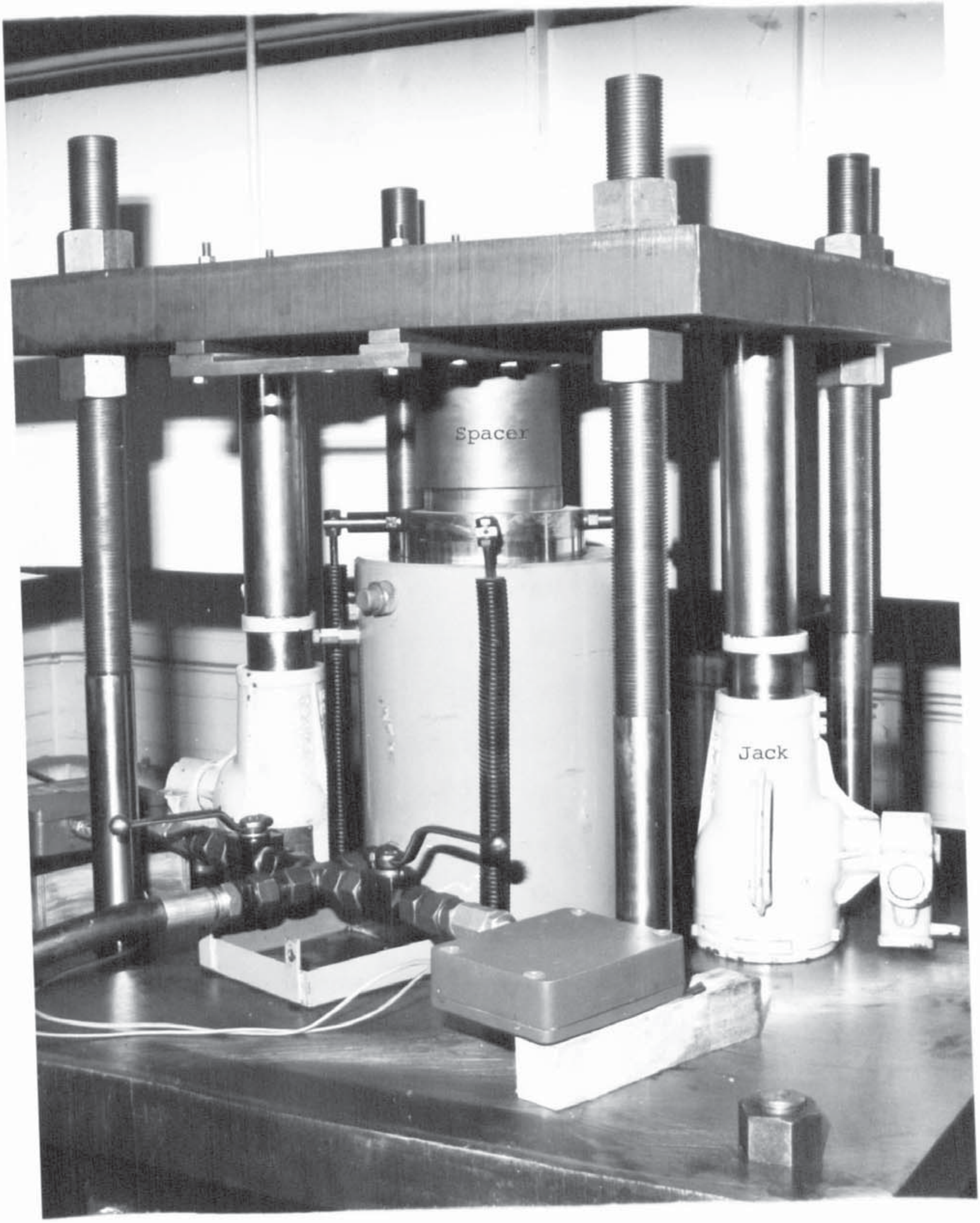


Plate 4.1 Jacks and 150 mm Spacer in Position

on the specimen was considered but this would result in a reduced cross-section especially where the deformed bars are concerned. Having a reduced area would cause premature failure within this region instead of the anticipated failure near or at the gauge length zone where all the measurements were being taken.

The possibility of welding a larger cross-section onto the specimen either by arc or friction welding was considered. Both of these operations would result in high temperatures being applied to the specimen and cause a potentially weak area away from the gauge length. Another disadvantage with this method was that the welding operations, 2000 were anticipated, were costly in terms of man hours and equipment.

The final option was to have mechanical wedges which would clamp the specimen along part of its length as it was pulled through the tapered wedge blocks. The teeth in the wedges would indent into the specimen resulting in it being securely fixed into the wedge blocks. This method was typical of the sort used in most tensile testing machines and after looking at the other possibilities, it was decided that this system would be flexible enough to accommodate the different sizes and shapes of material to be tested.

4.3.1 Wedge Block

After deciding upon the method of gripping the specimens it was necessary to design a suitable wedge block and wedges. The design took the form of two stages with the first being the connection to retain the wedge block against the main plates and the second the design of the upper block where the wedges would be housed.

A 150 mm diameter hole was bored into the two main plates and through this would fit the lower section of the wedge block. A 3 mm clearance was allowed on this section, through which a pin would pass giving the block some lateral movement and a degree of rotation. This pin would need to take the full force applied to maximum specimen size and was therefore manufactured from a high grade steel. The movement about the pin would allow the specimen to be loaded axially and prevent any torque or movement being applied to it.

Appendix A gives the design calculation for the pin and advocates the use of a 50 mm grade 55 steel pin with a minimum bearing length of 50 mm either side of the lower section of the wedge. To retain the pin in the correct position and allow for rotation, angle section of 20 mm thickness was attached to the underside of the main plates through which the pin would pass and have retaining pins either side of the angle plates. Fig. 4.2. shows a general arrangement of the pin assembly.

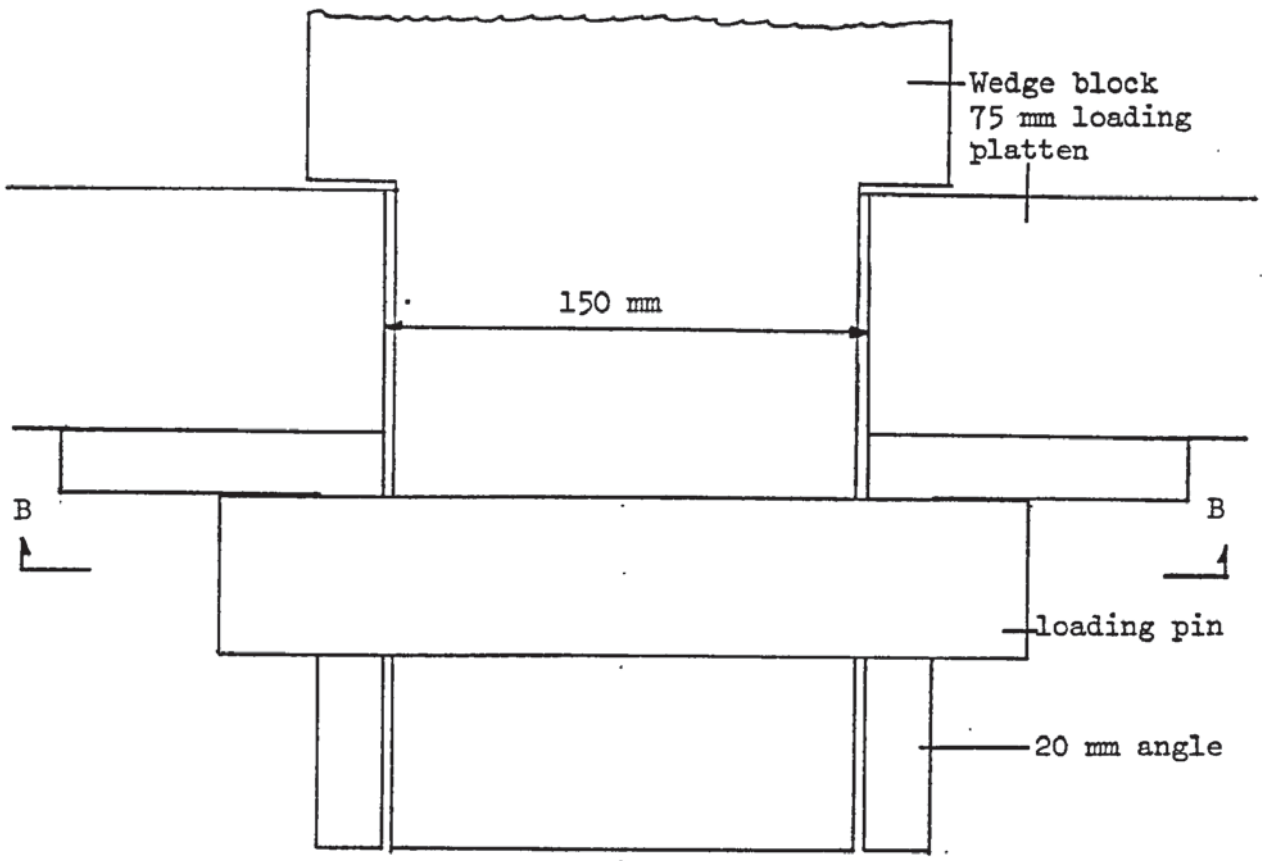
To allow for the force applied to the specimen to be distributed against the walls of the wedge block, a wedge angle had to be decided upon. This angle would allow lateral movement of the gripping surfaces when the wedges were moved up and down. Limited to an overall section size of 200 mm, a 9° angle was chosen with a minimum distance of 45 mm from the lower corner to the side of the section.

Appendix A gives the design calculations used to check the critical stresses against the allowable ones given in BS 449[(15)].

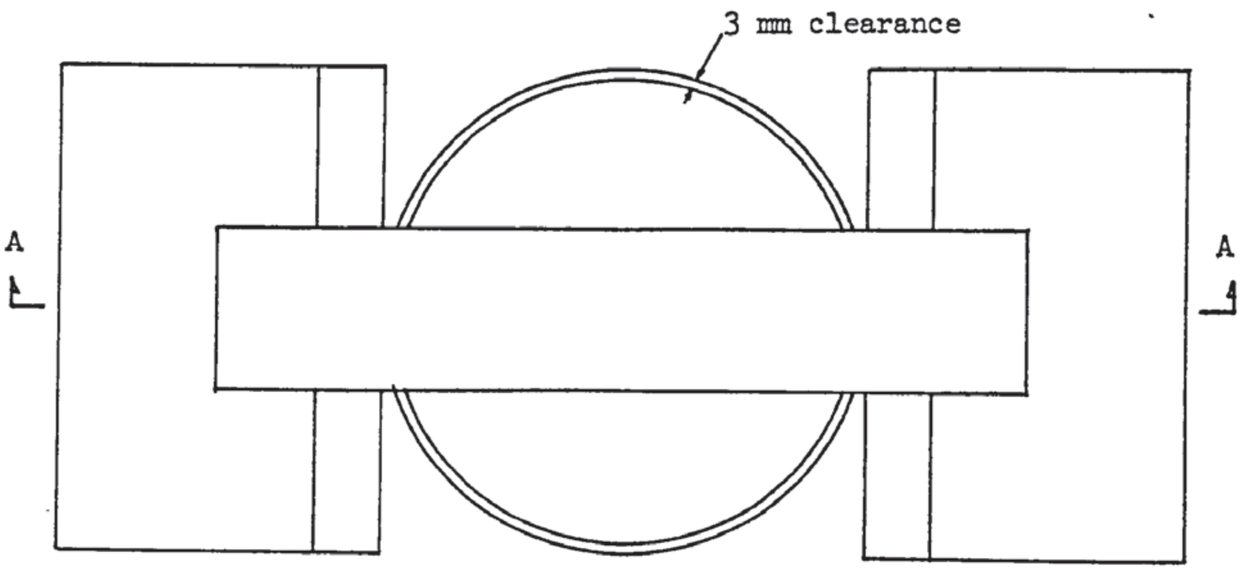
4.3.2 Wedges

So that the full range of specimens could be gripped, two sizes of wedge were necessary. One pair for sizes up to 20 mm and the other for the range 20 - 30 mm. The difference between the pairs was the depth and alignment of the teeth and the thickness of section.

The alignment of the teeth were such that the specimen would be gripped along four separate rows of teeth approximately 90° to each other. After looking at wedges from proprietory machines and



Section A-A



Section B-B

FIGURE 4.2 Loading pin arrangement

actually drawing to scale the specimens and wedge aperture, the depth and alignment of the teeth was arrived at. Although this configuration would not suit all the shapes of the specimens due to the deformation, ie, ribbing along their surfaces, the main criteria than when fully gripped, the wedges did not protrude out of the wedge aperture. The wedges were manufactured from EN24 steel and then hardened to a Rockwell hardness number of 55 to protect the teeth from wear and damage.

To enable the wedges to gain some purchase onto the specimen during the initial loading, it was necessary to be able to move both wedges simultaneously. A tie bar, connected to one wedge and moving in a slot in the other, placed at the back of the pair was used. A key, with teeth cut in the diameter, that would fit into one wedge and engage in teeth on the wedge block, would enable the one wedge to move in the wedge aperture. Turning the key would result in both wedges moving simultaneously due to the connecting tie. To allow the wedges to move smoothly, slots were placed both in the wedges themselves and the wedge block. Plate 4.2. shows the wedges for the smaller size with the connecting tie, slots, teeth and key hole clearly visible.

4.3.3 Prestressing Anchorages

The testing programme called for the prestressing steel to have tests performed upon it similar to the reinforcement steel. However, the wedge arrangement described above in Section 4.2.3 was not suitable for testing the prestressing steel. This was discovered during the tests and it was therefore necessary to develop a suitable arrangement to enable the prestressing steel to be tensioned. Prestressing anchorages were obtained,(Plate 4.21, in the hope that they would fit under the reinforcing wedges causing the prestressing

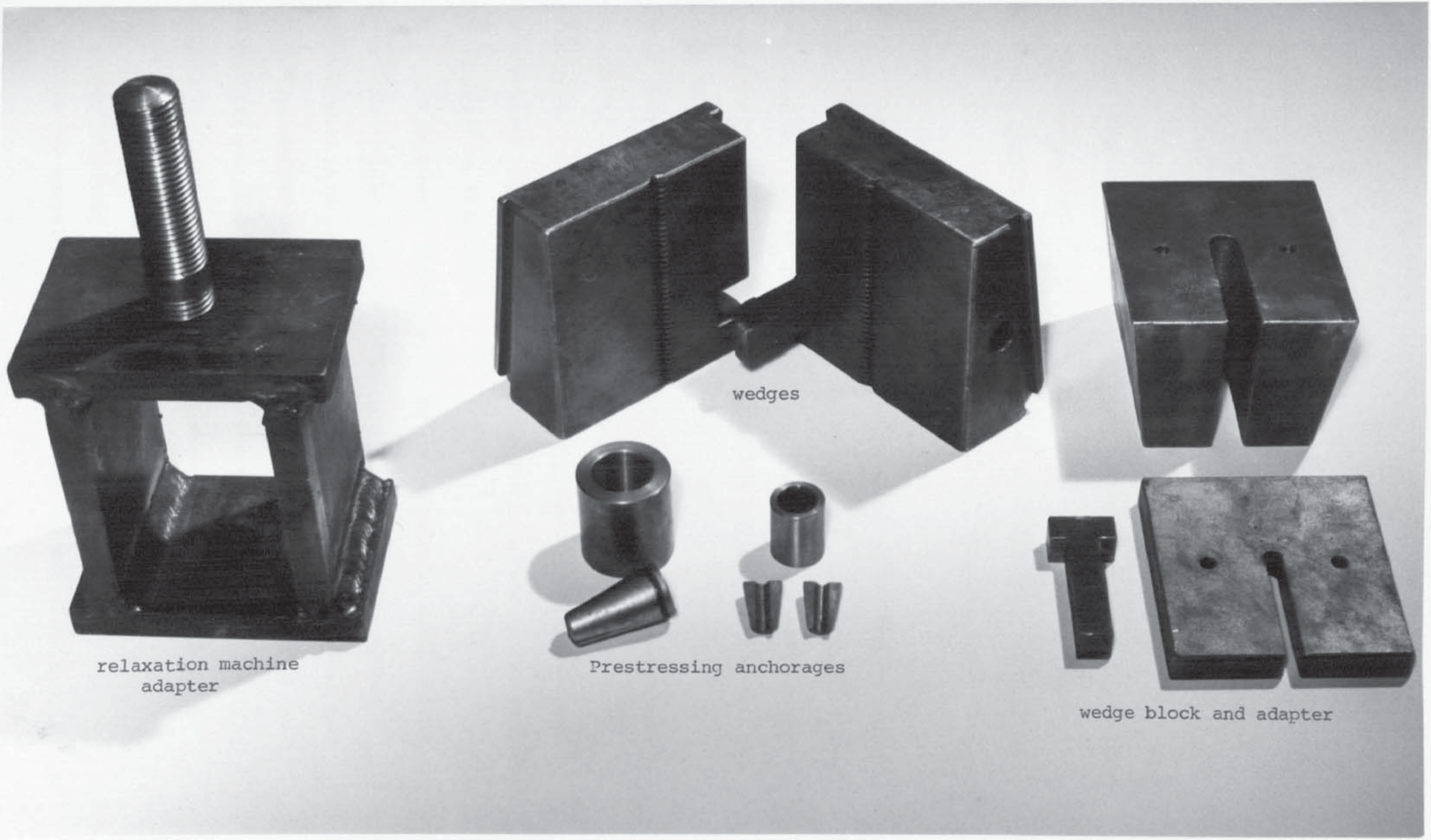


PLATE 4.2 Specimen Anchorages

steel to be tensioned against the underside of the wedges by the anchorages and not gripped by the teeth of the wedges.

However, the anchorage barrels were too large to fit under the wedges and this resulted in a solid wedge being developed with a removable slotted plate, so that the two different sizes of wire and strand could be accommodated,(Plate 4.2). The slots on both the main wedge and the removable plate were designed so that the prestressing steel would be loaded centrally through the testing frame and 'T' sections,(Plate 4.2), and were placed in the slot during testing to prevent the wedge from becoming distorted due to the wedging action of the wedge blocks.

Another limitation to the testing frame arose when relaxation tests on the prestressing steels were performed. The equipment being used could not record the decay in the load to the accuracy required. Arrangements were made to use a proprietory relaxation machine situated in the Department of Metallurgy.

Anticipating the use of this machine an adaptor was designed and manufactured to transfer the load through the movement of the cross-loads to the specimen. This adaptor was a box arrangement through which the specimen would pass and then locate in the anchorages and is shown in Plate 4.2.

Unfortunately during the tests the relaxation machine produced large fluctuations in the recorded plot which made it unusable. Attempts were made to correct this error but were to no avail and even organisations outside the University who were contacted could not perform the necessary tests. It was therefore not possible to obtain the relaxation results on the three prestressing steels.

4.4 Instrumentation

Since the majority of the main testing rig was to be made in the

the Department's workshop, with the larger items being manufactured by or through Aston Services Limited, it was necessary to obtain equipment that would supply and monitor temperature, strain and load.

4.4.1 Furnace and Furnace Control

A maximum specimen temperature of 700°C was required, which resulted in a furnace having an upper limit of approximately 1000°C to allow for heat losses. A cylindrical tube furnace was chosen with an inner tube diameter of 87.5 mm which had been dictated by the size of the largest specimen and strain gauge. This inner tube was made from silicon which had the electrical heating elements wound around it. The option of having a split furnace to ease the setting up procedure was considered, but the extra cost (double the straight tube) would not be compensated by the ease of assembly. The silicon inner tube was protected in a large diameter stainless steel tube with the void being filled with insulating material. Due to heat losses through the ends of the furnace from draughts and convection and the need to obtain a low temperature gradient over the heated length, a three zone furnace with each zone 150 mm long was obtained. These zones were independently controlled by using Eurotherm thyrister units and by using a preselected temperature on the digital display, with the temperature on the measurement coming from a Ni-Cr/Ni-Al thermocouple attached to the specimen. The variable power inputs to each zone could be set to obtain the required temperature over the whole of the heated length. To reduce the heat losses during testing Meckechnie Ceramic Wool Fibre was lightly packed into the top and bottom apertures of the silicon tube.

To enable a second sample to be heated whilst the first was being tested under temperature, duplicate sets of furnace and controls were obtained. The controls were contained within a mounting box and the furnaces were suspended on arms which were pivoted to the test rig. The furnaces could be locked into position using taper threaded locking screws which in turn were mounted on split collets to allow easy rotation of the furnace assembly. Fine adjustment of the position of the silicon tube was possible by having slots on the suspending arms through which the bolts of the furnace passed.

4.4.2 Strain Measurement

The need for accurate strain measurement is paramount when the objectives include the determination of yield stress and elastic modulus. The methods of measuring and recording the strain are limited when it is considered that the gauage length is confined within the furnace which has an operating temperature in excess of 700°C. Electrical strain gauges to withstand such temperatures are extremely expensive and are not reusable. Standard mechanical gauges cannot be read or assembled within the confines of a tube furnace. The solution was to have a mechanical device connected to the specimen over a set gauge length but having the measuring device outside the furnace. The extensometers shown in Plate 4.3. were chosen and it was the method of recording their displacement that needed further consideration. Two transducers were decided upon as they would give a continuous record of the extensometer displacement which would be fed into a computer or to a plotter. These transducers were type D2/500A manufactured by PDP Electronics Limited with an operating range of ±12.5 mm and temperature range -10°C to +50°C. By using the ceramic wool in the end apertures of the furnace the temperatures would be kept low enough to prevent the upper temperature limit being exceeded. This was checked using thermocouples, when a 700°C test was being performed, and the maximum temperature recorded at the transducers was 45°C. The transducer output was fed into an amplifier from which

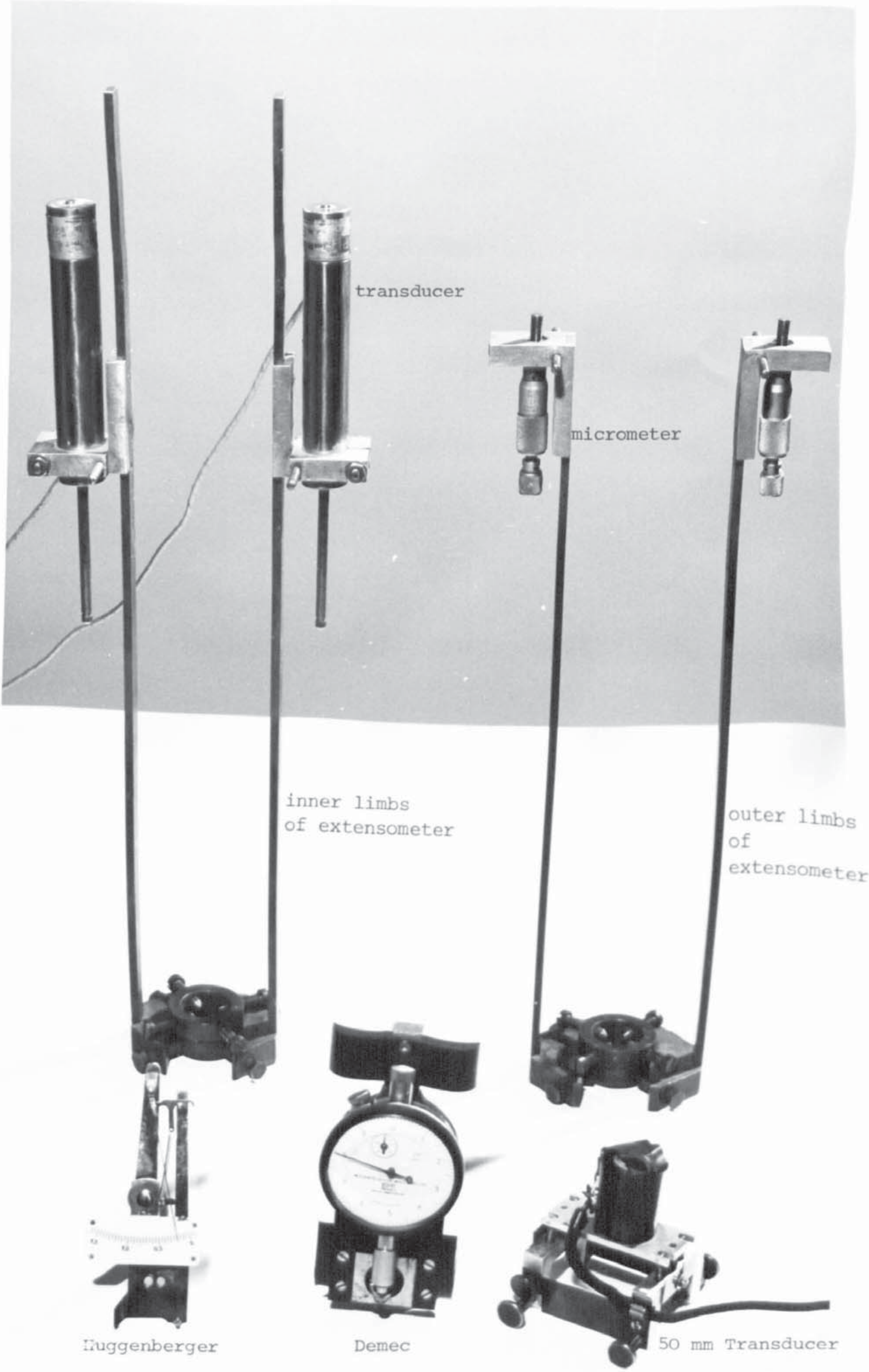


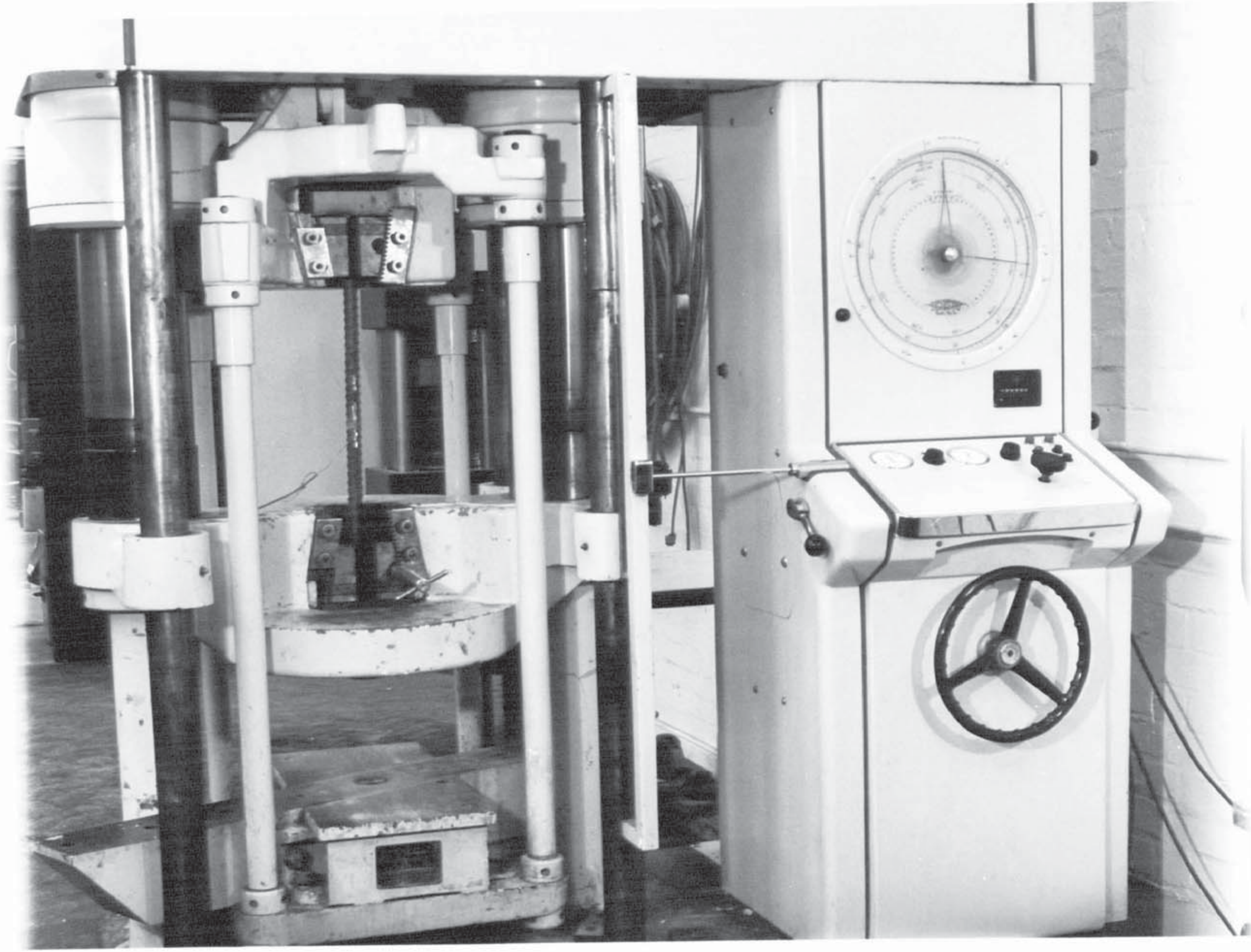
PLATE 4.3 Strain Gauges

the output could be that from a single transducer or an average of both transducers.

Quartz was considered the best material for the extensometers themselves since it had extremely low thermal expansion properties. However, the frailty of such material, considering 1000 tests were to be performed, ruled out its use. Nimonic 80A was chosen which would have low creep properties over the temperature range envisaged but, as later discovered in the initial temperature tests, succeptable to thermal expansion. By using a detachable collet and pointed fixing screws, all the sizes of steel could be used with one size of extensometer. The ability to move the position of the transducers allowed for different gauge lengths to be accommodated and calibration was made easy with metric micrometers onto which the transducer barrels rested.

It was decided that room temperature tests should be performed in another testing machine, an Avery Denison type T42 B4 was available (Plate 4.4), as well as the main testing rig. However, the extensometers could not be used in the Avery Denison machine due to the restriction between crossheads. It was therefore necessary to use another form of strain measurement and then check it against the extensometers. Unfortunately the strain gauge associated with this machine, which gave a continuous plot of load against extension, could not be detached and used on the test frame. This gauge was a Baldwins strain gauge (Plate 4.3) based on a 50 mm gauge length and capable of accepting specimens up to 30 mm diameter. Extension of the gauge length resulted in an armature moving a small transducer which was then input into a graph plotter. Also input, was the load from the machine which resulted in a continuous plot of load against extension. The magnifications on the axes could be adjusted to give a well proportioned

PLATE 4.4 Avery Denison Type T42 B4 Testing Machine



graph over the full size of paper, which then could be converted into stress and strain. Therefore, a third gauge was needed, so that it could be calibrated against the Denison gauge and then the extensometer. In fact three other gauges were used in the calibration and these were:

(i) Huggenbergers (Plate 4.3) - two knife edges, one moveable, one fixed, which converts the movement onto a pendulum pointer on a scale. Usually used in pairs, the gauges are fastened directly onto the specimen.

(ii) Demec gauge (Plate 4.3) - two circular discs, called demec spots, are adhered to the specimen using araldite at a set distance of 50, 100, 150 or 200 mm. The gauge fits into the centre of the spots and has one moveable point which records the extension on a dial gauge.

(iii) Electrical strain gauges - a thin film, its size depending upon its usage, containing a wire element is adhered to a prepared area of the specimen using an appropriate adhesive. Movement within the element causes a voltage change which can either be picked up on a Pekel Wheatstone bridge arrangement or a data logger and converted directly into strain.

One of the major disadvantages with the above is that they only record discrete values which reduces the likelihood of recording the yield point accurately. Also, large strains, usually after yield, become difficult to measure. Section 6.2.2 gives details of the calibration carried out to check both the Denison gauge and the extensometers. Plate 4.5 shows the high temperature extensometers attached to a 25 mm unisteel specimen (furnace not shown) together with the wedge block and wedge arrangement.

4.4.3 Load Application and Measurement

The load was applied by means of a 1000 kN Losenhausen hydraulic ram operated from a type EP320 controller (Plate 4.6). The controller was capable of operating several rams and its central position resulted in it being some distance from the testing frame.

The ram had a 150 mm diameter piston with a travel of 150 mm. It was fitted into the upper section of the frame and place centrally between the columns (Plate 4.1). The self weight of the frame resulted in a quick compression of the extended piston but without the load it took a full five minutes for the piston to revert to its original position using only the return springs.

The need to record the applied load continuously resulted in the decision to obtain either a load cell or pressure transducer. The load cell would register the applied force between the ram and loading plate which would then be converted into an electrical output. The pressure transducer would record the pressure exerted by the hydraulic oil which was being pumped into the ram. This method was given preference over the load cell arrangement mainly due to the high cost of the load cell and instrumentation.

Since 75% of the tests would be performed within the range 0 to 200 kN, it was decided to obtain a pressure transducer with good accuracy over this range rather than one to cover a much wider range resulting in less accuracy at the lower loads. The yield and proof loads were expected to occur below 200 kN and loads above this would

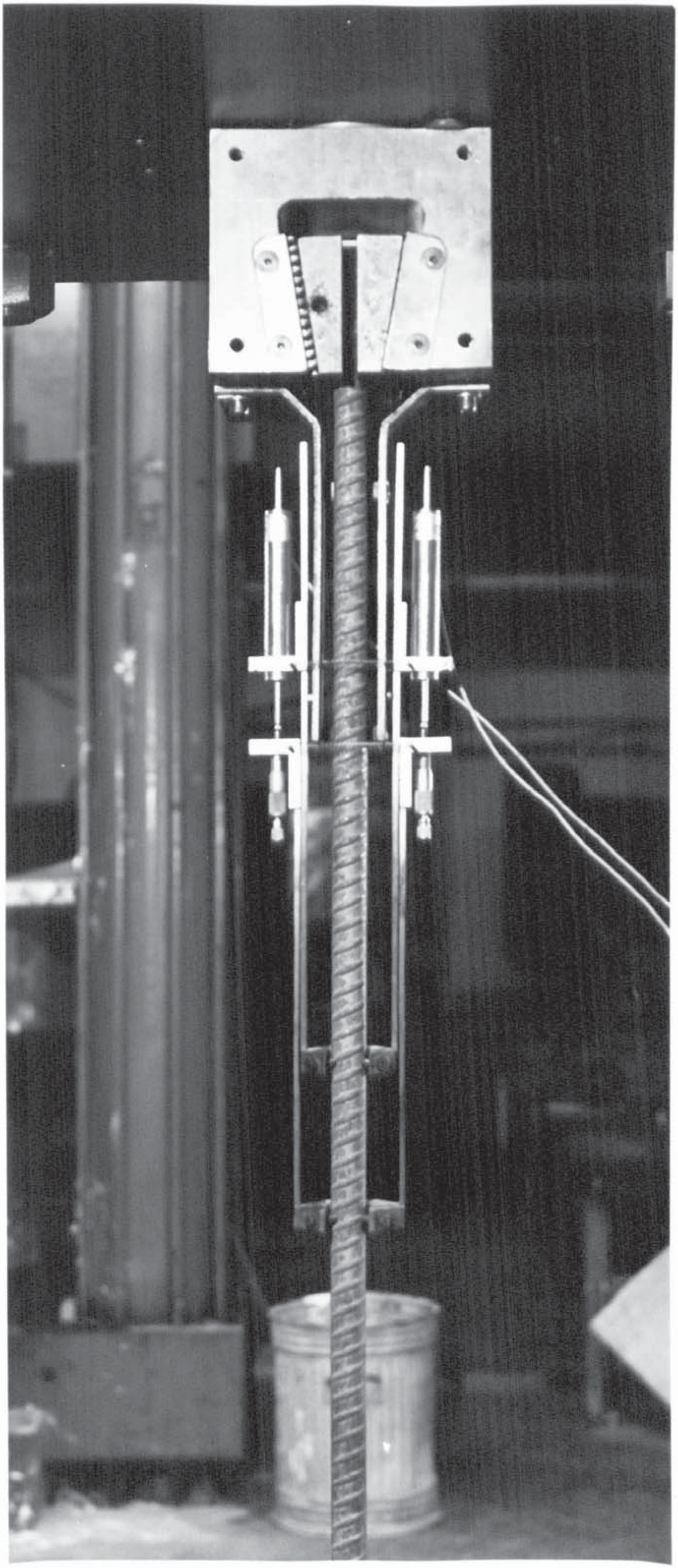


PLATE 4.5
Arrangement of gauges and wedges for tensile test

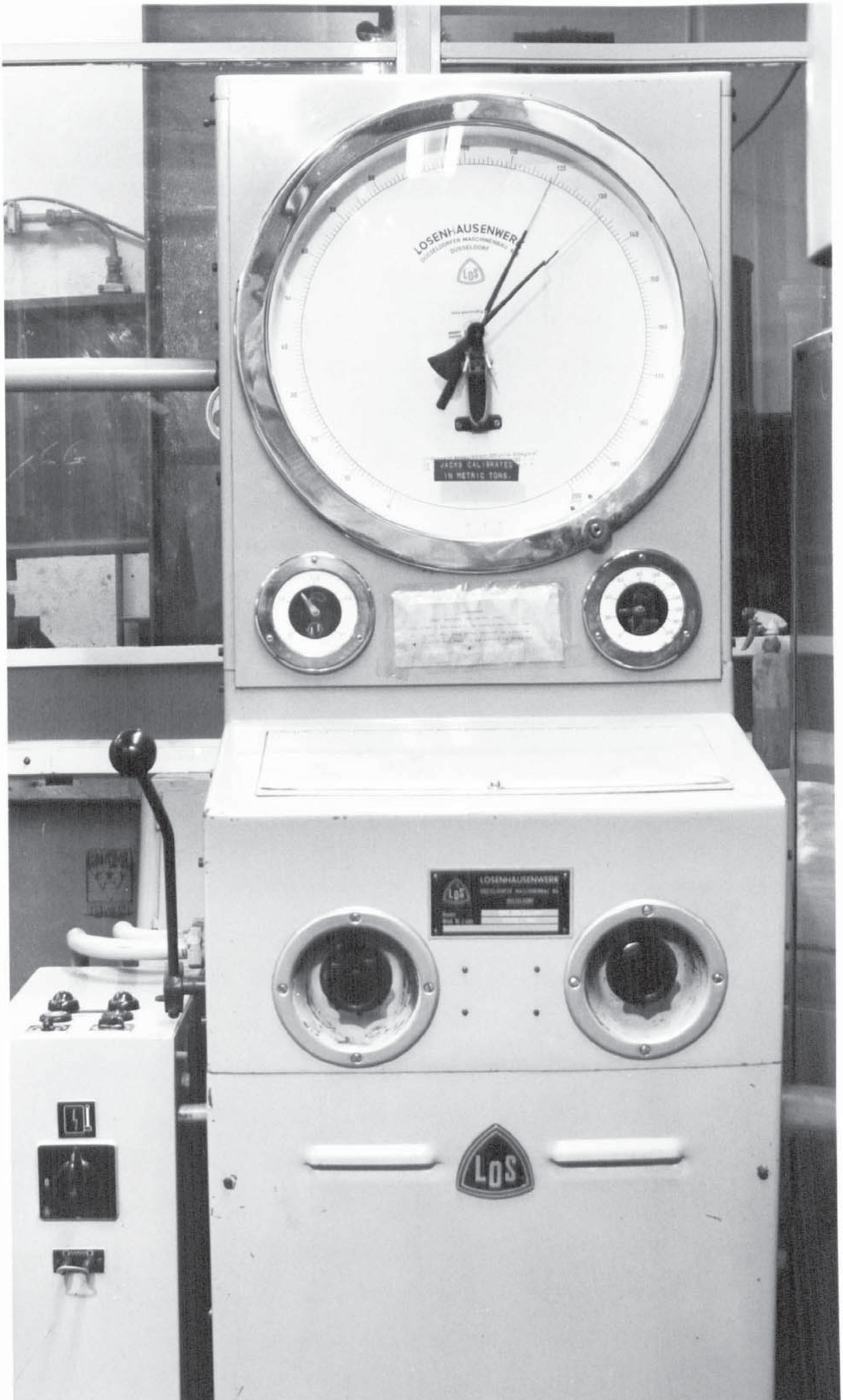


PLATE 4.6 Losenhausen Type EP 320 Controller

be recorded directly from the control dial of the Losenhausen machine. However, an error in the recording of the load on the actual machine after yield took place resulted in the ultimate load registered being highly inaccurate. This error will be covered more fully in Section 6.2.4. It was therefore necessary to obtain another transducer to cover the range above 200 kN and to record the ultimate loads of the larger sections. In hindsight, it would have been cheaper to obtain a single load cell rather than two pressure transducers, cost being the initial reason for rejecting the load cell.

The output from the transducers was fed into an amplification unit which was modified to accept both transducer inputs. The unit was able to output from either transducer to a suitable recording device.

4.4.4 Temperature Measurement

It was the temperature of the specimen rather than the furnace that needed recording. One method of measuring the temperature was employed and this was by using thermocouples. A common type was used, a Nickel-Chromium/Nickel-Aluminium (Ni-Cr/Ni-Al), usually called Chromel-Alumel. The two wires from this thermocouple were fibre glass insulated which had a short term resistance up to 700°C. However, repeated use at this temperature resulted in deterioration of the insulation causing the thermocouple to become inaccurate. The specimen surface temperature was measured by twisting the thermocouple wires either side of the section to get the point at which the wires separated as close to the surface as possible. This separation point being the position at which the temperature is measured. The alternative method of welding the end of the wires together, inserting them in a small hole drilled in the specimen and then peening over the edges, was not adopted as it was too time consuming and resulted in a weak area of the specimen from which premature fracture could propogate.

The thermocouples, usually a minimum of three on each specimen, were connected to the furnace control, the recording device and to a digital thermometer. One thermocouple was attached to the specimen in each of the three furnace zones and connected directly to the digital thermometer from which a continuous reading was displayed. This thermometer was a Comark Series 5000 No5115 for use with Chromel-Alumel thermocouples.

4.4.5 X - Y Recorder

The outputs from the load, strain and temperature measuring equipment were in a form that could be input into a computer, data logger or graph recorder. A terminal to the computer or data logger was unavailable for use over long periods which narrowed the alternatives down to only a graph recorder. A Bryans X-Yt 29000 series recorder was chosen which would enable stress/strain or load/strain graphs to be plotted directly with the added advantage of having a time base for use in creep and relaxation tests. By using the variable input controls the size of the plot could be adjusted to give the maximum size possible on the available paper space.

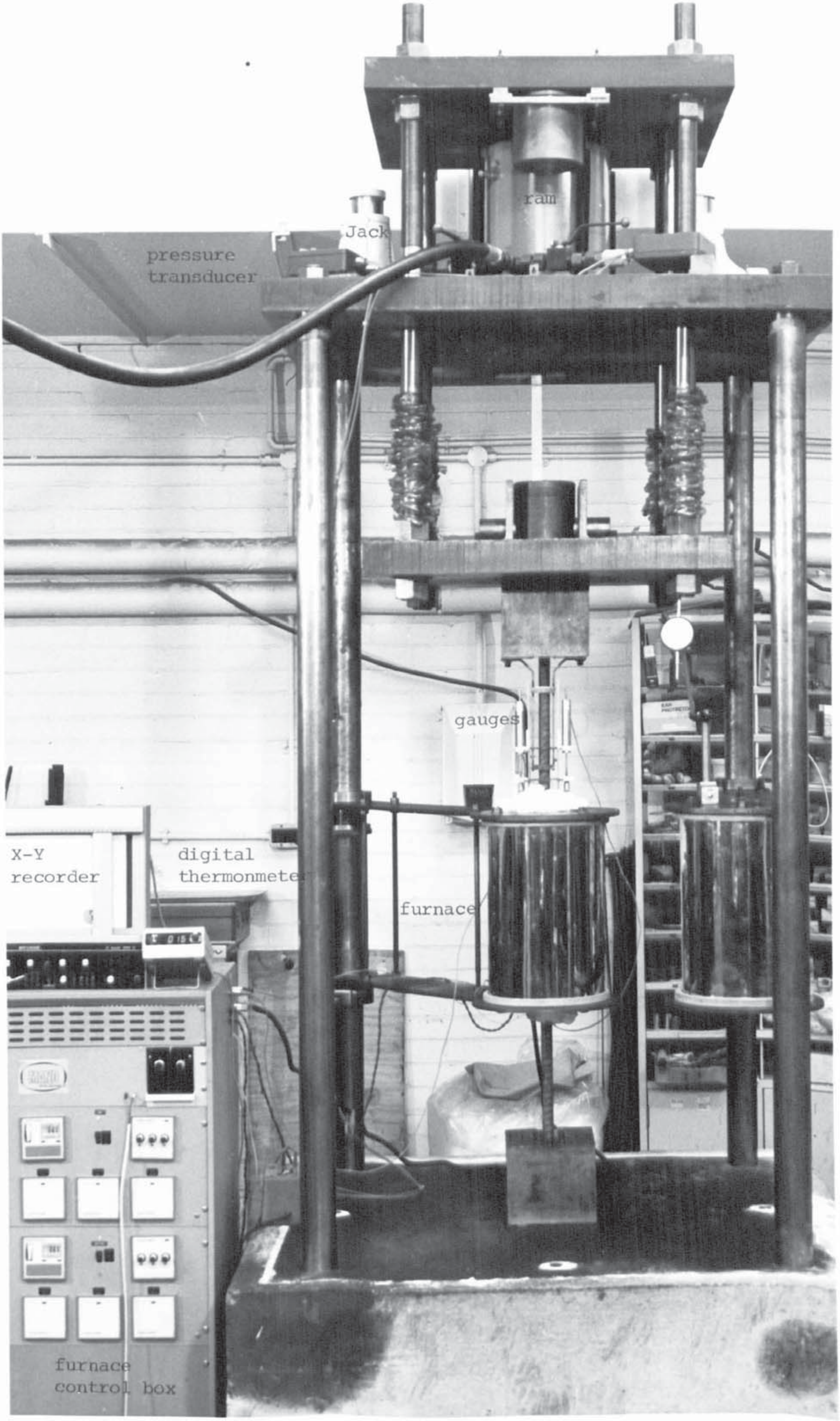
The complete arrangement of testing frame and instrumentation is shown in Plate 4.7.

4.5 Ancillary Testing Equipment

The major item of equipment used apart from the testing frame and associated equipment was the Avery Dension test rig (Plate 4.4).

The Avery Dension testing machine with a 500 kN (50 ton) limit is of the type commonly found in those laboratories where the testing of materials takes place. When used in tension, the specimen is

PLATE 4.7 Complete Testing Frame and Instrumentation



gripped between the cross-heads by wedge action grips and the load recorded on a large dial with a scale to suit the appropriate loading range.

CHAPTER 5

Test Programme and Procedures

5.1 Introduction

The test procedures outlined below were designed to give a set of results that could be directly related to the typical fire situation. These results could then be used to analyse the expected performance of the reinforcing or prestressing steels during or after a fire. The procedures also took into account the need to have uniformity between the different types of test and to keep them as basic as possible to reduce experimental error and allow for the easiest method of preparing each test.

From each of the tests, four main parameters were required although only two, usually load and strain, would be obtained as a permanent record on the X - Y recorder. There parameters were:

(i)	load	-	measured from pressure transducers
(ii)	strain	-	" " extensometers
(iii)	temperature	-	" " thermocouples
(iv)	time	-	

As with a normal reinforced or prestressed concrete analysis, three major strength parameters were required from the steel and these could be deduced from the individual plots. These were:

(a) yield or 0.2% proof stress

(b) elastic modulus

(c) ultimate tensile strength

The elongation at fracture or at a point when fracture was about to occur was measured after the specimen had been removed from the test machine together with an estimate of its reduced area.

Before any tests took place, it was necessary to perform certain preliminary tests and these are described in Chapter 6. Included in

Chapter 6 are the room temperature results and it is the average of these results against which the major strength parameters are normalised. This method of presenting the results would allow for the variation in strength of similar steels and the determination of each of the required strength parameter values, at different temperatures, for an untested specimen, from only a prior knowledge of the corresponding room temperature value.

At the beginning of the research nominally identical tests at each temperature were programmed. This was to allow for variations in the material, however, this condition was relaxed when the results showed that the difference between the tests on the same type and size of steel was reasonably small to suggest that taking one result instead of an average would not lead to large discrepancies between the two methods (Section 7.4 and 8.5).

The rates at which load or strain and temperature were applied to each specimen and the time at which it was to remain at the required temperature needed finalising before the tests commenced. This was to ensure that wherever possible the test procedures were perfomed in a uniform manner. In these circumstances British Standards and Codes of Practice were used to give guidance as to suitable rates. When the value of lower yield stress or specified proof stress is to be obtained BS 3688[17] gives a recommended strain rate of between 0.001 and 0.003 per minute. Since the loading machine was away from the recording equipment, strain rate control was not practical. An equivalent loading rate initially based on the specified minimum characteristic strength, nominal area and elastic modulus was used. This rate was revised after preliminary tests on the Avery Denison machine (Plate 4.4), fitted with a strain rate regulator, had given the necessary parameters.

BS 476[1] gives the standard heating curve (Fig. 5.1) for fire tests where the furnace temperature is determined from the relationship

$$T - T_o = 345 \log_{(10)} (8t + 1)$$

where t = time of test in minutes

T = furnace temperature at time t

To = initial furnace temperature

This heating curve is used for the determination of the fire resistance of elements in building construction. However, since it is the reinforcement and prestressing steels that are being investigated and it is assumed that spalling of the concrete does not occur for purposes of the tests, then due to the concrete cover, the steel temperature would not follow this heating curve. A heating rate that could be reproduced for each test was required. Section 6.2.3 gives details of the temperature calibrations performed and as long as the time to reach the specified temperature was within the times given in CP110[5] section 10 for fire resistance, the heating rate was taken to be acceptable. A heat input setting on the controller of 80% maximum would give an acceptable heating rate for all the size and temperatures required without stretching the performance of the furnaces to their maximum.

Since the specimens had different cross-sectional areas it was necessary to ensure that the whole of the section had reached the specified temperature. Rather than adopt different times which could be calculated from the size and conductivity of the steel a standard soaking time based on CP110[5] fire resistance times was used for each size of specimen. If more than one soaking time was used, this would add another permutation to an already large test programme. The maximum fire resistance time of four hours was unpractical in terms

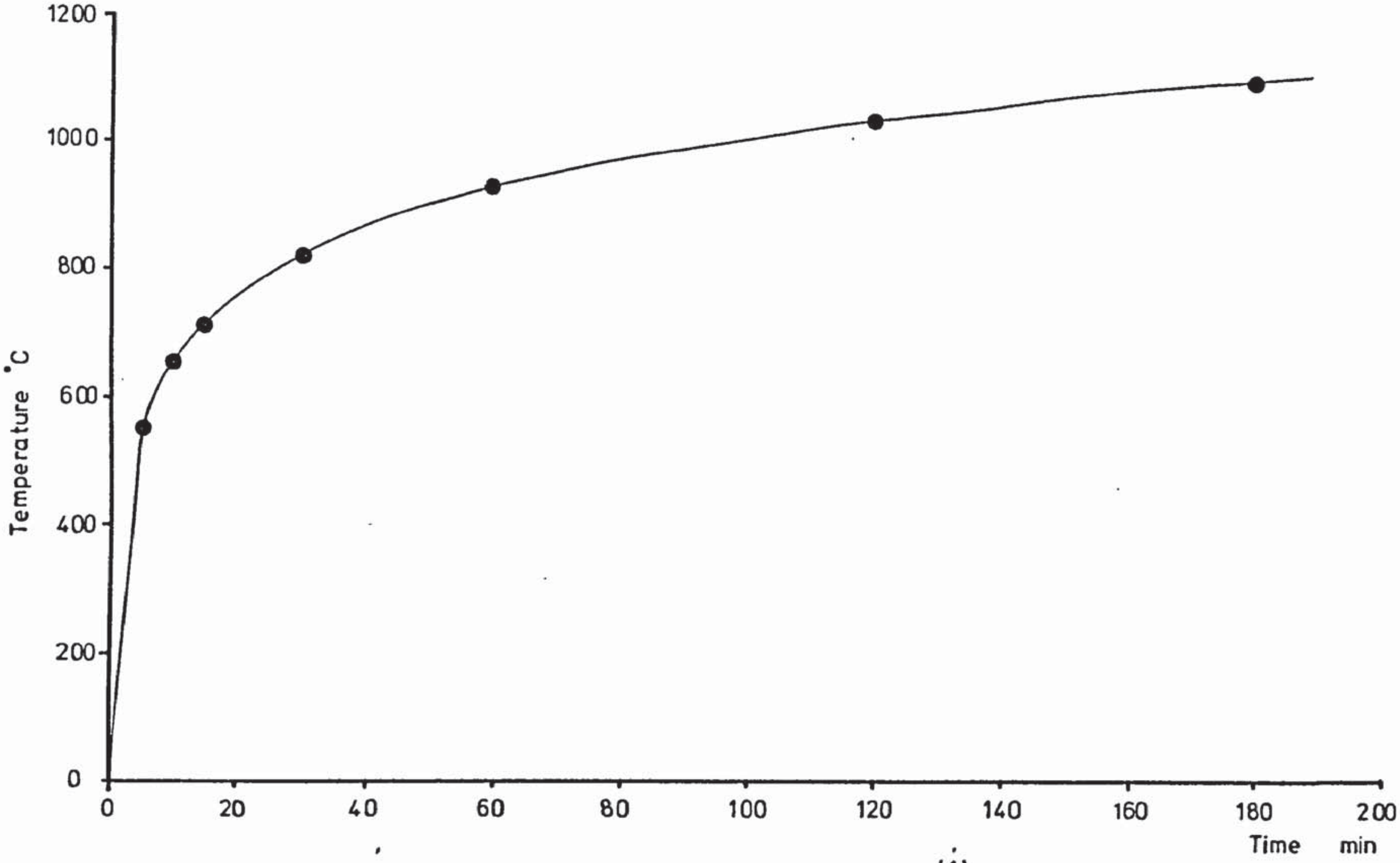


FIGURE 5.1 BS 476 Standard heating curve[1]

of the length of each test and the difficulty in sustaining a temperature within the limits given in BS 3688[17] ($\pm 5^{o}$C) for such a period of time. The minimum fire resistance time of half an hour was chosen as the soaking period and this would be the time after the whole of the heated section of the specimen had reached $\pm 5^{o}$C of the specified temperature.

Three of the test procedures were common to both types of steel (reinforcing and prestressing) with the tests on the reinforcing steels being designated by a number and the prefix series. Similarly the same procedure had the identical number but for the prestressing steels which had the prefix prestress, ie, series 1 and prestress 1 were identical procedures performed on reinforcing and prestressing steels respectively.

Before each test commenced the specimen had its colour code identification recorded (Section 6.3), the cross-sectional area determined (Section 6.4), and if possible, an extended gauge length of 250 mm which straddled the extensometer gauge length.

Separate specimens were used for each temperature increment of 100^{o}C starting from 100^{o}C and increasing up to a maximum of 700^{o}C whenever possible.

5.2 Series 1 and Prestress 1

A specimen with entensometers and thermocouples attached was placed through the furnace and suspended from the top loading platten of the test rig. The furnace position was adjusted until the extensometer had an equal clearance both internally and externally from the furnace's silicon tube. After the transducers were connected to the strain amplifier and the thermocouples to the digital thermometer and furance controller, the furnace ends were lightly packed with

Meckechnie Ceramic Wool Fibre. Springs and rollers were fitted to the extensometers and the output from each transducer was adjusted with the micrometers until they both registered the same position on the X-Y recorder. The strain amplifier was changed to output the average of the two transducers and after the furnace input controls and specified temperature were set, the furnace was switched on. With the aid of the digital thermometer the furnace control was adjusted until all three zones were within $\pm 5^{o}C$ of the specified temperature ($700^{o}C$ maximum) and the half hour soaking period commenced. At the end of this period the strain due to the expansion of the specimen and extensometers was recorded and the X axis (strain component) of the X-Y recorder re-set to a position where a full load/strain plot could be recorded. After adjusting the X axis to allow for the initial movement of the loading plattens a tensile test to failure was performed at the specified temperatures. After the specimens had been removed from the test rig the extended gauge length was re-measured and the cross-section area was determined by using a vernier gauge.

The results from this type of test procedure would be used to give guidance for the analysis of the performance of the steels, in terms of the strength parameters, at different temperatures over the range for which a fire would be expected.

5.3 Series 2 and Prestress 2

This procedure is concerned with the residual properties of the steel after being subjected to an elevated temperature and simulates the behaviour of an unloaded structure after a fire incident, ie, a structure designed for snow loading, being subjected to a fire.

Specimens, usually four, one of each type for a specific size with the thermocouples attached, were placed inside the furnace and the ends lightly packed with ceramic fibre after their position had been adjusted to give the required heated length. After reaching the required temperature (700°C maximum) to within ±5°C and left to soak for half an hour, the specimens were allowed to cool naturally to room temperature. An extensometer was fitted to each specimen in turn, the instrumentation adjusted as described above in 5.2 and a tensile test performed to failure, again recording extension and area after removal from the test machine.

5.4 Series 3 and Prestress 3

The procedure for arranging the specimen and gauges into the furnace and test rig was identical to that described in 5.2. However, instead of raising the temperature of an unloaded specimen, a load was applied equivalent to the working stress for the steel. For the reinforcement this was equivalent to yield or 0.2% proof stress divided by 1.8 and to 70% ultimate tensile strength for the prestressing steels. These strength parameters were obtained from the room temperature tests (Section 6.6) on samples of similar size and type.

For each specified temperature level strain, temperature and time were recorded and the test continued until either the strain rate became very small, or if the test had been running for over three hours and the strain was non uniform, or the specimen had failed. If failure had not occurred, the specimen was cooled to room temperature and a tensile test performed on it in the test rig.

This procedure would give the necessary information to determine the performance of the steels when they had simultaneously been subjected to a stress and an elevated temperature and it would simulate the effect on the steel in a structure loaded to its full design capacity and then being subjected to a fire. All the above procedures are shown in Fig.5.2 in the form of a diagrammatic description.

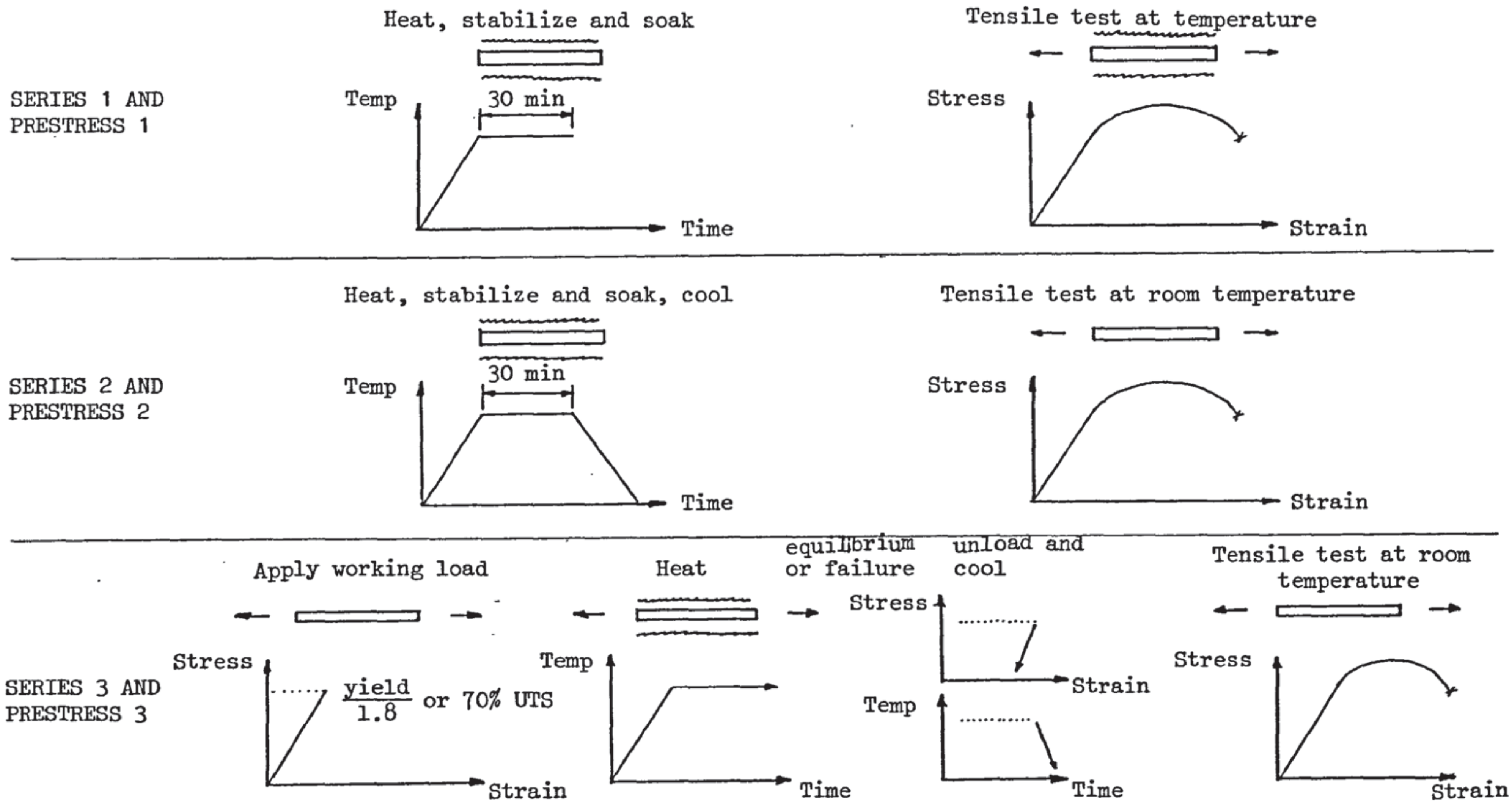


FIGURE 5.2 Test procedures

CHAPTER 6

Premliminary Tests

6.1 Introduction

This chapter describes the calibrations performed on the separate items of equipment that constitute the testing apparatus. It also describes the identification adopted for each specimen, how they were prepared and the determination of the density, cross-sectional area and gauge length. Before the results from the main test programme (Chapter 5) could be analysed, the strength parameters obtained from room temperature tests on each batch, size and type of steel needed to be determined. The tests and subsequent results are shown in Section 6.6 of this chapter.

6.2 Test Rig Calibration

To sustain a high level of accuracy, regular calibration and checking of the instrumentation were needed. These were performed using standard calibration equipment which had known limits or standard calibration charts. After all the measuring equipment had been checked the overall performance of the test rig needed to be assessed and this is described in 6.2.4. The major constraint imposed on the output from the equipment was the size of paper used on the X-Y recorder and the scale of the axis to give a plot from which the major strength parameters could easily be obtained (ie, yield or 0.2% proof stress, ultimate tensile strength and elastic modulus).

6.2.1 Load Calibration

When a tensile test was performed by the procedures described in Chapter 5, the load measured from the pressure transducer was input into the Y axis of the recorder. The scale chosen was based on the largest ultimate tensile strength value that had been obtained for each size from the room temperature tests performed in the Avery Denison machine (Table 6.1).

SIZE	FULL SCALE LOAD (kN)
25 mm	400
12 mm	80
8 mm	40
5 mm	40
7 wire (9.3 mm)	160

TABLE 6.1 Full scale load for each size of steel

An appropriate capacity proving ring, which had recently been calibrated on a grade A machine, was placed between the wedge block in the lower platten of the upper frame and the upper platten of the lower frame (Plate 6.1). To compensate for the surfaces being non-parallel, ball bearings were placed at either end of the proving ring. The scale of the axis was adjusted using the variable control so that increments of load corresponded to the major divisions on metric graph paper. This procedure was repeated until the whole of the axis, where possible, was correctly adjusted (Table 6.2).

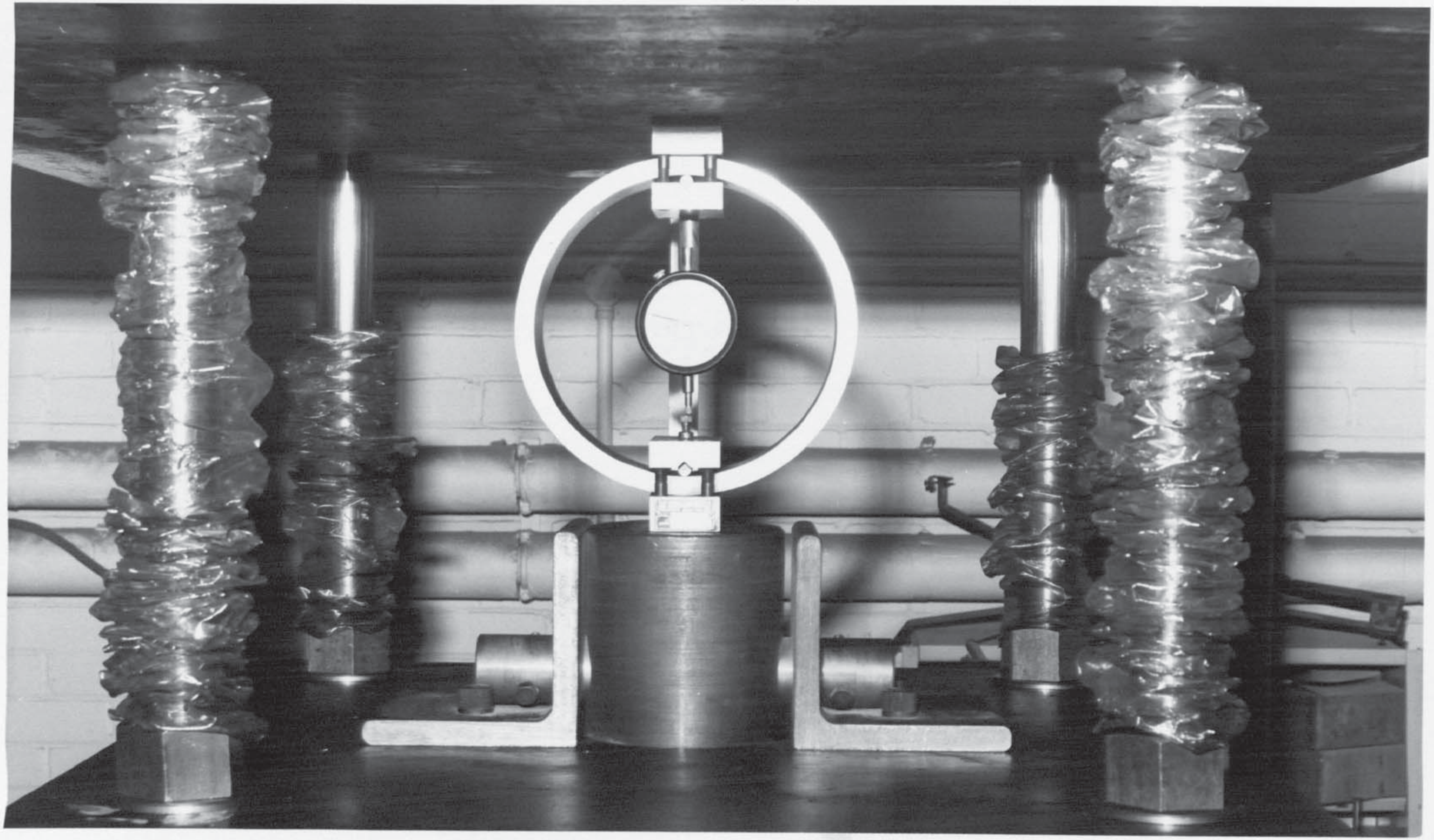
Half way through each set of test procedures and after each change of type of steel the calibration was re-checked and corrected if necessary.

During some of the calibration checks an appropriately sized proving ring was used to calibrate the Losenhausen control panel dial. This was performed so that when the load was applied to obtain the yield or 0.2% proof stress the loading rate could be controlled (Fig. 6.1).

6.2.2 Strain Calibration

The extensometers were calibrated in a similar manner to that

PLATE 6.1 Position of Proving Ring for Load Calibration



Load	Proving Ring Divisions			Pen Movement (mm)			
kN	50 kN	100 kN	200 kN	5 and 8 mm (50 kN P/R)	12 mm (100 kN P/R)	7 wire (100 kN P/R)	25 mm (200 KN P/R)
0	0	0	0	0	0	0	0
5	171			20			
10	339	124		40	20	10	
15	510			60			
20	679	250		80	40	20	
25	853		110	100			10
30	1025	372		120	60	30	
35	1198			140			
40	1370	499		160	80	40	
50		620	218		100	50	20
60		742			120	60	
70		865			140	70	
75			326				30
80		992			160	80	
90		1120				90	
100		1247	432			100	40
125			541				50
150			649				60
175			757				70
200			865				80

TABLE 6.2 Load Calibration Chart

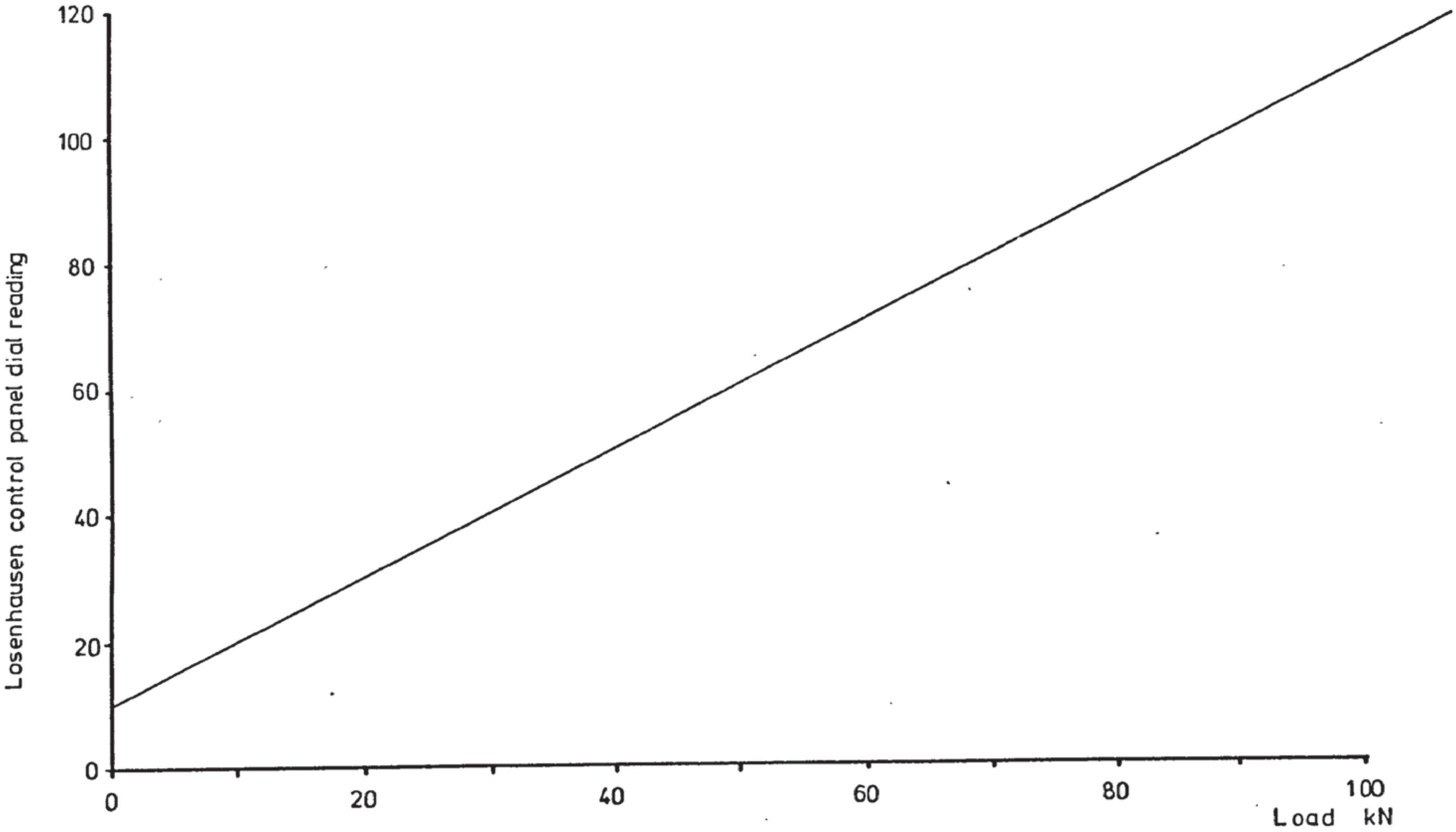


FIGURE 6·1 Losenhausen control panel dial calibration chart described above for the load calibration operation. The transducers were first adjusted to give approximately the same pen deflection on the recorder and then, depending upon the size of material and its gauge length, a suitable input range was chosen to produce on the X axis approximately 1.0% strain for full scale deflection for the reinforcement and 2.5% for the prestressing steel. The micrometers on which the transducers rested were moved in turn and the average output altered to give the required deflection along this axis, as shown in Table 6.3 below

	Reinforcement			Prestressing steel	
Size (mm)	8	12	25	5	9·3 (7 wire)
Gauge length (mm)	40	60	125	50	50
Micrometer movement to produce 50 mm deflection on X axis of recorder (mm)	0.08	0.12	0.25	0.25	0.25
Equivalent % strain	0.2	0.2	0.2	0.5	0.5

TABLE 6.3 Strain Calibration Chart

The other gauge to be used during the tests was the 50 mm transducer gauge from the Avery Denison machine. This gauge had been re-calibrated after an initial calibration test had shown that the strain being recorded was incorrect. This gauge was then checked against Huggenberger, demec and electrical strain gauges and the results are shown in Fig. 6.2. To check the extensometer calibration, the same demec gauge, as that used to produce Fig. 6.2 together with the extensometer were tested at room temperature and 90°C on a section of 12 mm diameter mild steel. The elevated temperature being obtained from high intensity lamps instead of a furnace. The results are shown in Fig. 6.3 and they may be compared with Fig. 6.2 which was obtained from the Avery Denison. The method of calibrating the extensometers

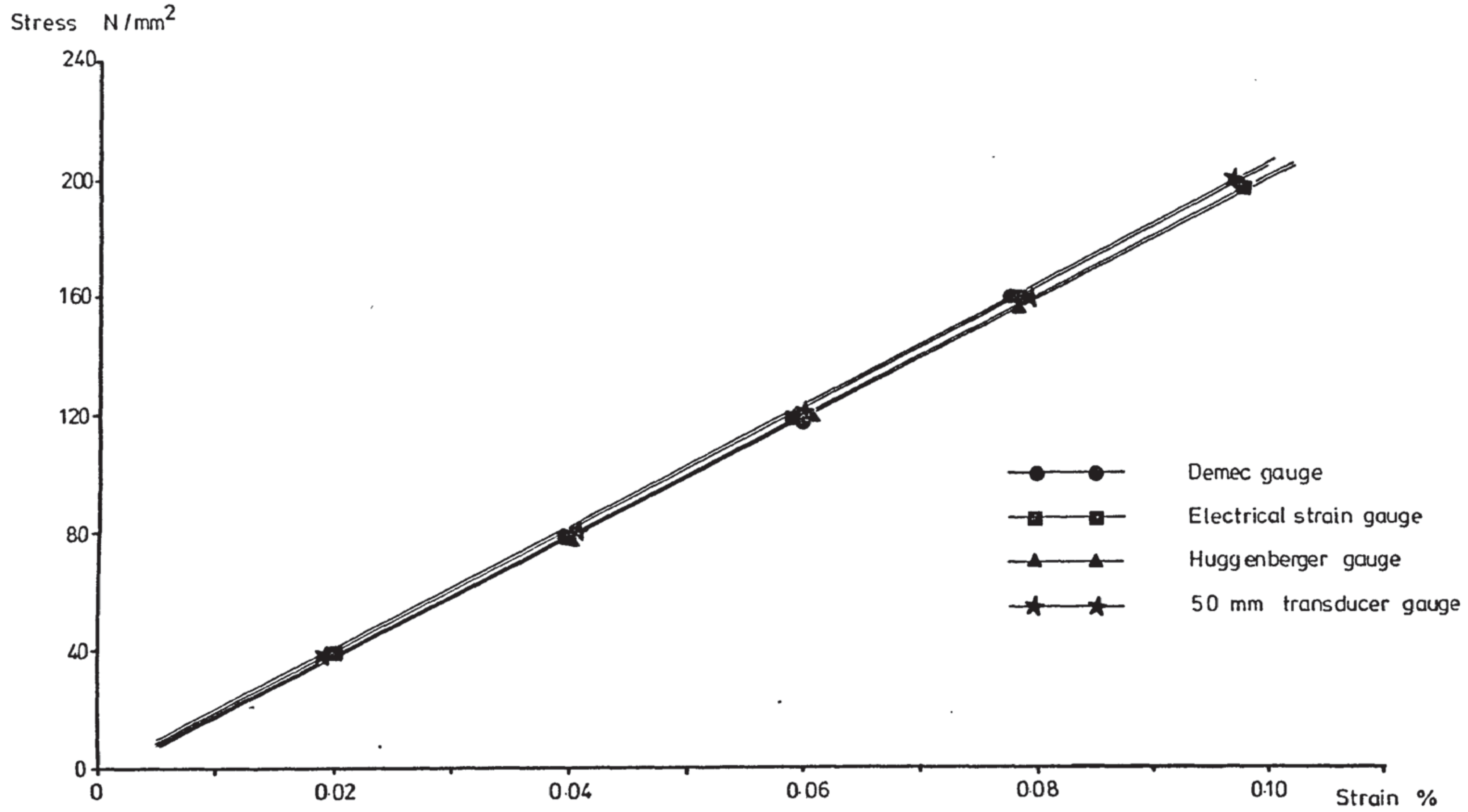


FIGURE 6·2 Strain gauges used in calibration check on Avery Denison machine

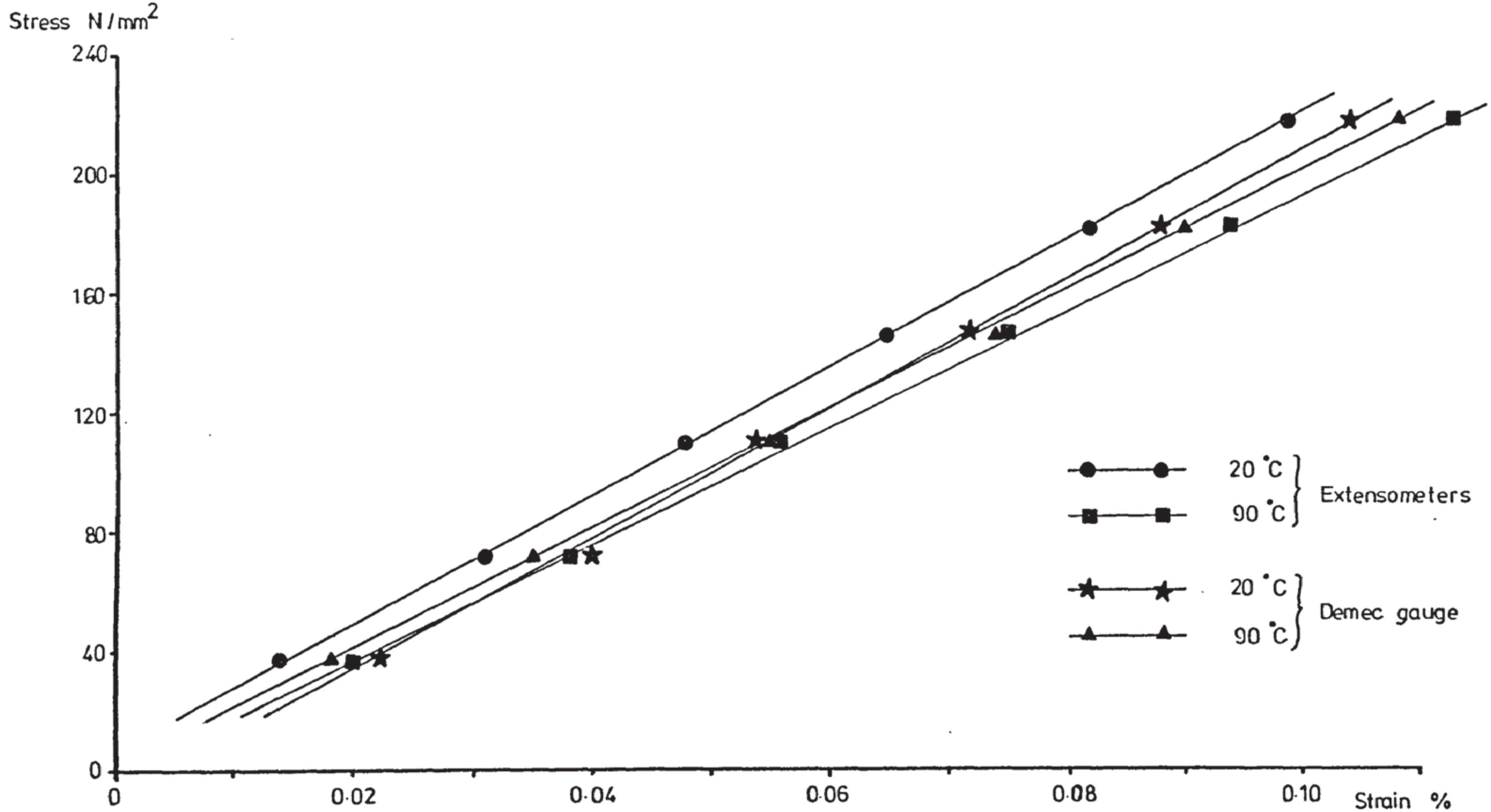


FIGURE 6·3 Extensometer calibration chart was assumed to produce a true reading of the strain.

Similarly with load calibration the pen deflection from the strain was checked regularly. It was usual to do this whenever the load was calibrated and also when there was a change in material size.

6.2.3 Temperature Calibration

When it was necessary to record the temperature of the specimen, the Y axis of the recorder needed to be calibrated. This was obtained by placing a thermocouple first in melting ice (0°C) and then in boiling water (100°C) and the scale adjusted accordingly to produce a pen deflection of 20 mm for this temperature rise. To check the scale at the higher temperatures, a bunsen burner was used and two thermocouples, one connected to the recorder and the other to the digital thermometer, were placed near the flame.

The melting ice method was also used to check the reading from the digital thermometers and furnace control to which the thermocouples, used to measure the specimen temperature, would be connected.

6.2.4 Test Rig Errors

The major error arising from the test rig was the recording of the friction from the bushes in the lower frame through which the columns of the upper frame passed. Also, since the platten movement was controlled by the amount of oil contained within the ram, the increase in oil as the piston moved up was being recorded as a load and this contributed towards the above error. When the yield or 0.2% proof stress was being recorded the platten movement was only approximately 2.0 mm and this error was not substantial. However, at the maximum load (up to 30% extension) this error was large enough to be significant. The platten movement needed to be calibrated against the load and this was done each time the load measurement was calibrated. Therefore, by recording the platten movement at the maximum load, the recorded level could be adjusted accordingly to account for the error. A typical calibration is shown below in Table 6.4.

Platten movement (mm)	Load correction (kN)
0	0
25	0.2
50	0.4
75	0.7
100	1.0
125	1.35
150	1.65
175	2.0
200	0.4*
225	0.8
250	1.2
275	1.55
300	1.9

*Note. Above 175 mm movement, the spacer (Section 4.2) was introduced

TABLE 6.4 Load Correction

Initially the control of the furnace was found to be very difficult with the specimen temperature overshooting the required level especially at the lower temperatures, Another factor affecting the furnace control was that all three zones were controlled by one thermocouple. The heat losses were much greater from the top and bottom zones and it was not until the control thermocouple had been moved to the top zone that any satisfactory control was obtained.

To evaluate the furnace performance a test was performed on each furnace whereby the maximum size steel (25 mm) was heated to the maximum temperature (700°C) with an 80% power input setting from which the results in Fig. 6.4 and Fig 6.5 were obtained. If there had not been a decrease in temperature in the top zone of furnace 2, due probably to an incorrect power input adjustment, both specimens

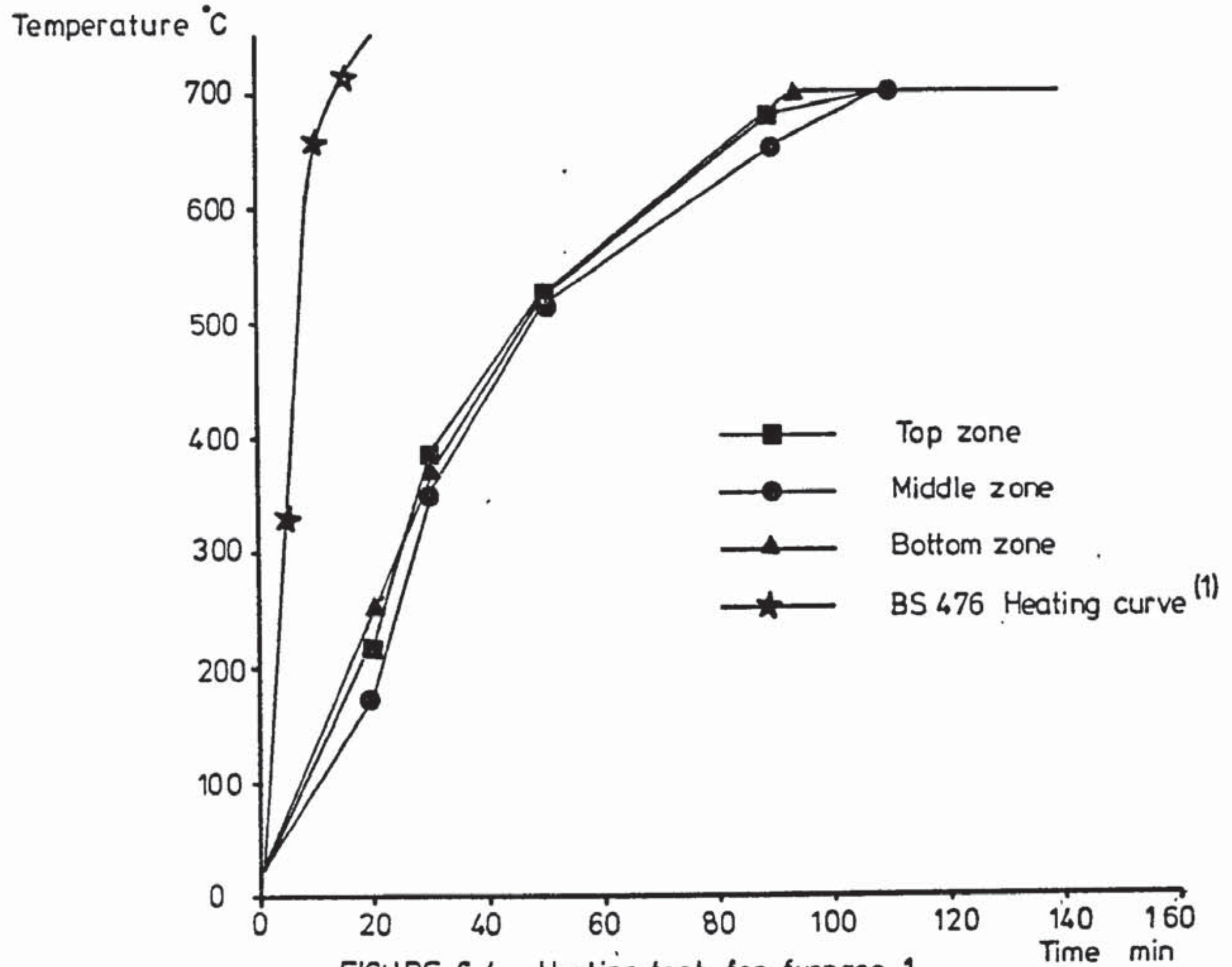


FIGURE 6·4 Heating test for furnace 1

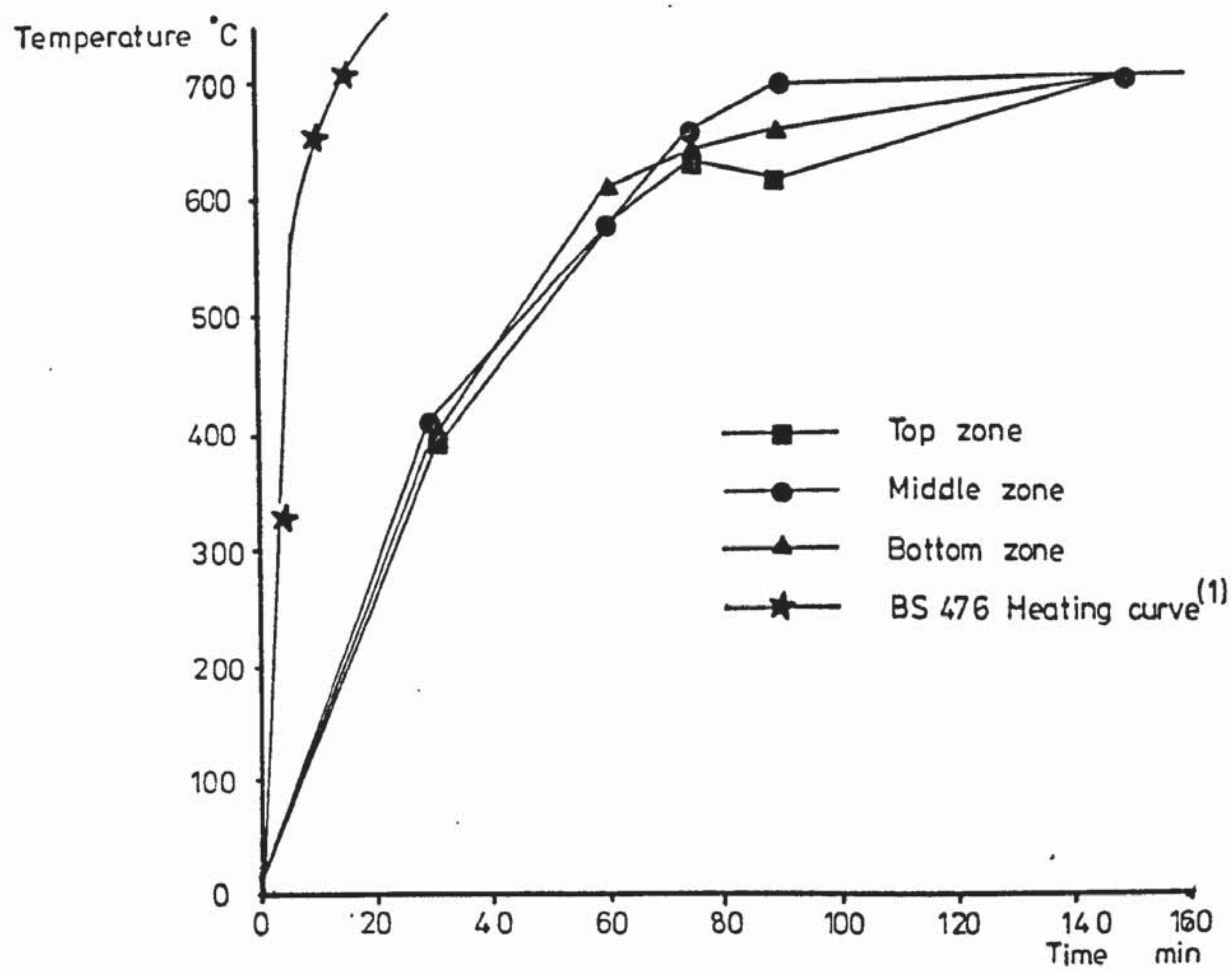


FIGURE 6·5 Heating test for furnace 2

would have reached their maximum temperature, with the required temperature gradient, within two hours.

6.3 Specimen Preparation and Identification

To complete the main test programme approximately 700 specimens would be required with each one having its own unique identification.

The reinforcing bars were delivered in either 2 or 6 metre lengths with the prestressing steel in 50 m coils. Two separate deliveries of steel were made but the specimens were prepared in similar manners. The ideal length of each specimen was 1.315 m but specimens cut to 1.315 $\pm$ 0.02 m would still be usable in the test rig.

After being cut a colour coding was given to each specimen and was based upon the type of material, its procedure number, the test temperature and whether it would be used as a duplicate test. The coding, in the form of dots, was placed near the ends of the specimen so that fractured specimens could be reassembled if necessary at a later date. The code was split into three sections:

1. procedure number in the material colour code of the specimen
2. test temperature code
3. duplicate test code (same colour as material code)

Material type	Colour code	Test temperature	Colour code
Mild steel	yellow	100	yellow
Unisteel	blue	200	green
G.K. TorBar	green	300	red
Square twisted	red	400	blue
		500	white
5 mm Mill coil	yellow	600	white white
5 mm Stabilised wire	red	700	white white white
9.3 mm 7 wire strand	green		

TABLE 6.5 Colour Coding

The colour coding for Unisteel tested at 500°C under series 3 loading and being the duplicate test would be

blue blue blue   white   blue

An anomaly in this system arises when the temperature code was the same as the material code and it was required to distinguish between specimens at different procedures, ie, Torbar at 200°C under series 2 loading would have the same number and colour of dots as the duplicate test of Torbar at 200°C under series 1 loading (3 green). This was resolved be leaving adequate space between the three coding sections.

6.4 Cross-sectional Area and Gauge Length Determination

After each specimen had been prepared and colour coded its cross-sectional area was determined using equation 6.1 obtained from BS 4449[10] and BS 4461[11]

Gross cross-sectional area (in mm^2) = effective cross-sectional

$$\text{area} = \frac{M}{0.00785\ L} \qquad \ldots\ldots \qquad 6.1$$

where M is the mass of the bar (in kg)
L is the length of the bar (in m)

It was not possible to obtain this area by mechanical methods due to the deformation along the bars.

The cross-sectional area obtained from each specimen is given in Appendices B & C together with the test results. Table 6.6 shows the recommended areas used by the manufacturers.

Rather than have different gauge lengths for each individual specimen the gauge length for the extensometers was based on 5.65 So (where So is cross-sectional area)[16][17] for each size of steel used. The values obtained were rounded up to a convenient size and these are shown in Table 6.3.

Nominal size mm	Cross-sectional area mm^2
8	50.3
12	113.1
25	490.9
5	19.6 † *
9.3	52.3 ‡ *

† obtained from BS 4482 (18)

‡ obtained from BS 3617 (13)

* for information purposes only

TABLE 6.6 Cross-sectional areas

6.5 Density Tests

The density of steel used in equation 6.1 above was 7.85 Mg/m^3, however, it was decided that the actual density from several samples of the steel being used should be obtained and compared to the value given in the standards (10)(11)

Small samples were taken from the offcuts of the bars and each weighed, first in air and then wholly immersed in water on a chemical balance. The mass measured whilst the specimen was immersed in water was equivalent to the volume (density of water = 1.0 kg/mm^3). The average of the calculated densities from the measured masses for each type and size of steel is given in Table 6.7.

6.6 Room Temperature Tests

Room temperature tests were performed in the Avery Denison machine and the test rig on specimens cut from the two batches of steel delivered. This was necessary so that the results obtained on

Nominal Size mm	Type	No of density tests	Approx Mass in air gms	Average measured density Mg/m^3
8	Mild steel	12	5	8.069
8	Unisteel	6	20	8.097
8	TorBar	6	6	8.076
8	Square twisted	4	6	8.146
10	Square twisted	8	7	8.112
12	Mild steel	6	11	7.958
12	Unisteel	3	12	7.903
12	TorBar	6	12	7.917
12	Square twisted	12	11	7.952
25	Mild steel	6	51	7.838
25	Unisteel	3	48	7.748
25	TorBar	6	51	7.742
25	Square twisted	12	47	7.792
5	Mill coil	4	7	8.139
5	Stabilised wire	4	7	8.234
9.3	7 wire strand	4	3	9.351

TABLE 6.7 Density Test Results

the specimens used in the procedures given in Chapter 5 could be compared with the corresponding room temperature value for the batch from which the specimen was originally taken. The taking of samples from both batches only applies to the reinforcement as enough prestressing steel was available from the original coils delivered to complete the tests. Whenever possible, samples for use in both machines were cut from the same length of bar and the cross-sectional area obtained by using the method given in Section 6.4.

Table 6.8 to 6.11 show the 95% confidence limits and the coefficient of variance for the tests performed.

Where: 95% confidence limit = mean $\pm$ 1.96 standard deviations

and coefficient of variance = $\frac{\text{standard deviation}}{\text{mean}}$

These two values will show the spread of results obtained from the tests.

6.7 Discussion of Results

The results contained within this chapter enable all the further test results to be expressed in a normalised form, enabling elevated temperature properties to be related to room temperature properties.

6.7.1 Calibration Results

The accuracy of the load and strain measurements were directly related to the accuracy of the equipment used to calibrate them. Although the proving rings did not always produce a linear chart their accuracy was related to the machine on which they were originally checked. The micrometers used to calibrate the strain were again an accepted calibration device with the movement being directly converted to a voltage for use on the recorder. Figures 6.2 and 6.3 give a

Type	Batch No	Yield or 0.2% proof stress		Ultimate tensile strength		Elastic Modulus	
		95% confidence limits N/mm^2	Coefficient of Variance %	95% confidence limits N/mm^2	c/v %	95% confidence limits kN/mm^2	c/v %
Mild Steel	1	337.7 ± 43.6	6.5	467.3 ± 65.5	7.1	211.56 ± 18.31	4.4
	2	369.0 ± 15.4	2.1	487.0 ± 39.1	4.1	203.13 ± 11.17	2.8
Unisteel	1	491.5 ± 3.0	0.3	711.1 ± 13.4	1.0	208.66 ± 28.79	7.0
TorBar	1	485.1 ± 25.9	2.7	586.7 ± 36.8	3.2	205.32 ± 8.56	2.1
	2	499.1 ± 27.8	2.8	596.4 ± 30.8	2.6	210.64 ± 13.30	3.2
Square Twisted	1	471.0 ± 34.9	3.8	569.8 ± 54.9	4.9	206.76 ± 5.17	1.3
	2 (10 mm)	448.9 ± 8.6	1.0	511.1 ± 27.1	2.7	208.57 ± 5.37	1.3

TABLE 6.8 8 mm Room Temperature Results

Type	Batch No	Yield or 0.2% proof stress		Ultimate tensile strength		Elastic Modulus	
		95% confidence limits N/mm^2	Coefficient of Variance %	95% confidence limits N/mm^2	c/v %	95% confidence limits kN/mm^2	c/v %
Mild steel	1	326.0 ± 37.5	5.8	443.6 ± 28.2	3.2	208.88 ± 24.91	6.0
	2	293.0 ± 13.2	2.3	452.3 ± 22.1	2.5	212.72 ± 20.55	4.9
Unisteel	1	473.8 ± 20.6	2.2	639.0 ± 10.5	0.8	209.87 ± 29.52	7.1
	2	502.7 ± 4.5	0.5	608.9 ± 10.5	0.9	214.26 ± 39.28	9.4
TorBar	1	492.8 ± 34.3	3.5	587.4 ± 52.1	4.5	204.64 ± 20.24	5.0
	2	519.9 ± 12.8	1.3	593.3 ± 15.4	1.3	222.37 ± 15.09	3.5
Square Twisted	1	550.7 ± 21.1	2.0	660.1 ± 25.9	2.0	205.03 ± 20.10	5.0
	2	503.7 ± 21.0	2.1	593.7 ± 6.9	0.6	217.05 ± 12.62	3.0

TABLE 6.9 12 mm Room Temperature Results

Type	Batch No	Yield or 0.2% proof stress		Ultimate tensile strength		Elastic Modulus	
		95% confidence limits N/mm^2	Coefficient of Variance %	95% confidence limits N/mm^2	c/v %	95% confidence limits kN/mm^2	c/v %
Mild steel	1	319.1 ± 6.8	1.1	464.5 ± 1.4	0.2	204.05 ± 21.42	5.3
	2	313.3 ± 2.7	0.4	485.3 ± 9.5	1.0	198.23 ± 34.21	8.8
Unisteel	1	557.5 ± 24.4	2.2	715.6 ± 9.4	0.6	195.65 ± 34.57	9.0
	2	492.9 ± 9.0	0.9	677.9 ± 7.5	0.6	194.09 ± 26.83	7.0
TorBar	1	450.3 ± 46.0	5.2	558.0 ± 73.3	6.7	244.24 ± 27.03	5.6
	2	460.2 ± 4.8	0.5	551.1 ± 18.8	1.7	222.91 ± 33.15	7.6
Square Twisted	1	459.0 ± 17.9	2.0	587.6 ± 2.3	0.2	226.50 ± 18.18	4.1
	2	441.7 ± 1.9	0.2	554.7 ± 8.8	0.8	221.19 + 24.85	8.0

TABLE 6.10 25 mm Room Temperature Results

Type	Yield or 0.2% proof stress		Tensile strength		Elastic Modulus	
	95% confidence limits N/mm^2	Coefficient of Variance %	95% confidence limits kN	c/v %	95% confidence limits kN/mm^2	c/v %
5 mm Mill coil	1606.2 ± 43.8	1.4	36.9 ± 1.3	1.8	203.27 ± 8.07	2.0
5 mm Stabilised wire	1464.8 ± 23.4	0.8	33.5 ± 1.2	1.8	204.12 ± 33.36	8.3
9.3 mm 7 wire strand	1864.5 ± 38.0	1.0	104.0 ± 0.4	0.2	199.54 ± 6.04	1.5

TABLE 6.11 Prestressing Steel Room Temperature Results

clear indication that the extensometers, used throughout the tests, could be made as accurate as the standard forms of strain measurement.

Apart from the standard $0^{\circ}C$ and $100^{\circ}C$ test, the temperature calibration was more of a performance test on the furnace's capabilities to reach the maximum temperature within four hours and to an accuracy of $\pm 5^{\circ}C$ (Figures 6.4 and 6.5).

6.7.2 Density Test Results

The average density values given in Table 6.7 do not agree favourably with the accepted value given in equation 6.1. However, the results suggest that the greater the mass of the sample, the closer to the accepted value the measured density becomes. The size of the sample was limited by the available apparatus and this must therefore give some doubt to the accuracy of the results especially for the smaller samples. To accept the values obtained and then use them in determining the cross-sectional area could question the accuracy of the subsequent results obtained. For this reason and the need to keep the tests and analysis as uniform as possible, the density of steel given as 7.85 Mg/m^3 in equation 6.1 was used throughout.

6.7.3 Room Temperature Test Results

From all the mean values given in Tables 6.8 to 6.11 the only one to fall below the characteristic strengths in Tables 6.12 and 6.13 was that from 10 mm square twisted steel, which had a mean 0.2% proof stress of 448.9 N/mm^2. The individual results from this batch of steel did not comply with section 20 of BS 4461 (11) with all the 0.2% proof stress values falling below the characteristic strength given in Table 6.12. Although similar specimens for use in the rest of the test programme will have an equally low strength, this will be

Type	Grade	Nominal size of bar mm	Specified characteristic strength N/mm^2
Mild steel	250	All sizes	250
All others	460/	6 up to and including 16	460
	425	Over 16	425

TABLE 6.12 Reinforcing steel characteristic properties (10)(11)

Type	Nominal size	Characteristic strength N/mm^2
Wire	5	1570 (30.8 kN)
7 wire strand	9.3	1788 (93.5 kN)*

TABLE 6.13 Prestressing steel, characteristic tensile strengths (12)(13)

*Note strength value obtained from characteristic load and nominal area compensated by them being normalised to the room temperature value and not as individual values.

The largest coefficients of variation obtained from the results (over 5.0%) were those from the 8 and 12 mm mild steel specimens of batch 1, the 25 mm torbar specimens also of batch 1 and the majority of the elastic modulus values, which was as large as 9.4% for the 12 mm unisteel. It was the variation of the strength properties within the material itself that was attributed to the scatter of results rather than any testing error or analysis. If the yield stress of the mild steel is considered, the lower points of the 95% confidence limit, even with the large coefficient of variation, are still greater than 250 N/mm^2 which is given in Table 6.12 for the characteristic strength. Also all the mean tensile strengths given are greater than the mean yield stress by a value greater than the 10% required by the appropriate standard[10][11]

The method of obtaining the elastic modulus presented a major difficulty in as much as it was a visual interpretation of the elastic range of the material and not a clearly defined point of reference. Some of the plots, especially those from the cold worked steels had little or no linear portion of the stress/strain graph as they became non-linear as soon as the load was applied. This made the elastic modulus calculation open to personal bias which would consequently have an influence on the 0.2% proof stress values. However, rather than suggest that this method of measurement was inaccurate, the fact that the other strength properties varied must infer that the elastic modulus was subject to variation. Also this value is very sensitive to the slope of the graph and if, with the scales being used, this was to change by as little as $\pm 1^\circ$ this would result in the modulus changing from 200 kN/mm^2 to 191 or 209 kN/mm^2.

The shape of the graphs produced were typical of their manufacturing process, with the torbar and square twisted steels producing the "typical" 'cold worked' stress/strain plot (Fig. 6.6) and the mild steel and Unisteel producing a typical 'hot rolled' plot (Fig. 6.7). However, an exception to this was the plots from the 8 mm and 12 mm size Unisteel from batch 1. This, however, can be attributed to it being subjected to more rolling processes and consequently cold working, to reduce its size and produce its deformed shape. Where no yield point was available for these steels the standard offset method of obtaining the 0.2% proof stress was used.

6.8 Conclusions

During the calibration tests, which proved to be as accurate as was possible, the error in the test rig was discovered. This meant that all the tensile strength values recorded on the plotter had to be reduced by a predetermined amount obtained from a separate test. The furnaces were able to reach the maximum temperature within the time limit needed and sustain it with the required accuracy.

The density tests were limited by the size of apparatus and this resulted in values which did not agree with the standard value. These results were subsequently ignored and the standard value of 7.85 Mg/m^3 used for obtaining the cross-sectional area.

Although a large number of tests were performed under similar testing conditions, variation in the strength parameters were obtained. This, however, could be related to the natural material variation and not experimentation or analytical interpretation. These mean values will be used as a standard, from which all the elevated temperature test results will be compared.

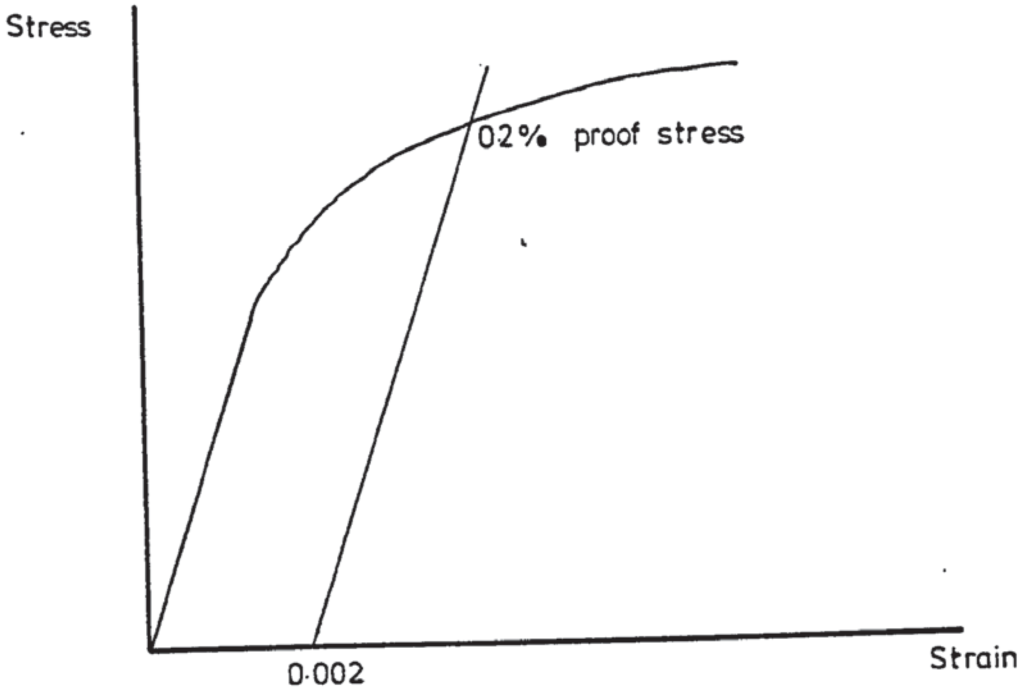


FIGURE 6.6 Cold worked bar stress/strain plot

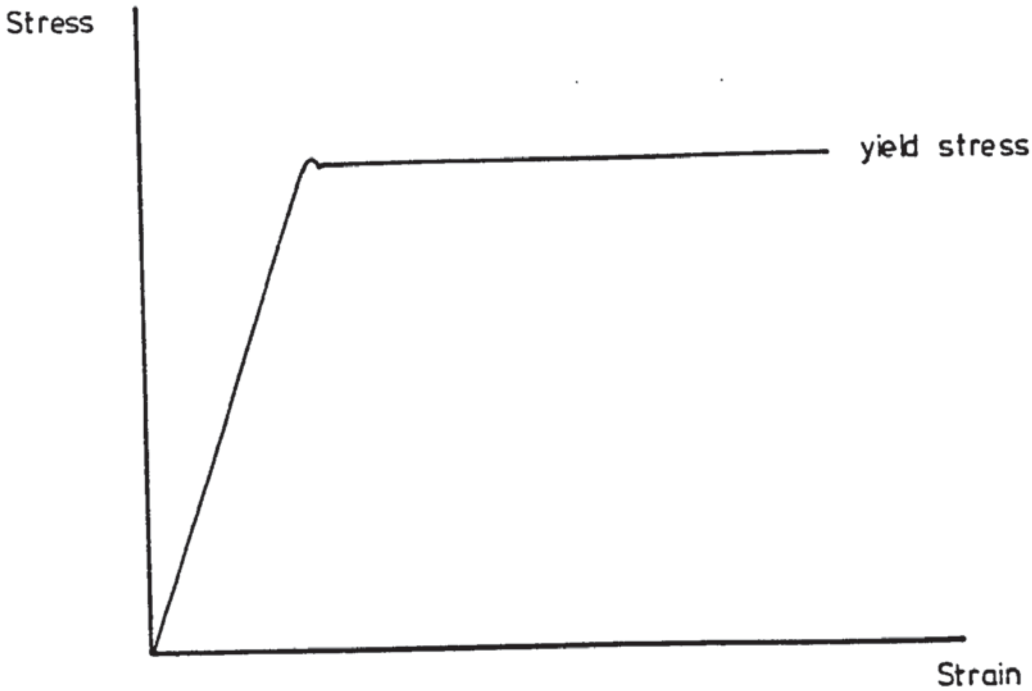


FIGURE 6.7 Hot rolled bar stress/strain plot

CHAPTER 7

Reinforcing Steel Results

7.1 Introduction

The results and subsequent discussions contained within this chapter were obtained from the reinforcing steels which had been subjected to the three separate test procedures outlined in Chapter 5. The individual results form each test are contained in Appendix B together with the prestressing steel results. Although the four types and three sizes of reinforcing steel are common to all three procedures, it will be convenient to discuss the results from each procedure separately. The average of the three main strength parameters at each temperature will be normalised in non-dimensional form using the mean room temperature values given in Tables 6.8, 6.9 and 6.10. The results from the batch 1 steels being used for the series 3 results and those from batch 2 for both the series 1 and series 2 results. The exception to this will be for the unisteel where the batch 1 results only will be used for all three series.

The normalised results will be given the following notation:

Normalised yield or 0.2% proof stress at temperature $t^{o}C$ - Y_t
Normalised ultimate tensile strength at temperature $t^{o}C$ - U_t
Normalised elastic modulus at temperature $t^{o}C$ - E_t

Although every individual plot of the tensile test has not been included it was noticeable that for each of the three series there was a change in the shape of the plots on certain types of steel. There are three main areas of interest from the tensile tests and each test series is sub-divided into recorded plots, individual test results and normalised figures.

7.2 Series 1

Before the specimens were tested at the required temperature, the net expansion from the specimen and extensometers was recorded after the 30 minute soaking period. These values were necessary for the series 3A test results and are included in the appropriate section.

a) recorded plots

The three sizes of torbar and square twisted type steels and also the 8 and 12 mm unisteel type (Section 6.7.3) retained the typical 'cold worked' shape of a linear section, followed by a non-linear portion with no yield point and continuing to work harden over the whole range of temperatures. All the mild steels and 25 mm unisteel had the characteristic 'hot rolled' shape plot of an elastic zone up to a yield point followed by a long plastic zone for temperatures up to 200°C. However, at 300°C the shape changed to a plot that had no distinctive yield point and instead of a plastic zone showed a work hardening region (Fig.7.1). Without a yield point it was necessary to adopt the offset method usually used for the 'cold worked' steels to obtain the 0.2% proof stress.

b) test results

The test results obtained from the plots after they had been corrected for test machine error (Table 6.4) are given in Tables B1, B2 and B3 in Appendix B. It is clear that for all the types and sizes, the three major strength parameters reduce with increasing temperature and in the majority of cases there is a close agreement between the duplicate tests at each temperature. It was for this reason that only one test was performed at each temperature for the 25 mm steels. Although the specimens were strained until either they failed or the maximum machine travel was reached, as with the case of the 25 mm mild steel specimens, it was not until the specimens had been tested at 400°C that they regularly failed within the 250 mm gauge length. Since this gauge length was contained within the limits of the furnace and

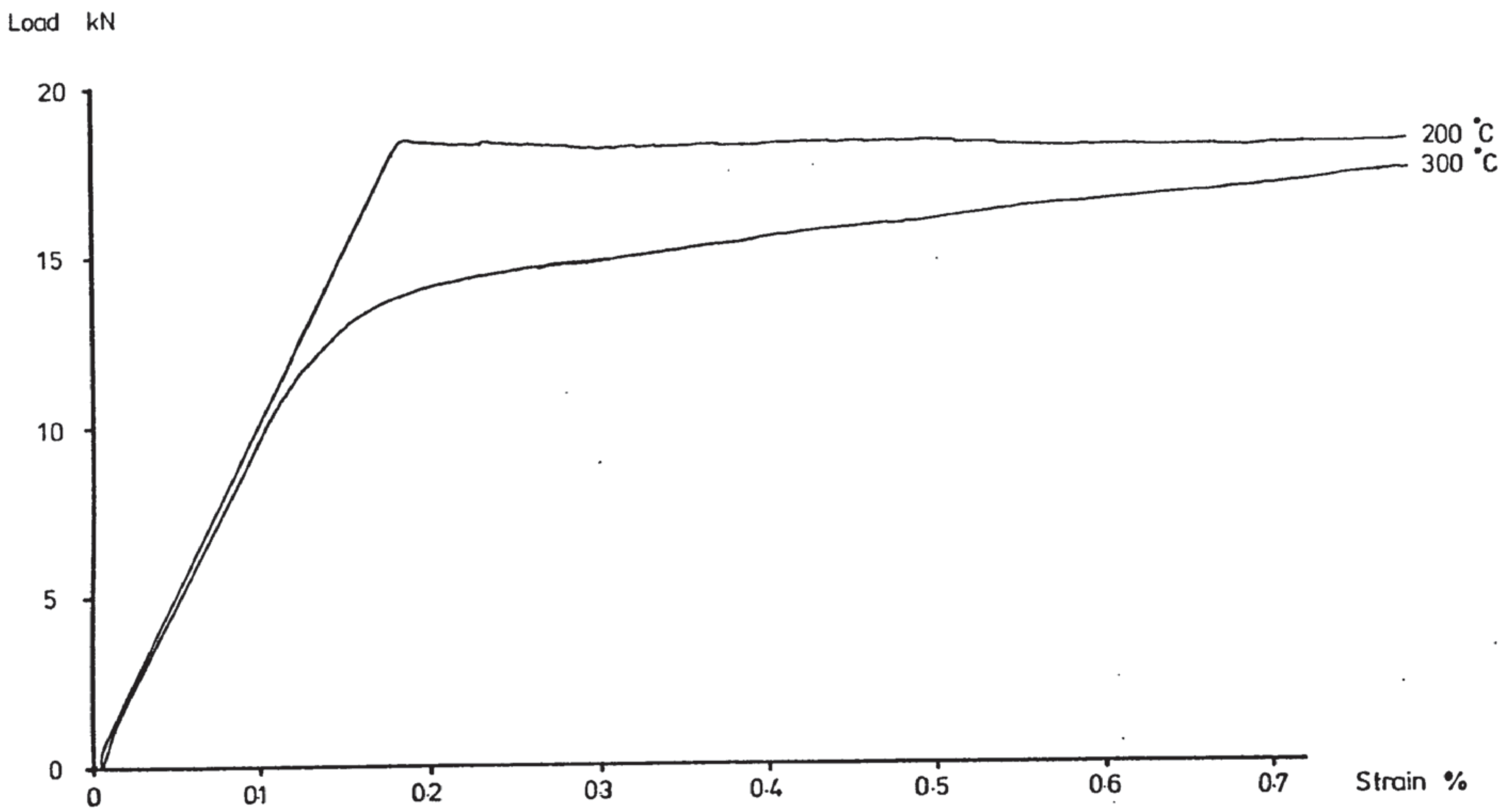


FIGURE 7·1 Change in shape of recorded plot for 8mm mild steel, series 1 maintained at the required temperature, those specimens that failed outside the gauge length also failed outside the heated zone. This suggests that above 300°C sufficient softening of the material has taken place to produce large enough deformations to propogate failure. Although this is not apparent from the yield stress results it is clearer from the ultimate tensile strengths and can be seen when these results are normalised.

c) normalised results

The normalised values, Y_t, U_t and E_t for all the sizes and types of steel tested under series 1 procedure are given in Figs 7.2 to 7.10. It is noticeable that, for each normalised set of results, the size and type of steel had little effect upon the general shape of the plots. The only exception to this was the Y_t values for the 25 mm steels where a segregation between the hot rolled and cold worked steels can be seen with Y_{100} to Y_{400} being higher for the cold worked steels but lower at Y_{700}. The overall shape of the Y_t plots shows a broad scatter up to 300°C followed by a narrow rapidly decreasing band of results to 700°C where Y_{700} for the hot rolled steels were contained between 0.19 to 0.24 and 0.095 to 0.19 for the cold worked steels.

For design and analysis it is the temperature at which the working load (yield or 0.2% proof stress divided by 1.8) is obtained which is of interest. This value is equivalent to $Y_t = 0.55$ and this occurs between 500 and 560°C for all the types and sizes of steel (Fig. 7.11).

The U_t values lie within a tighter band of results (Fig. 7.12) with the general shape being horizontal up to 300°C followed by a linear decrease coinciding with the specimens failing within the heated zone. Again the difference between the 'hot rolled' and 'cold worked' steels is not significant with both types having a 50% reduction in strength ($U_t = 0.5$) between 515 and 560°C.

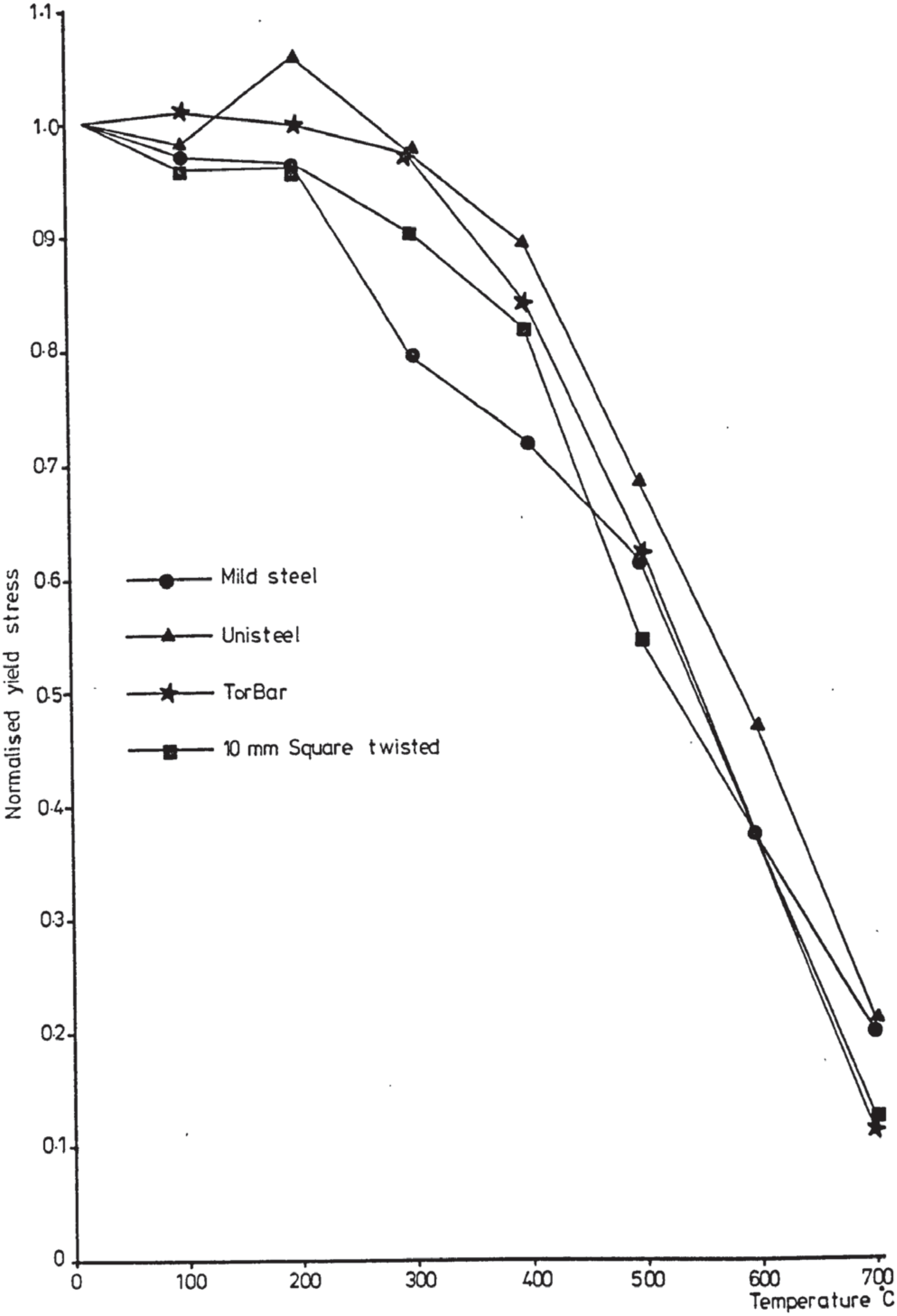


FIGURE 7.2 Normalised yield stress for 8 mm series 1

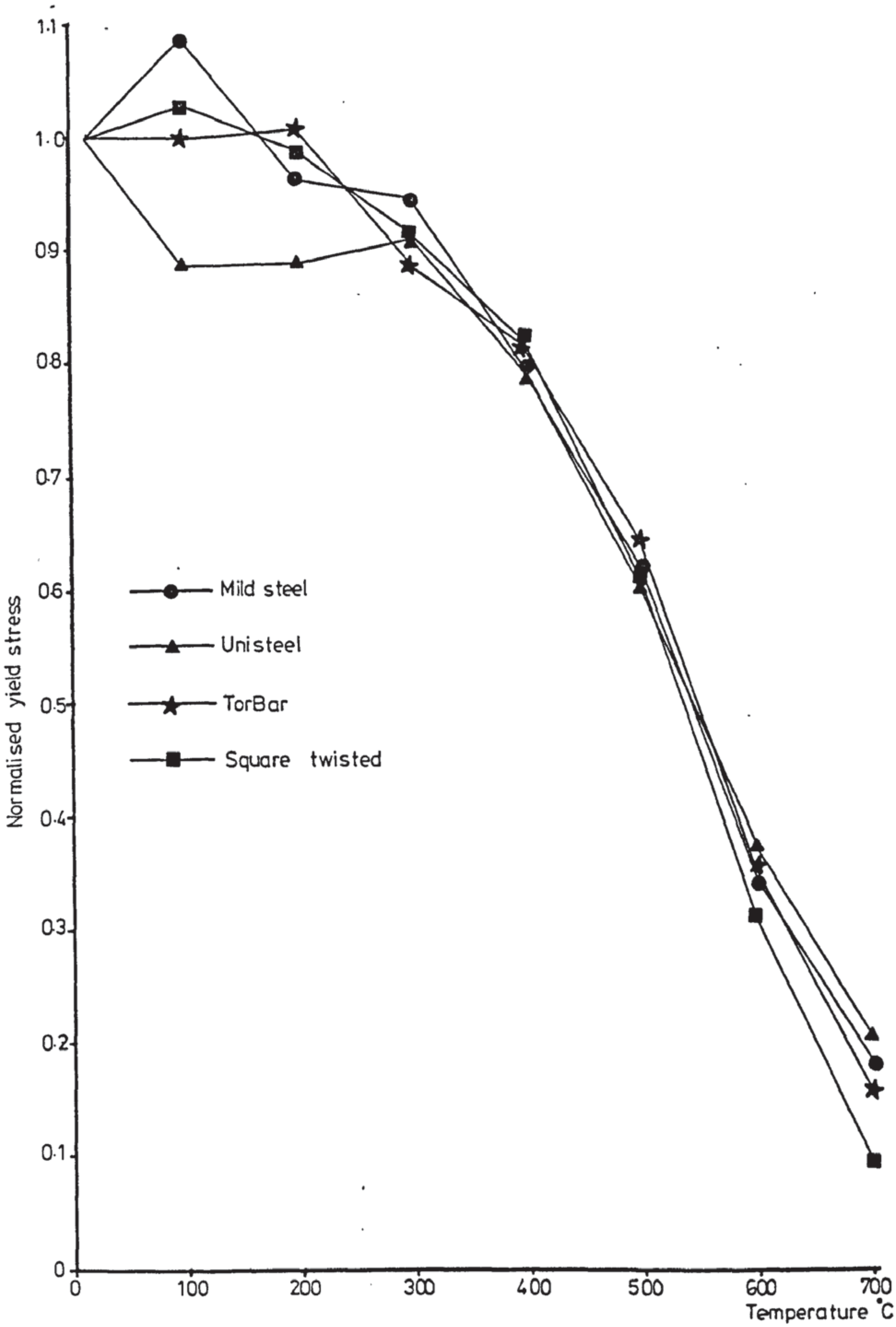


FIGURE 7.3 Normalised yield stress for 12 mm series 1

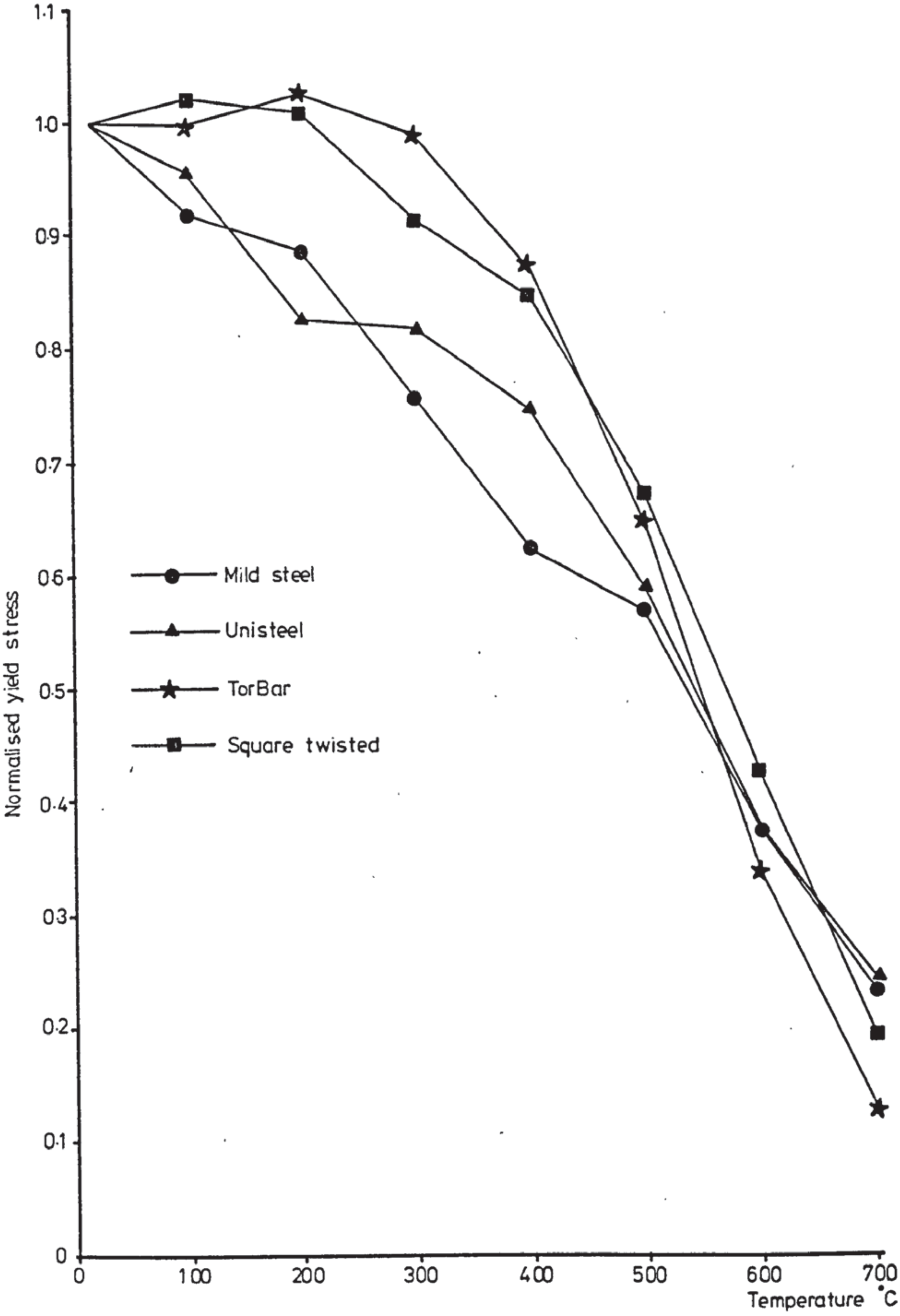


FIGURE 7·4 Normalised yield stress for 25 mm series 1

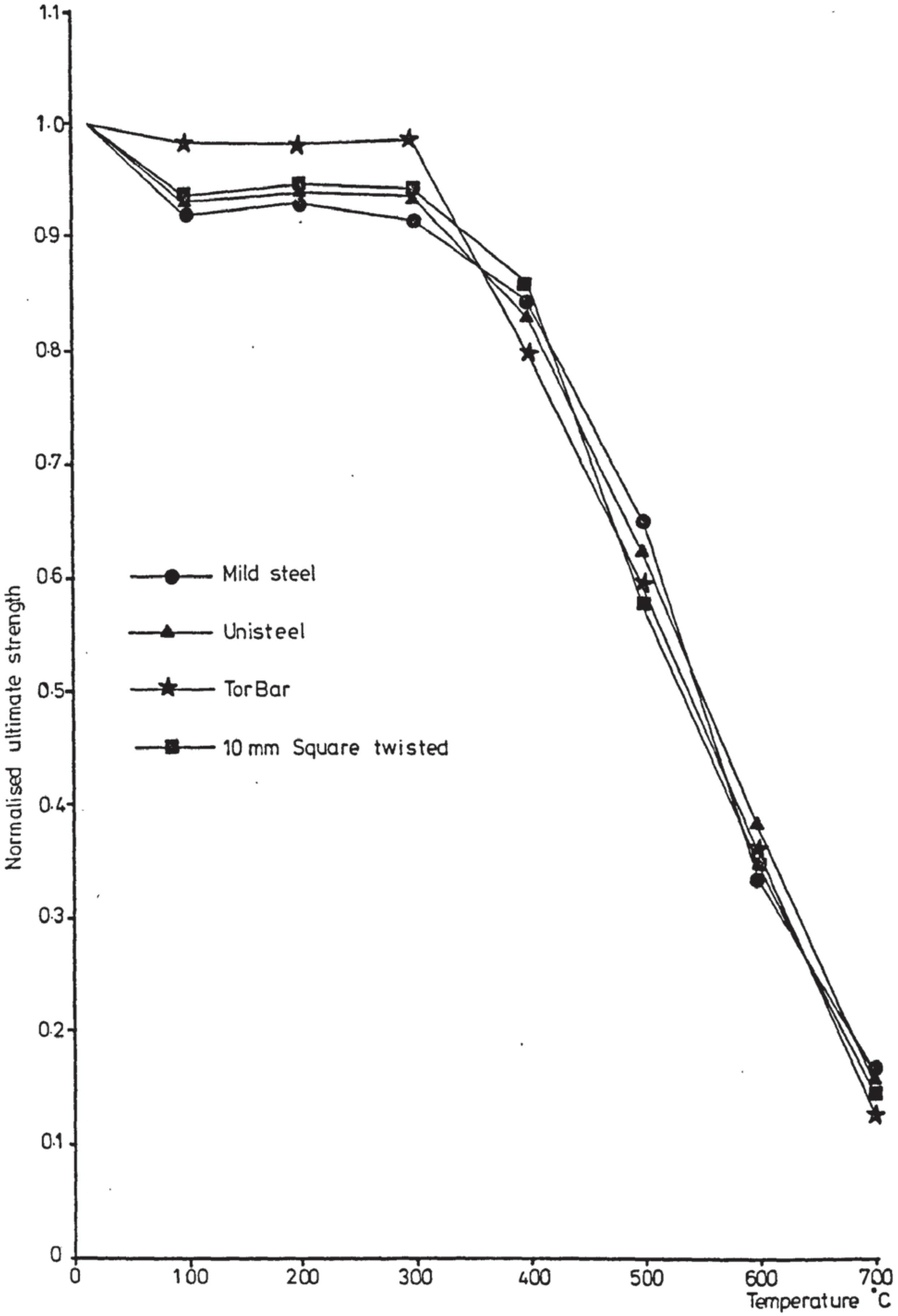


FIGURE 7.5 Normalised ultimate strength for 8 mm series 1

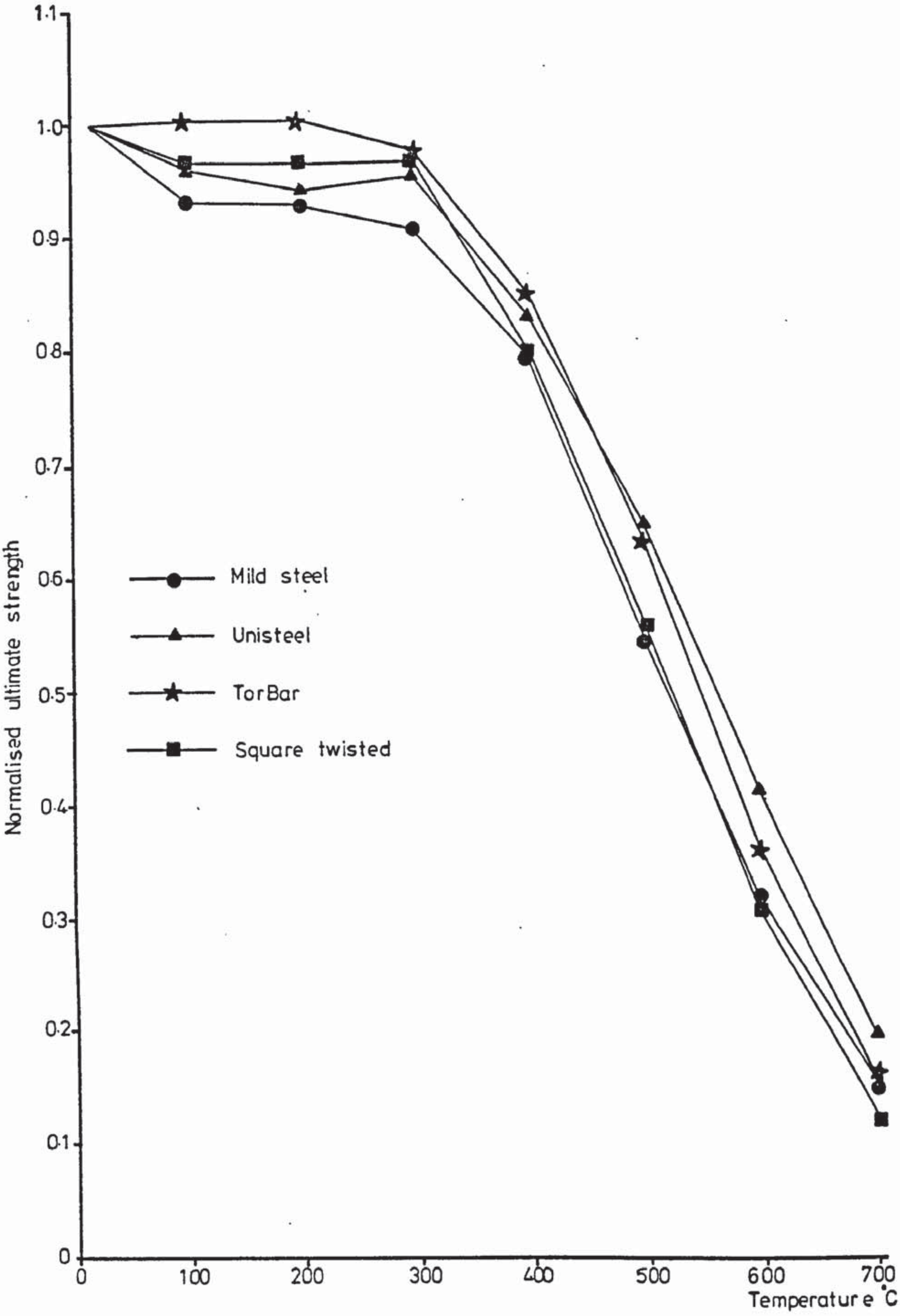


FIGURE 7.6 Normalised ultimate strength for 12 mm series 1

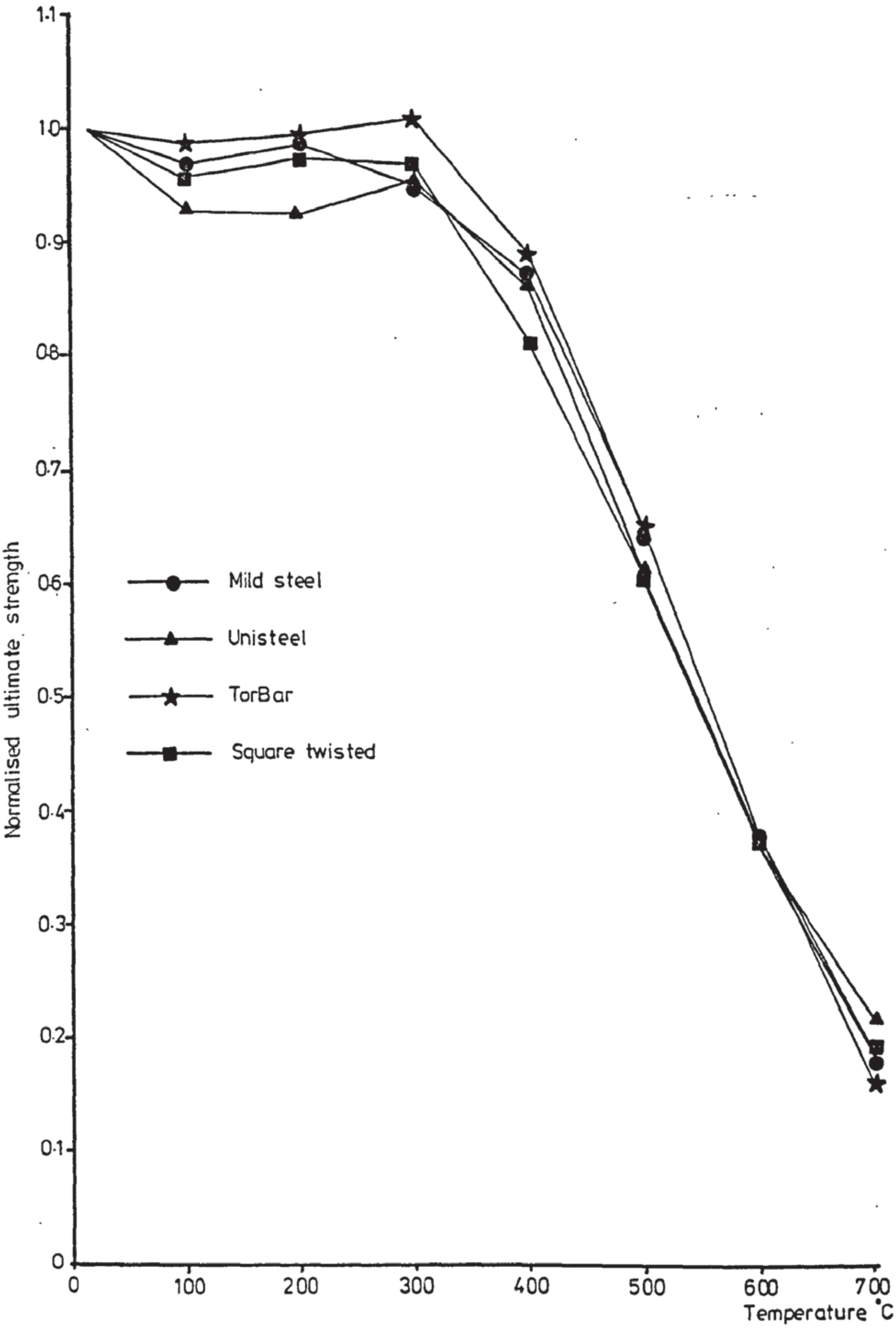


FIGURE 7·7 Normalised ultimate strength for 25 mm series 1

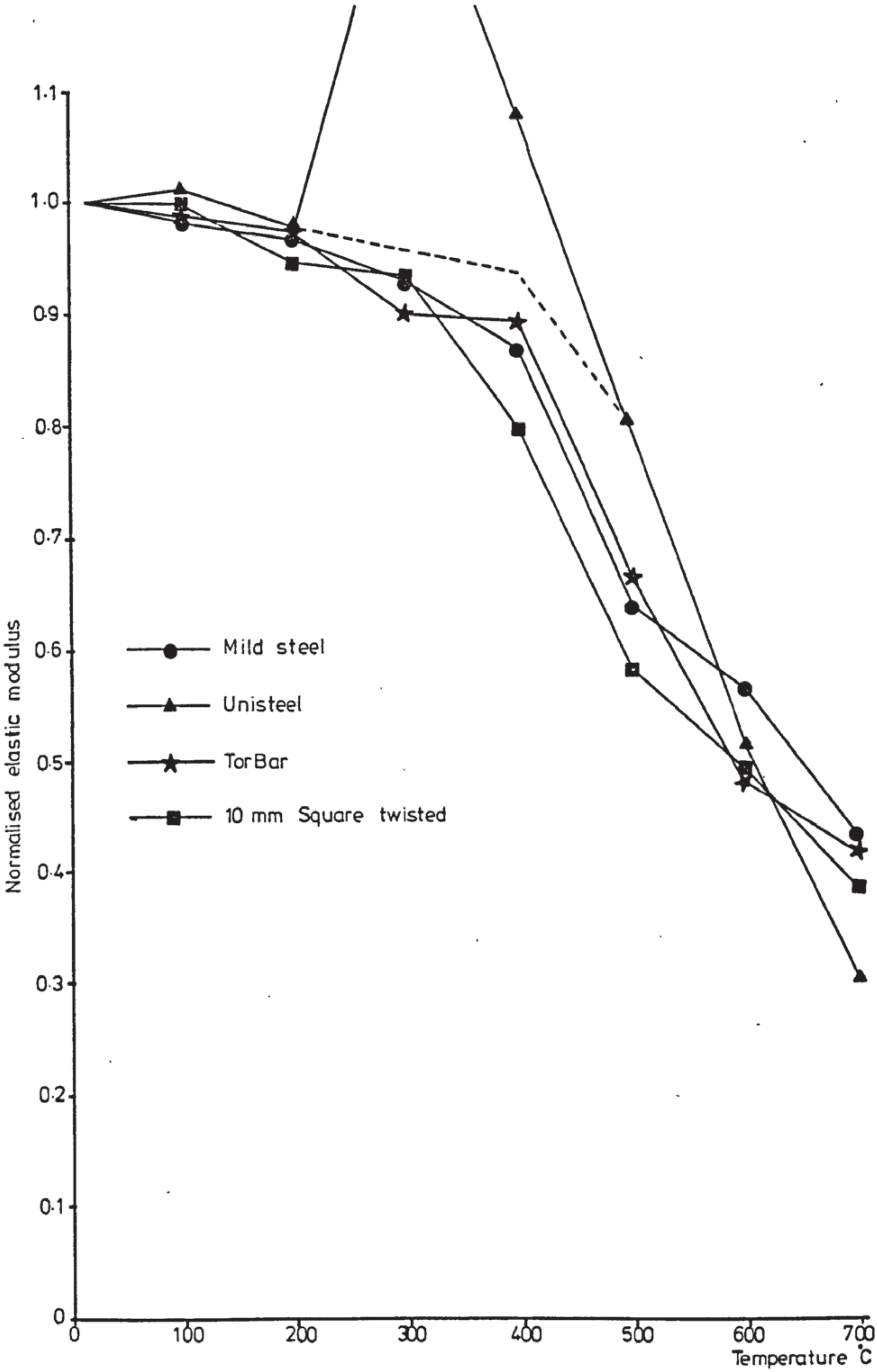


FIGURE 7.8 Normalised elastic modulus for 8 mm series 1

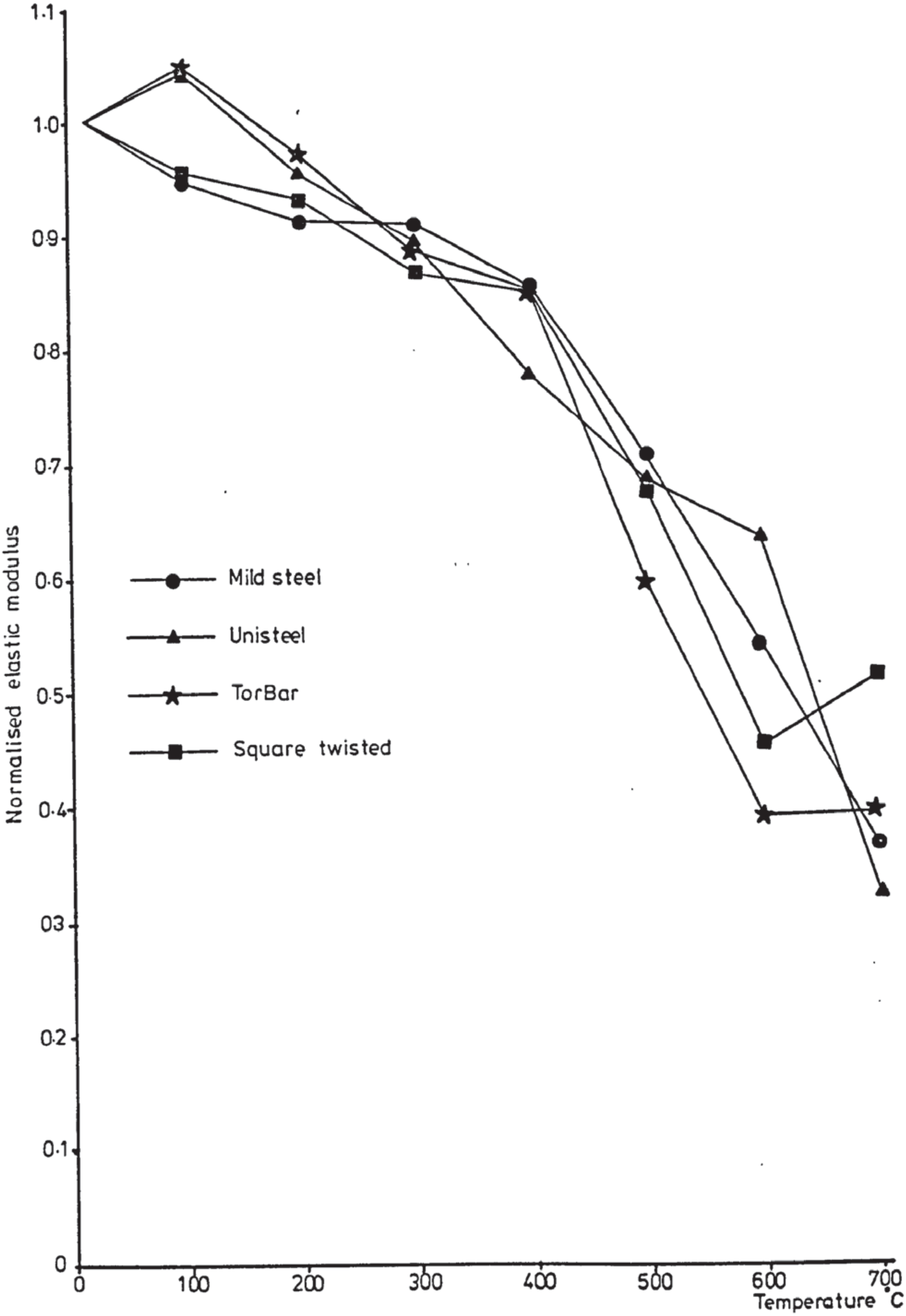


FIGURE 7.9 Normalised elastic modulus for 12 mm series 1

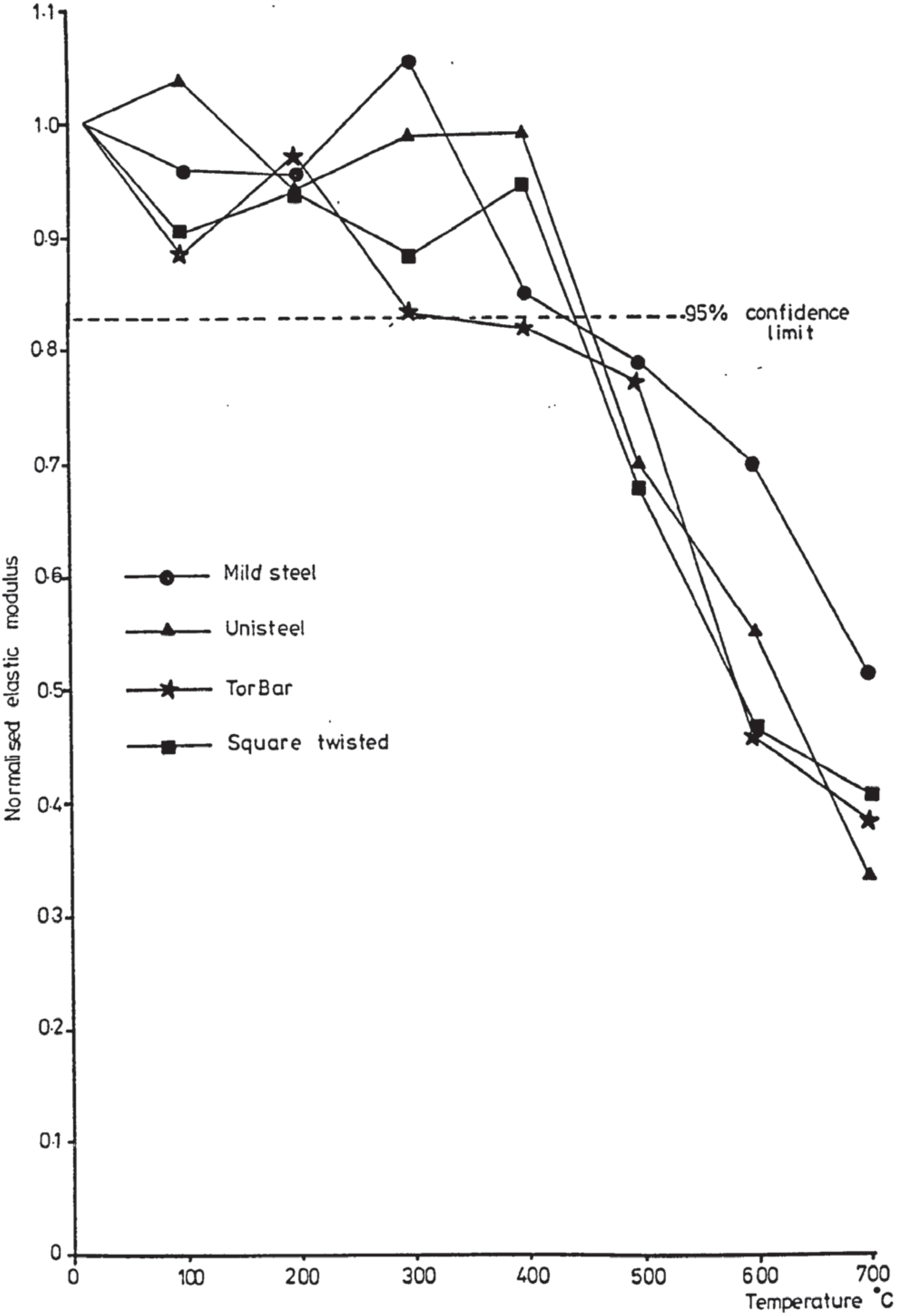


FIGURE 7.10 Normalised elastic modulus for 25 mm series 1

Although the E_t values (Figs. 7.8, 7.9 and 7.10) show a general decrease with increasing temperature above 400°C, they produce the widest scatter of results of the three normalised plots (Fig. 7.13), however there is little to suggest any difference between size and type of steel. The anomalies to this are the results obtained at the lower temperatures of the 25 mm size steels and the 8 mm unisteel at 300°C and 400°C. When the average of the 95% confidence limits from the room temperature values (Table 6.10) is placed on Figure 7.10 for the 25 mm steels, it is only the E_{400} for the torbar type of steel that lies outside the limits. This suggests that the other values lie within the natural scatter of results being obtained for the room temperature values and should not be taken to be significant.

However the two elastic modulus values obtained from the unisteel at 300°C (Table B3) were 283.56 and 269.22 kN/mm^2 which is greater than the upper confidence limit of 237.45 kN/mm^2 based on a mean of 208.66 kN/mm^2 (Table 6.8). A similarly high value of 255.70 kN/mm^2 for the duplicate test at 400°C was obtained but all three results are contrary to the other types of steel within this size and also the other sizes of unisteel. If these values had been caused by experimental error, there would have been a similar discontinuity in the 0.2% proof stress due to the offset method of obtaining them. Fig. 7.2 does not show this which suggests that the values are correct and the material was responsible for the results. If, however, these three results are ignored, the shape of the E_t plot for the 8 mm unisteel (dotted line on Fig. 7.10) is similar to the other three types of steel within this size range.

7.3 Series 2

Whenever practicable, four specimens, one from each type for a particular size (3 for the 25 mm size) were placed inside each furnace

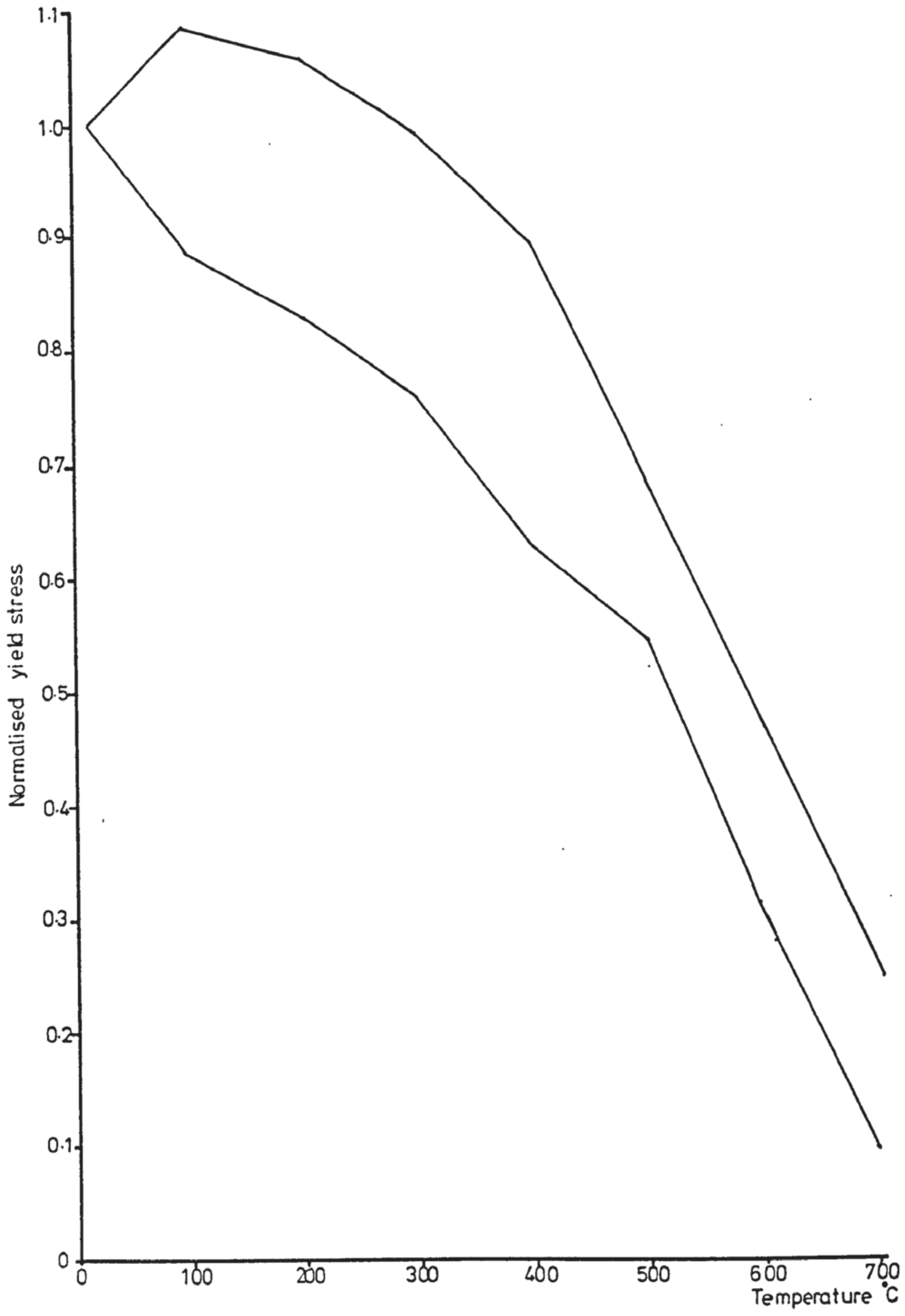


FIGURE 7.11 Scatter of normalised yield stress results for all sizes from series 1

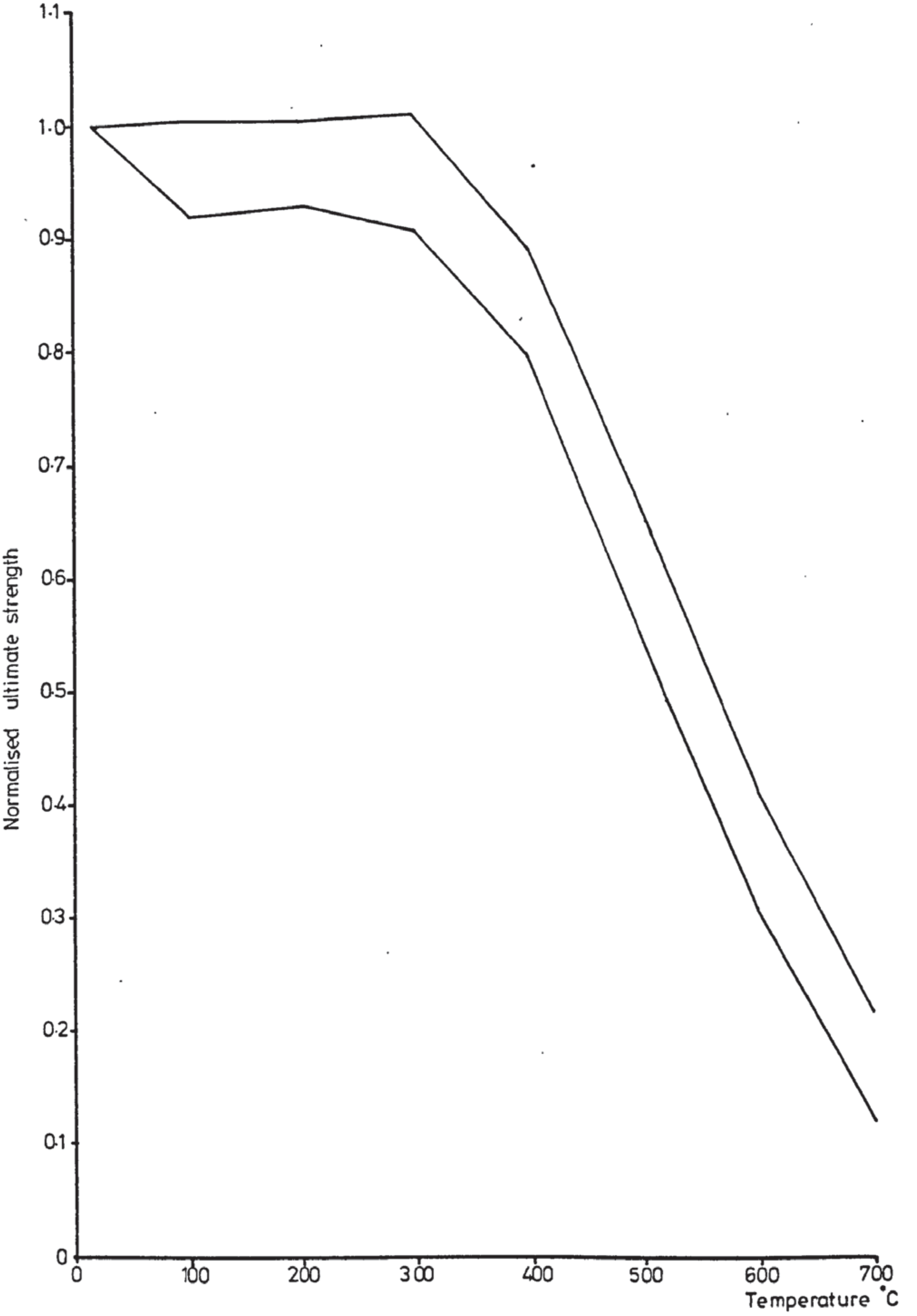


FIGURE 7·12 Scatter of normalised ultimate strength results for all sizes from series 1

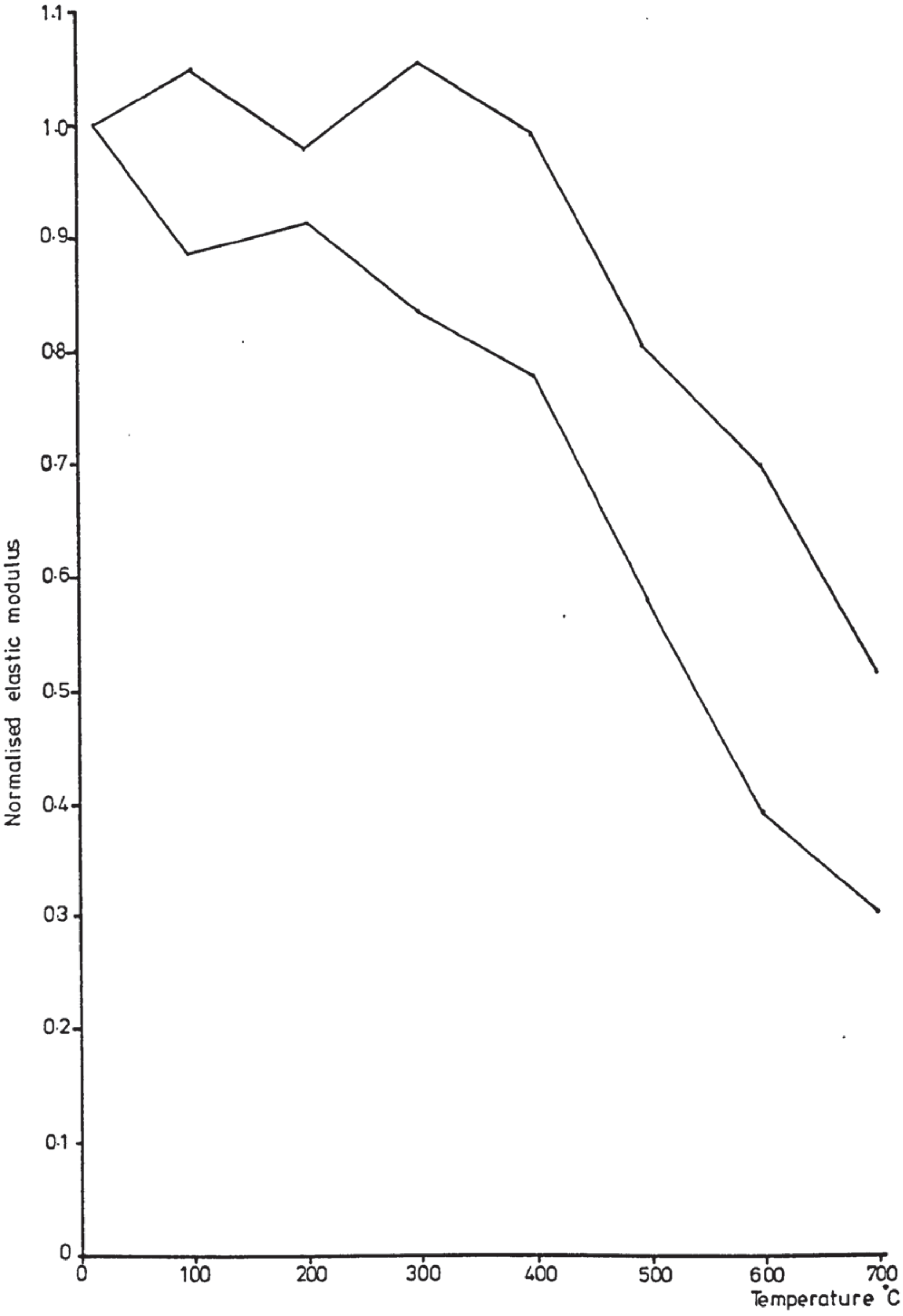


FIGURE 7.13 Scatter of normalized elastic modulus results for all sizes from series 1

and their temperature raised to the required level. This was possible because the extensometers were not attached until the specimens had cooled and were ready to be tested in the test rig without being enclosed by the furnace.

a) recorded plots

The recorded plots again showed a change in shape for some of the steels although this was completely opposite to that from the series 1 plots. Here, those steels producing the elastic/plastic shape (all mild steel plus 25 mm Unisteel) retained it over the whole temperature range but those steels producing the typical 'cold worked' plot (all torbar, all square twisted plus 8 and 12 m Unisteel) changed the shape of the plot between 200 and 300°C. An example of this can be seen in Fig. 7.14 for the 12 mm square twisted and clearly shows the change occurring at 200°C.

b) test results

The results given in Tables B4, B5 and B6 in Appendix B do not clearly show any significant changes in the three strength parameters. If, however, each recorded value for, say, 12 mm square twisted is plotted against the test temperature (Fig. 7.15) the general decrease in strength can be seen. Also the variation between duplicate tests is small for the proof stress and tensile strength, although this is larger for the elastic modulus but still within the extremes of the values obtained from the room temperature tests.

The permanent strain recorded after failure (elongation) does not show a clear pattern with none of the 8 mm unisteel failing within the gauge length or heated zone until the temperature had been 700°C and the 25 mm mild steel producing erratic values over the whole temperature range. Apart from these two extremes most of the types and sizes of

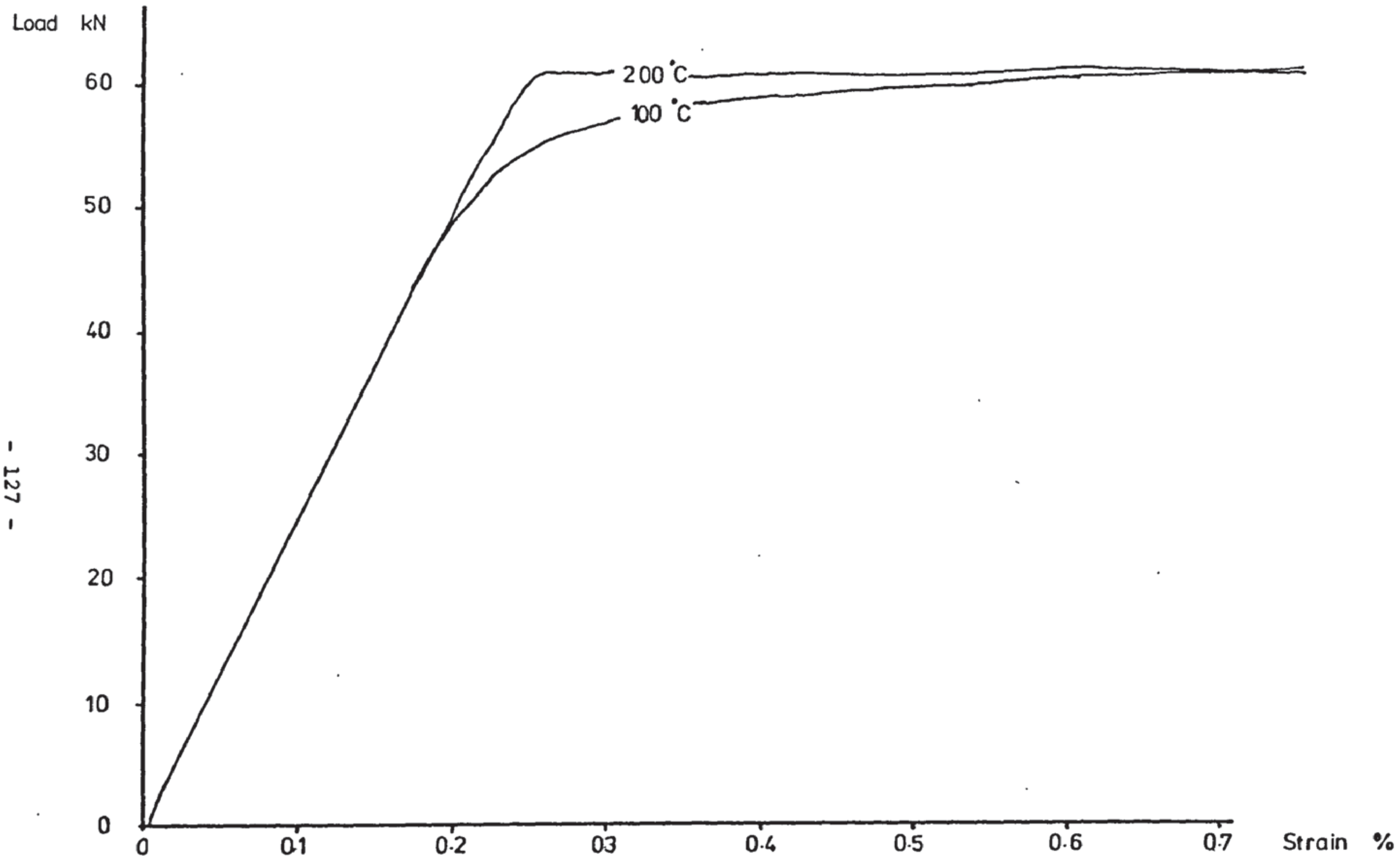


FIGURE 7·14 Change in shape of recorded plot for 12 mm square twisted, series 2

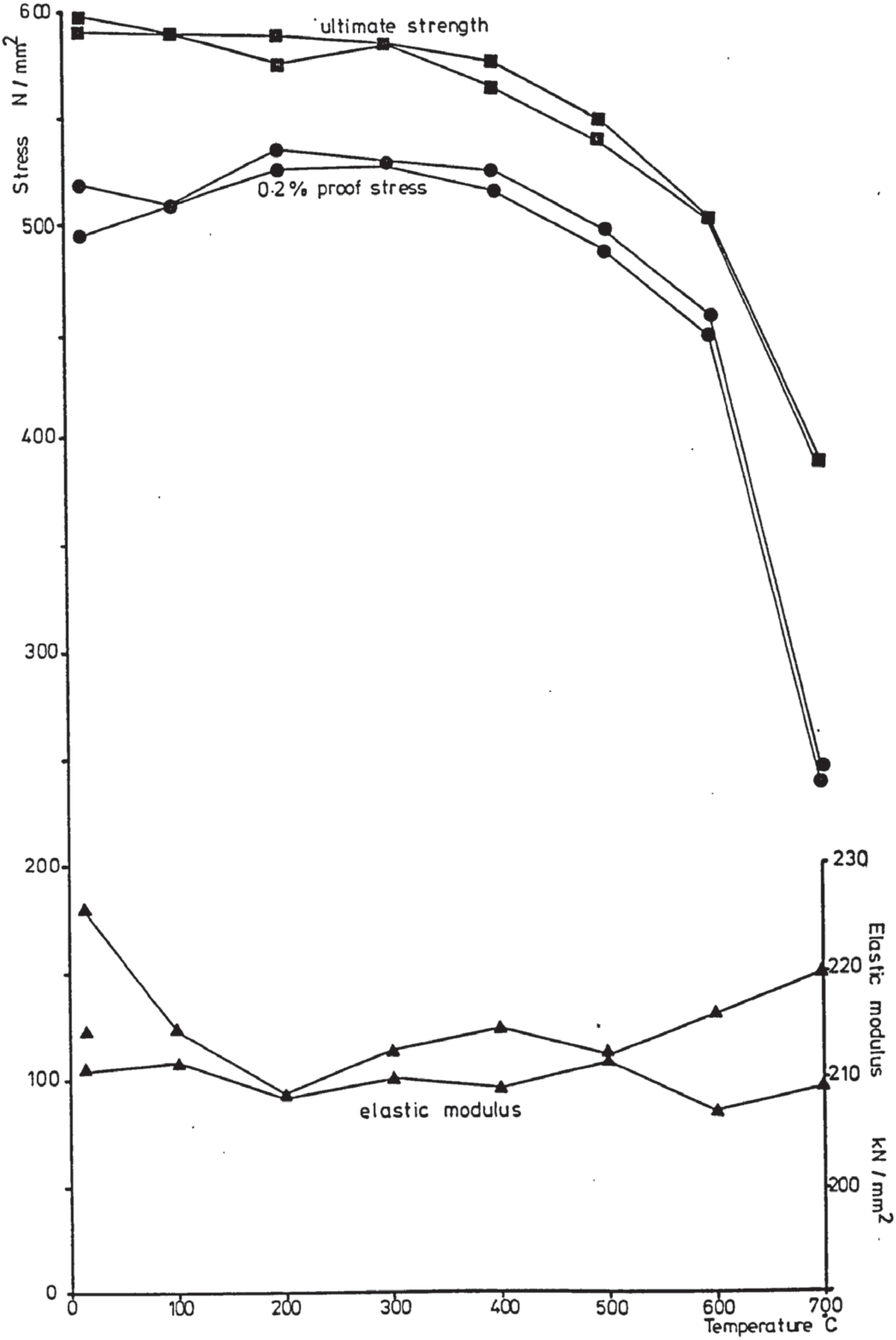


FIGURE 7·15 Full range of test results for 12 mm square twisted, series 2 steel failed within the gauge length when the temperature had been raised to 500°C and above.

c) <u>normalised results</u>

The normalised strength parameters are shown in Figs. 7.16 to 7.24 and again show that the size of steel has little effect on changing the general shape of the graphs. However, the manufacturing process of the steels does effect the yield and tensile strength with the 'cold worked' steels having greatly reduced strength with increasing temperature.

The Y_t plot shows a slight increase at the lower temperatures followed by a decrease, the steepness depending upon the type, above 500°C. It is only for the 12 mm square twisted that the yield or 0.2% proof stress falls below the working load ($Y_t = 0.55$) and this is only when the temperature had been at 700°C. Apart from the results at 700°C for the cold worked steels, the largest increase was 20% from both the 8 mm unisteel and 12 mm mild steel and a 15% decrease at Y_{600} for the square twisted steels.

There is also segregation between the two manufactured types of steel from the U_t results, but this is only significant at 600°C and above. All the types of steel and sizes showed little sign of an increase or decrease in U_t for temperatures up to 500°C.

It is only from the 25 mm size steels that the difference in the type of manufacturing can be seen from the E_t plots (Fig. 7.24) with the hot rolled steels producing a consistantly higher value than the cold worked steels. These results show that temperature has no effect upon the elastic modulus after the specimen has been allowed to cool and tested at room temperature.

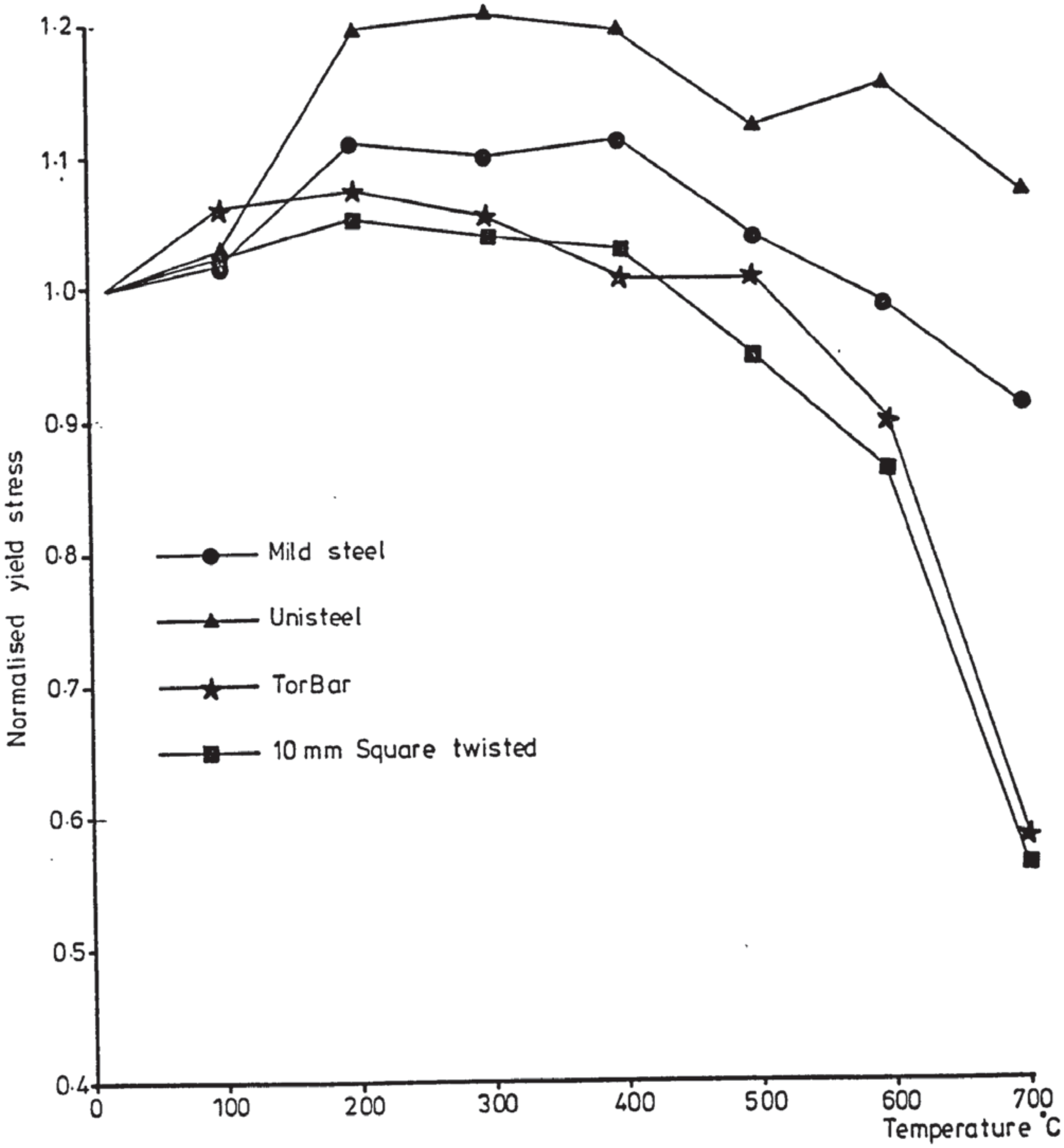


FIGURE 7·16 Normalised yield stress for 8 mm series 2

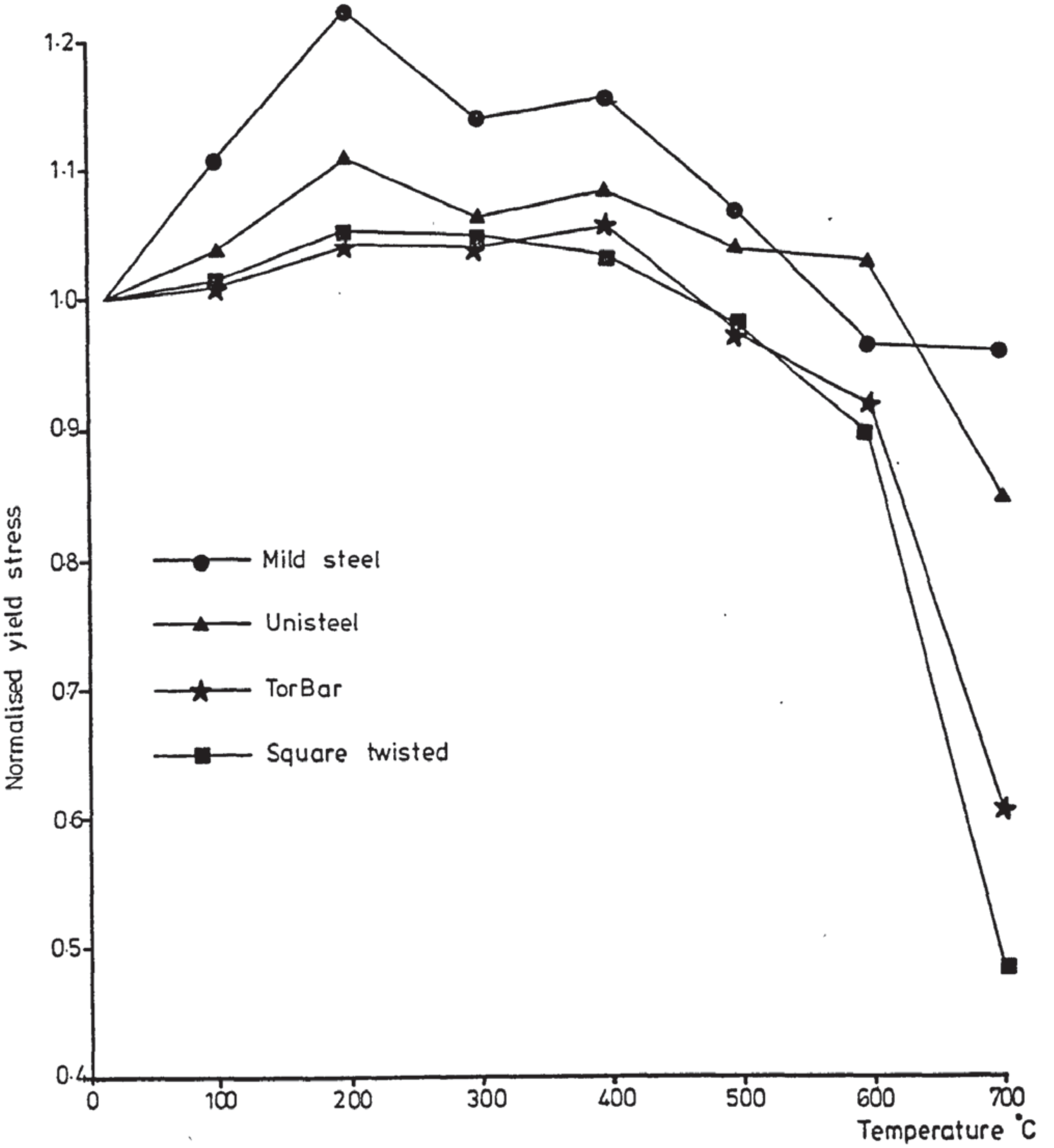


FIGURE 7·17 Normalised yield stress for 12 mm series 2

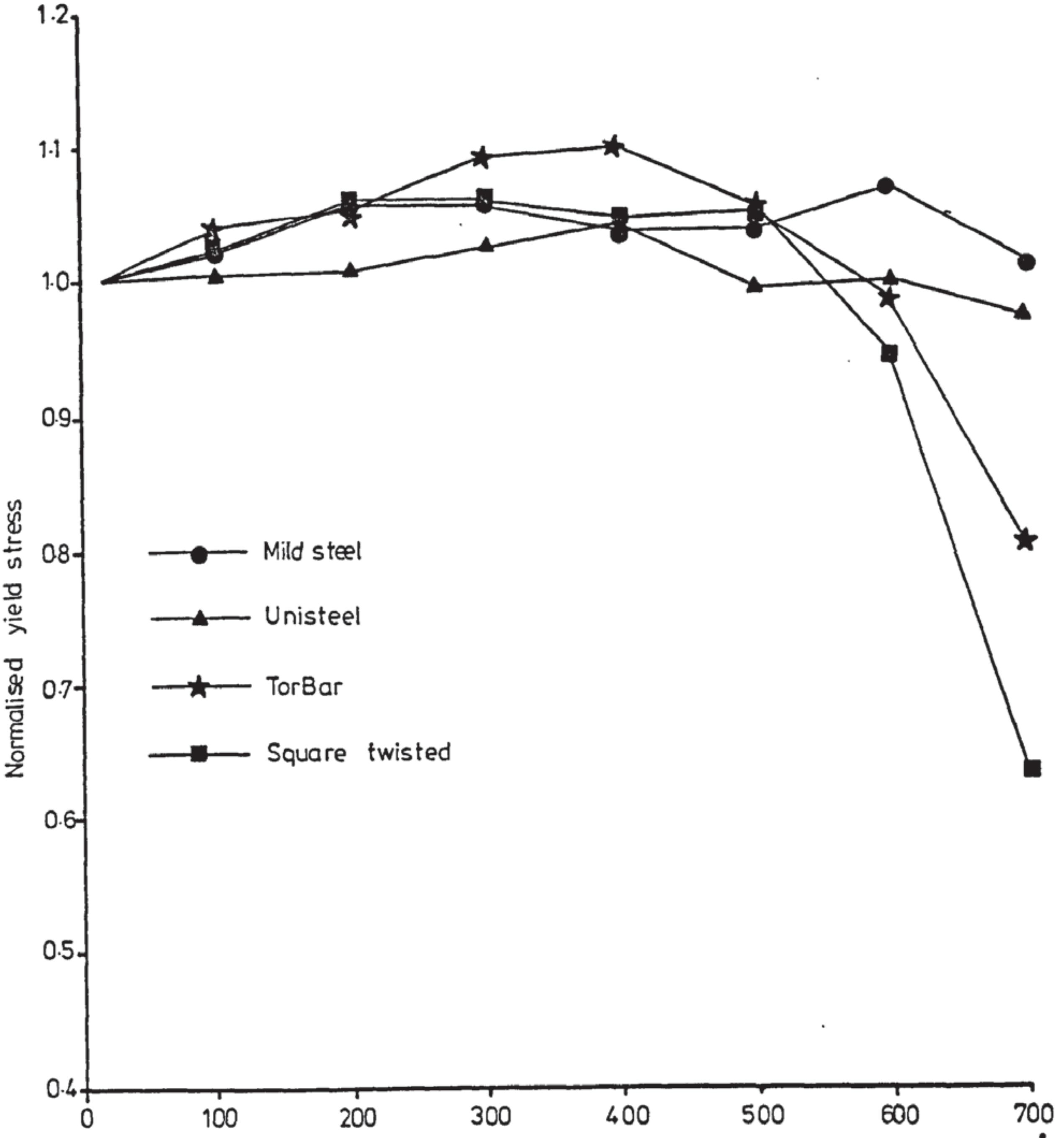


FIGURE 7.18 Normalised yield stress for 25 mm series 2

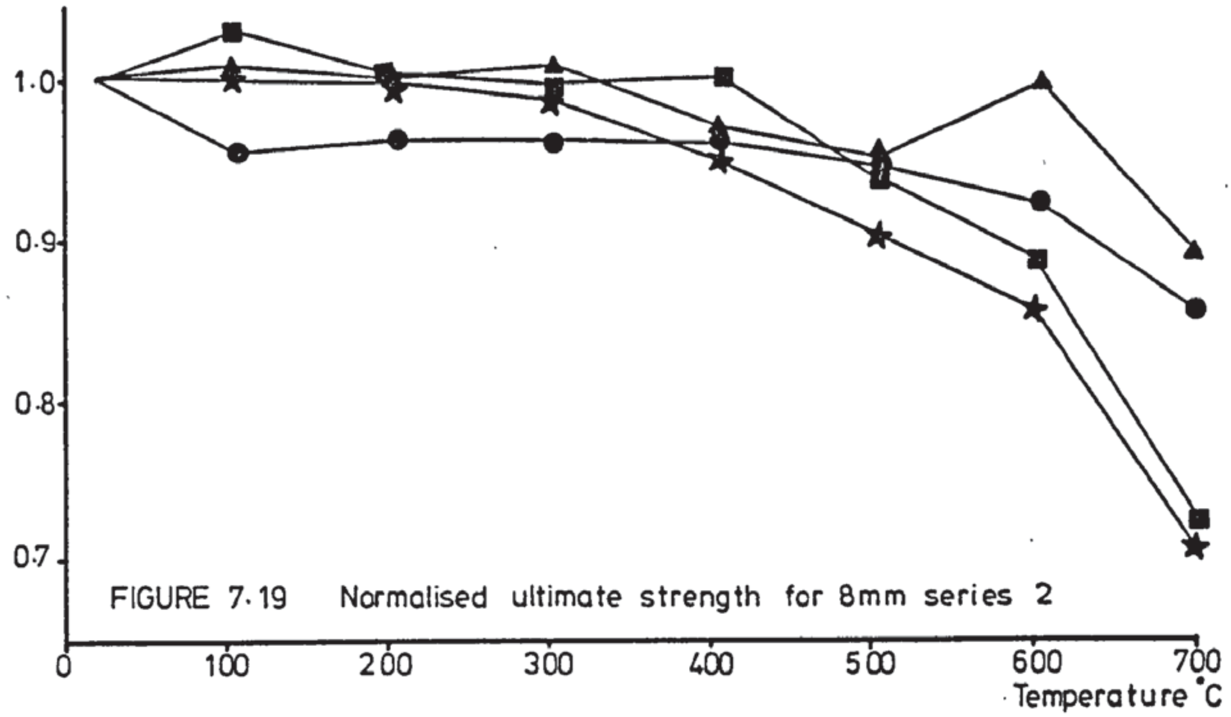


FIGURE 7.19 Normalised ultimate strength for 8mm series 2

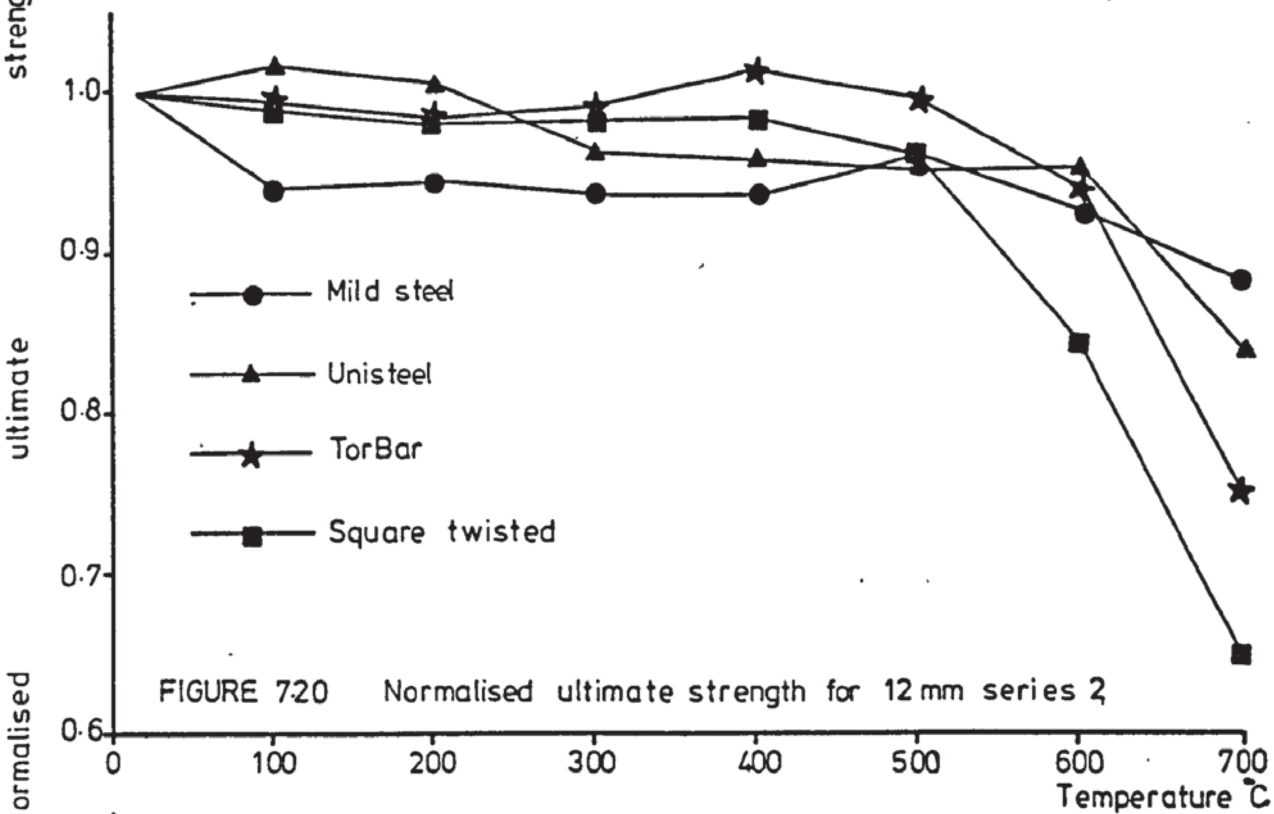


FIGURE 7.20 Normalised ultimate strength for 12 mm series 2

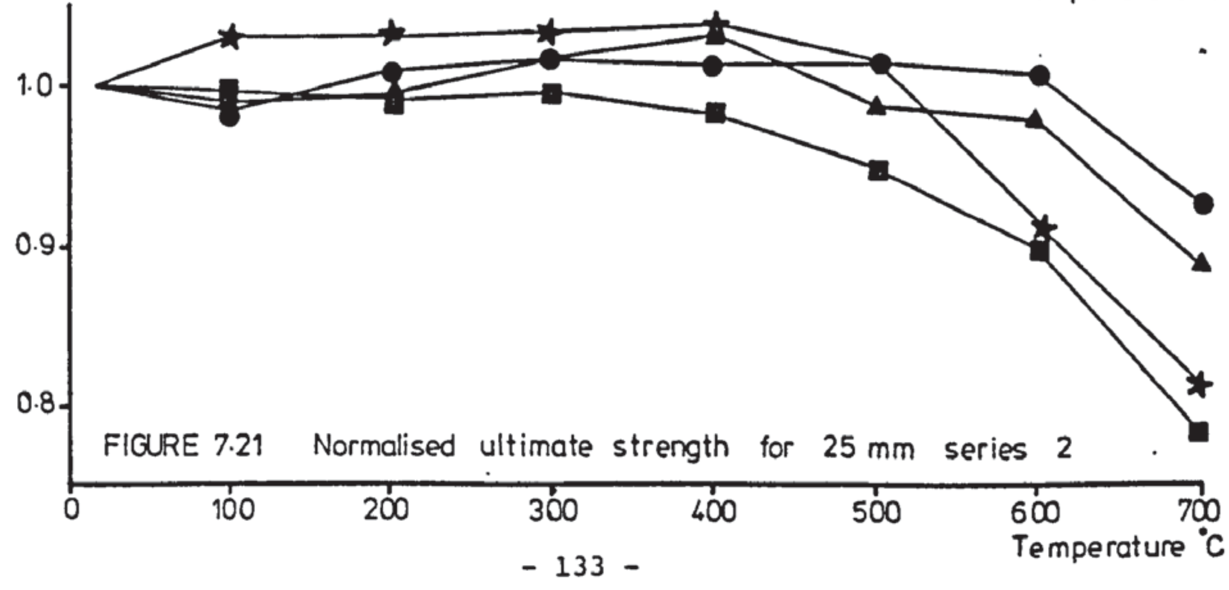


FIGURE 7.21 Normalised ultimate strength for 25 mm series 2

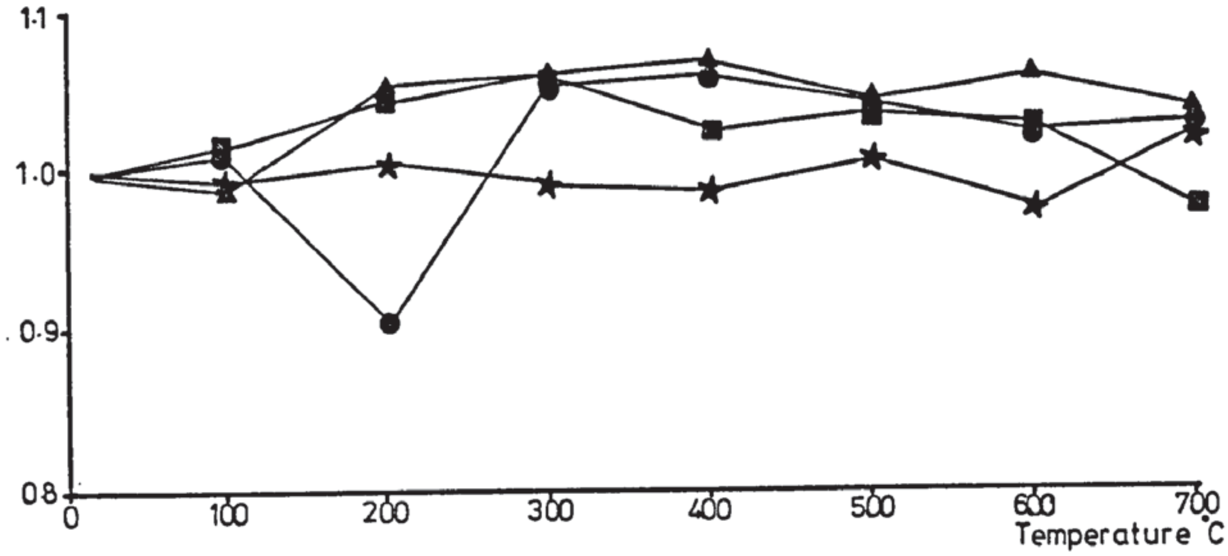


FIGURE 7·22 Normalised elastic modulus for 8 mm series 2

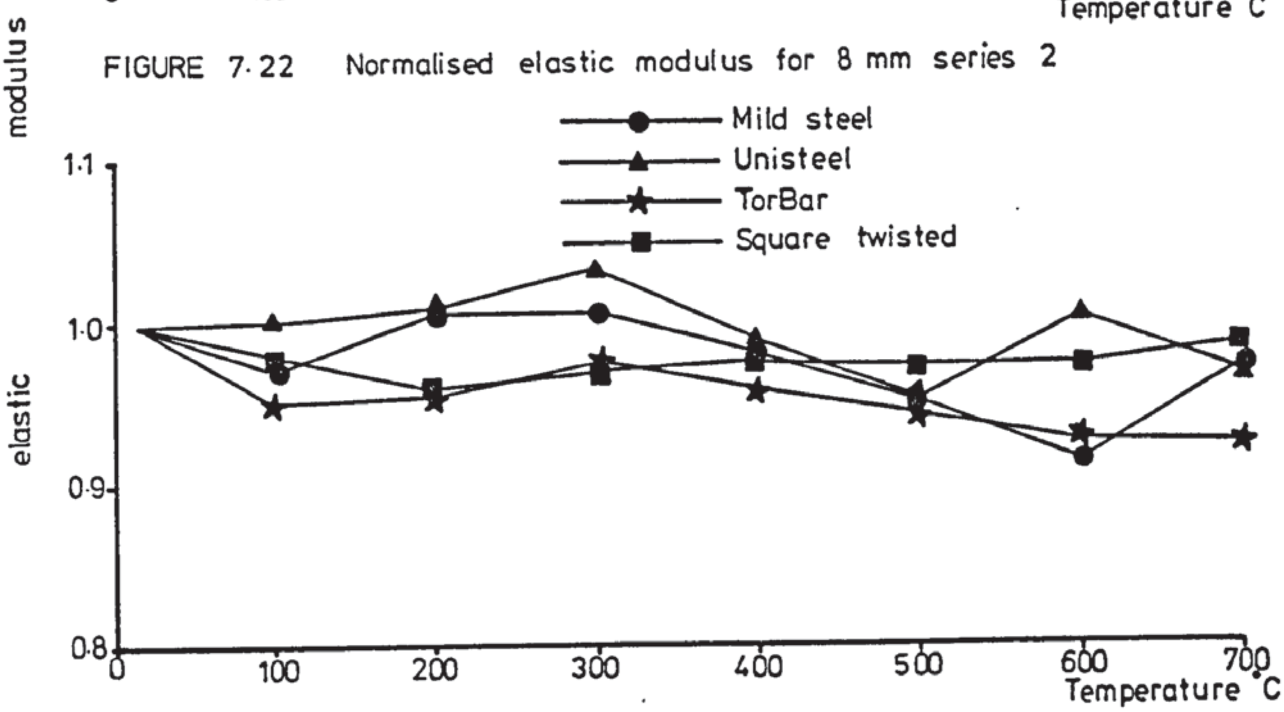


FIGURE 7·23 Normalised elastic modulus for 12mm series 2

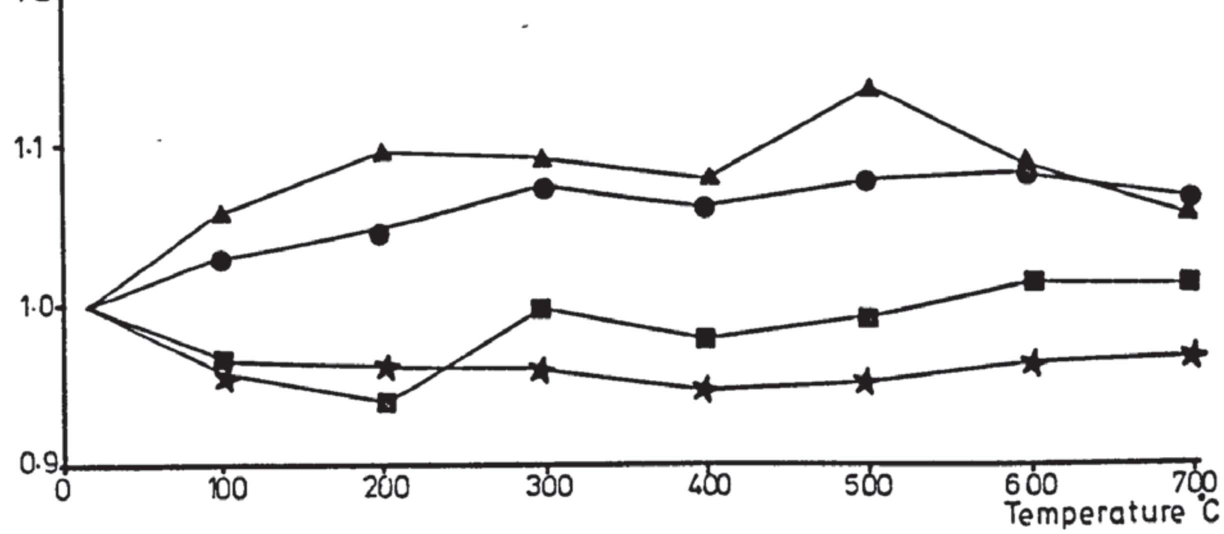


FIGURE 7·24 Normalised elastic modulus for 25mm series 2

7.4 Series 3

The procedure given in Chapter 5 for this type of test required that it should be performed in two stages. The first being signified by series 3A and the second by series 3B. Series 3A required each specimen to be stressed to the working load and then the required temperature applied. The working loads adopted for the different types and sizes based on the room temperature values (Tables 6.8, 6.9 and 6.10) obtained from the batch 1 steels are given in Table 7.1. The series 3B tests were those performed on the specimens that had obtained equilibrium, ie, the strain over a five minute period being minimal or had not failed and tensile tested after having the load removed and cooled to room temperature.

a) recorded plots

The plots from the series 3A tests showed that after the load had been applied and the temperature of the specimen increased, a negative strain was recorded on the plotter. This continued until the temperature approached the required level whereupon the strain changed from being negative to positive (Fig. 7.25). After careful consideration this was attributed to the extensometer limbs expanding differentially and a rate faster than the natural thermal expansion of the steel. The change from negative to positive strain occurred when the heat input was low enough to cause the inner limb to attain the same temperature as the outer one. However, any sudden temperature increase resulted in the strain becoming negative again and this meant that any temperature correction needed to be performed at the lowest possible heating rates.

The shape of the tensile test plots (series 3B) changed in exactly the same way as the series 2 results with the elastic/plastic shape

Type	Size mm	working load = $\frac{\text{yield or 0.2\% proof stress x nominal area}}{1.8}$ kN
Mild steel	8	9.44
	12	20.48
	25	87.03
Unisteel	8	13.73
	12	29.77
	25	152.04
Torbar	8	13.55
	12	30.96
	25	122.81
Square twisted	8	13.16
	12	34.60
	25	125.18

TABLE 7.1 Working loads for series 3A tests

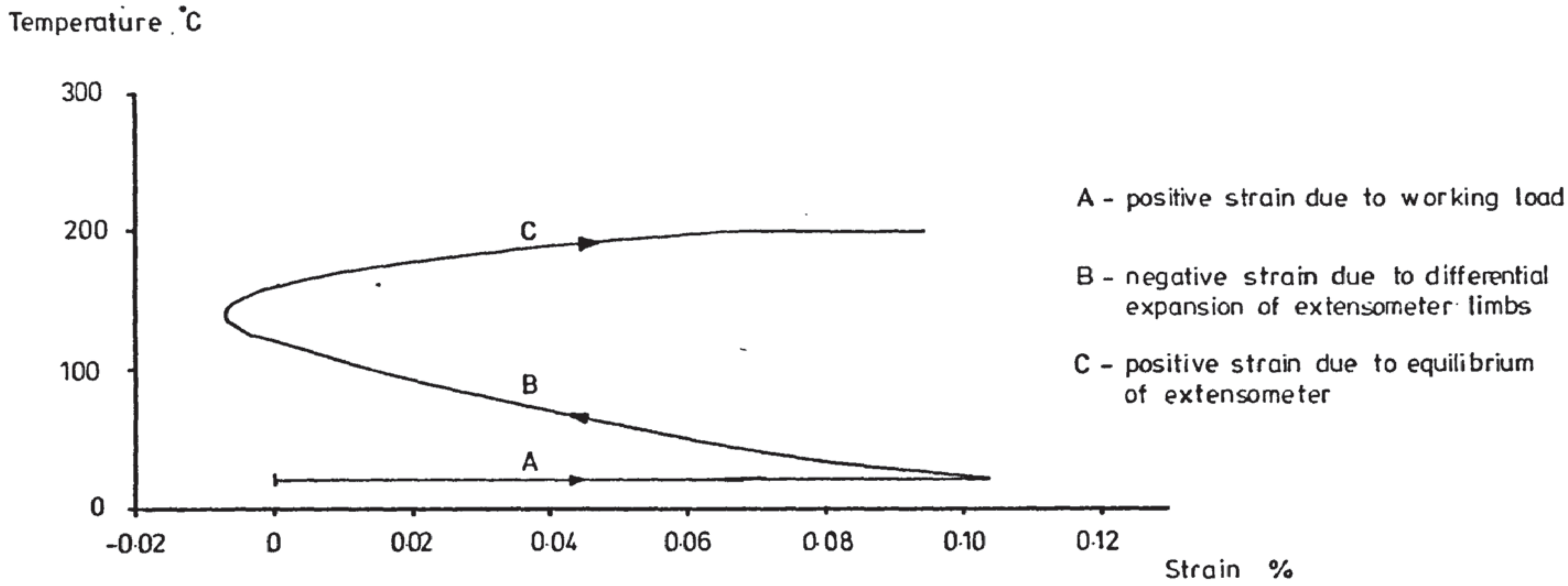


FIGURE 7·25 Recorded plot for 8 mm torbar, series 3 at 200°C remaining throughout the temperatures and the 'cold worked' shape changing to the elastic/plastic one between 200°C and 300°C.

b) <u>test results</u>

To eliminate the expansion of the extensometers and thermal expansion of the steel from the recorded strains of series 3B, it was necessary to use the results obtained during the heating cycle of the series 1 tests when no load was applied to the specimen. The average values obtained at each temperature are given in Table 7.2 and were subtracted from the recorded strains to give the net strain due the working load only. The full set of results are given in Tables B7, B8 and B9 in Appendix B. The results show that the net strain increased with increasing temperature for all the types and sizes of steel and that equilibrium for all types and sizes of steel occurs at 400°C and failure at 600°C. It is at 500°C that three different phenomenoms were observed:

i) equilibrium
ii) failure
iii) constant strain rate without any signs of failure even after a lengthy testing period (ie creep)

The 500°C results do not show a consistant pattern throughout the types and sizes of steels used. All the 12 mm sizes achieved equilibrium with the 8 and 25 mm square twisted steel, 8 mm unisteel and 25 mm torbar steel all failing. The only specimens to creep were the 8 and 25 mm mild steel, 8 mm torbar steel and 25 mm unisteel, with the rates varying from 0.001%/min to 0.035%/min for the 25 mm mild steel and unisteel specimens respectively.

The results from the series 3B tests given in Tables B10, B11 and B12 in Appendix B show little change in the strength parameters and

Temperature °C	Net strain recorded with zero load %
100	-0.030
200	-0.038
300	-0.025
400	-0.024
500	-0.010
600	-0.010

TABLE 7.2 Correction to recorded strain obtained from Series 1 tests

the majority of these specimens which were raised to 500°C failed within the gauge length.

c) normalised results

It was only the results from series 3B that could be normalised and these are given in Figs. 7.26 to 7.34. It is clear from these figures that size and type has little or no effect upon the three major strength parameters, although the scatter of results is wider than the results obtained from the other two series. In general the results for all the tensile strengths, apart from 8 mm torbar at 500°C, are approximately ±5% of the room temperature value, and the other two parameters showing a maximum of +17% and a minimum of -12% variation from the room temperature value. The exception to this is for the E_t for the 25 mm size steels (Fig. 7.34) where segregation between the manufactured types can clearly be seen with the 'hot rolled' steels having greater E_t values than the 'cold worked' steels.

7.5 Summary of Results

The major factor which is consistant throughout the results for all three test procedures is that the size, ie, nominal diameter, of the specimens does not affect the strength properties of the steel. Apart from this all the other points arising from the results can only be associated with each of the test procedures individually. Each test series has been sub-divided into general points, yield or 0.2% proof stress, ultimate tensile strength and elastic modulus with the more important points being included under the appropriate heading.

a) Series 1

i) General points

1) the shape of the elastic/plastic plot for the hot

Normalised yield stress

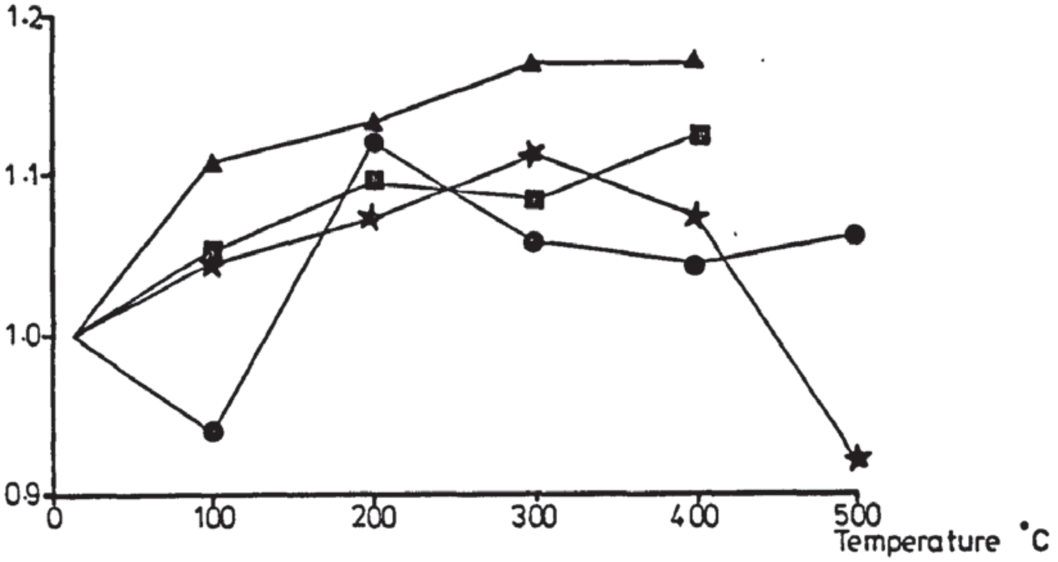


FIGURE 7.26 Normalised yield stress for 8 mm series 3

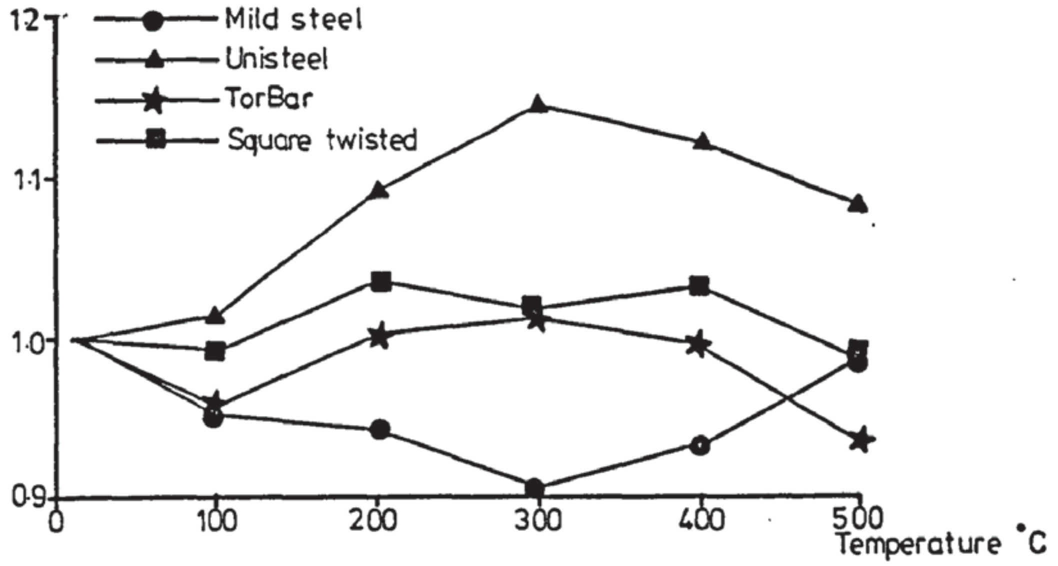


FIGURE 7.27 Normalized yield stress for 12 mm series 3

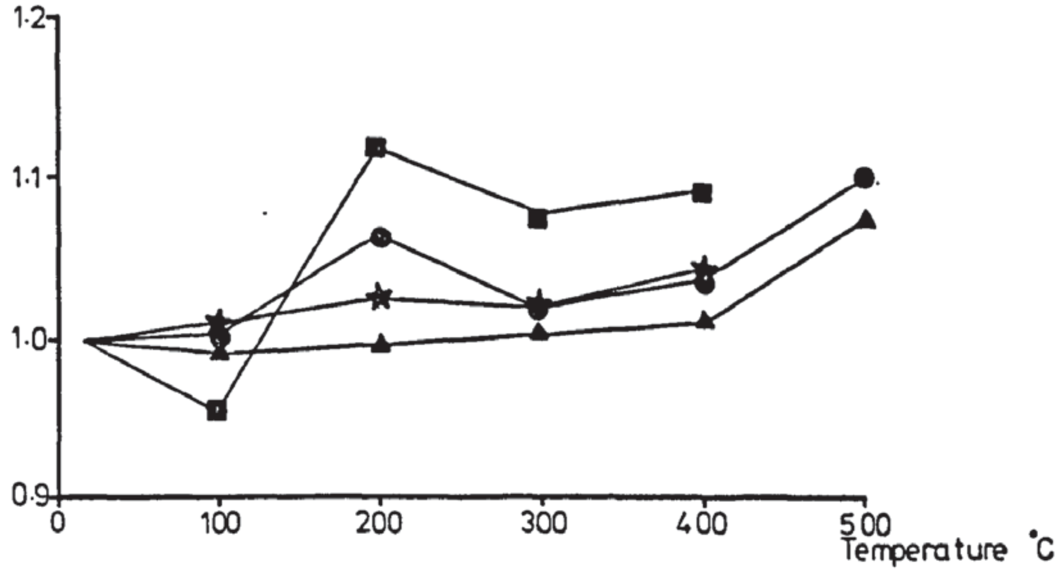


FIGURE 7.28 Normalised yield stress for 25 mm series 3

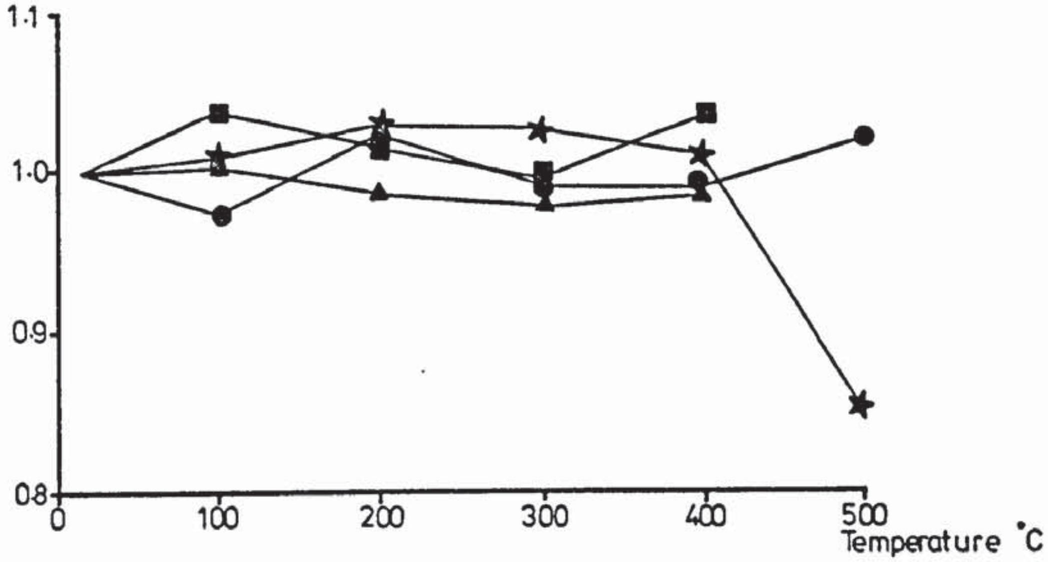


FIGURE 7.29 Normalised ultimate strength for 8mm series 3

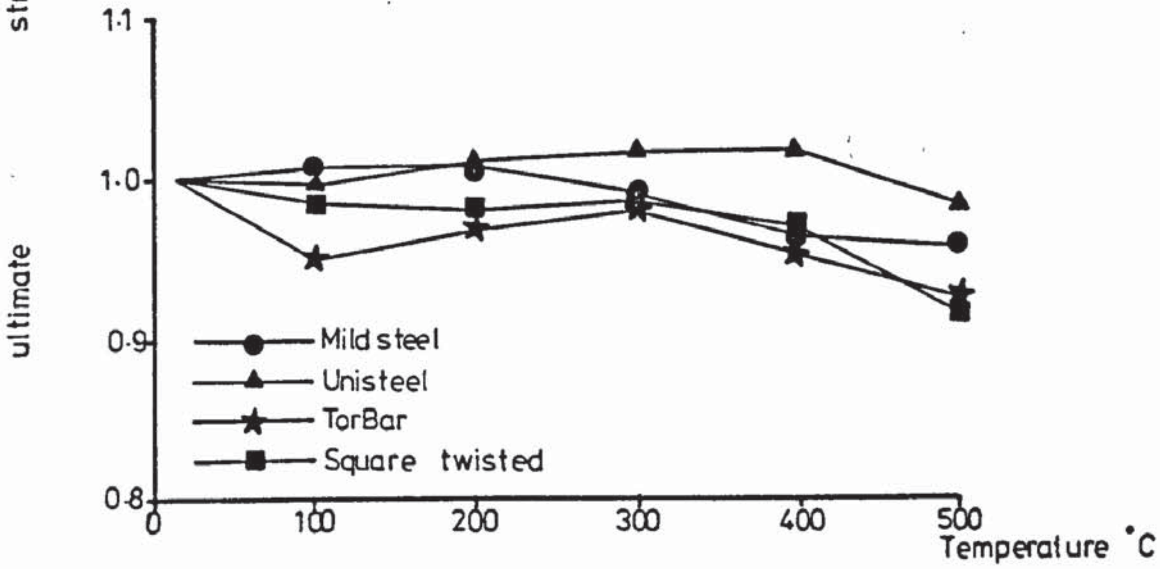


FIGURE 7.30 Normalised ultimate strength for 12 mm series 3

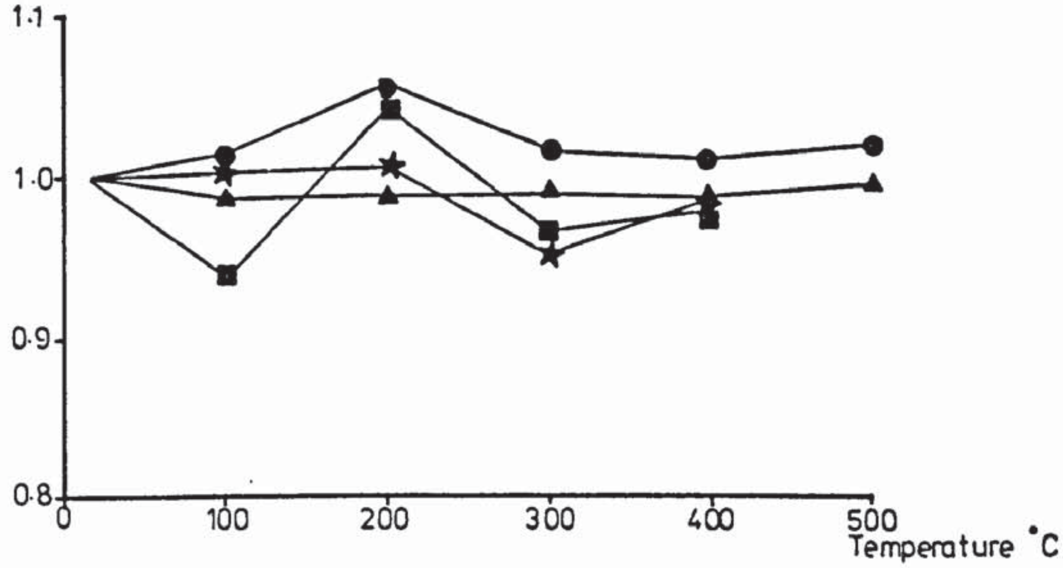


FIGURE 7.31 Normalised ultimate strength for 25mm series 3

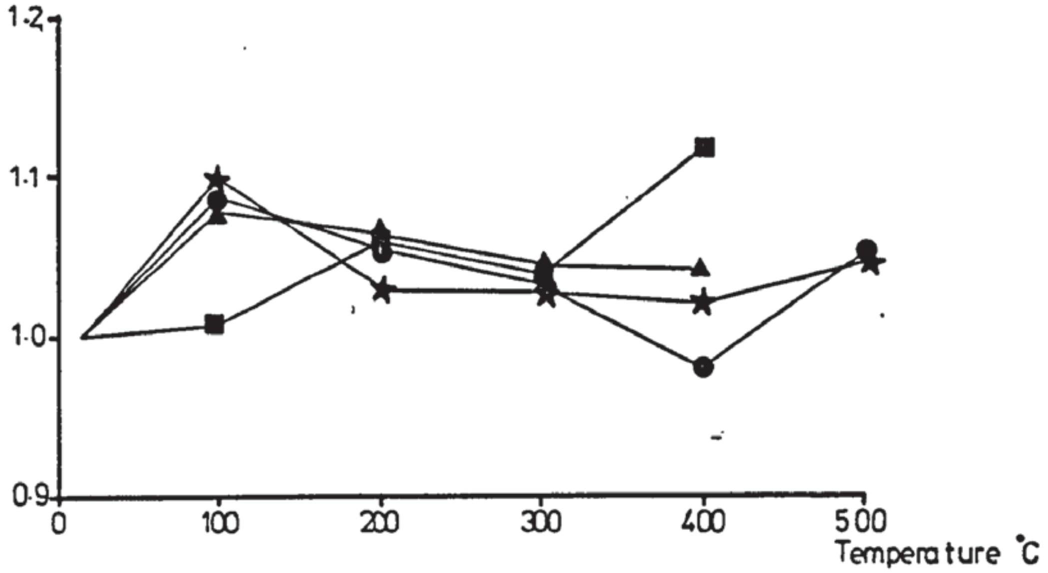


FIGURE 7·32 Normalised elastic modulus for 8 mm series 3

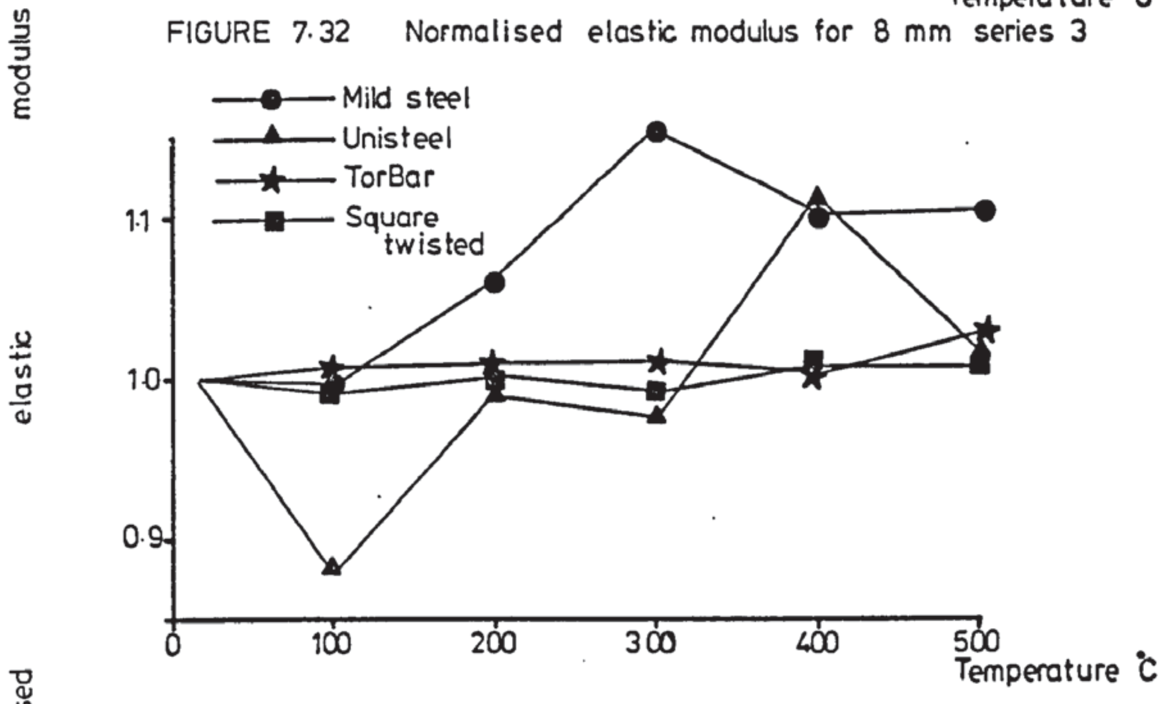


FIGURE 7·33 Normalised elastic modulus for 12 mm series 3

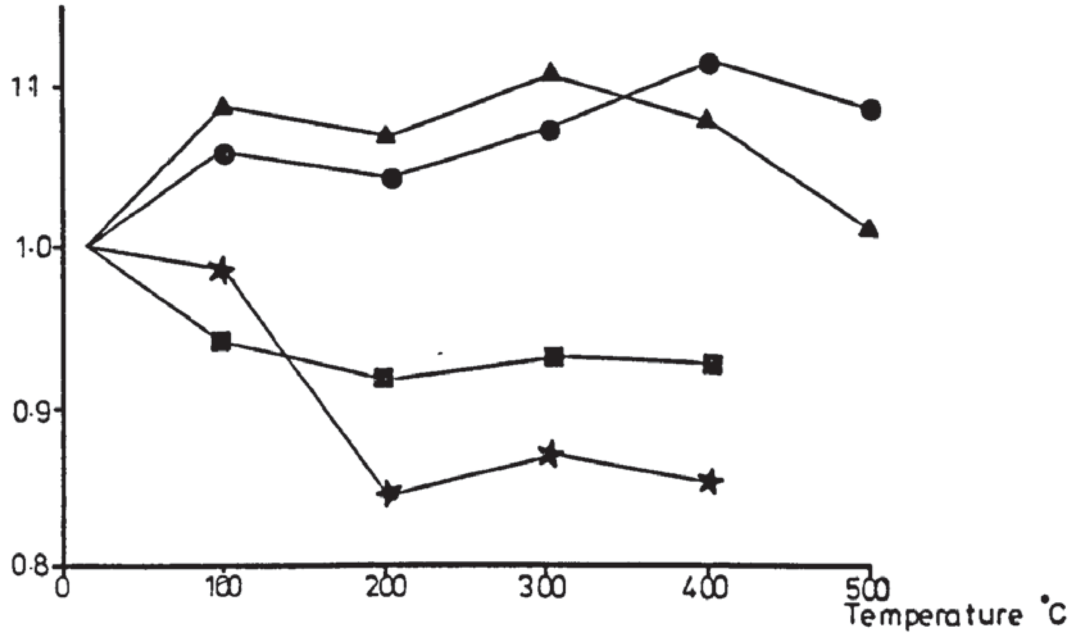


FIGURE 7·34 Normalised elastic modulus for 25 mm series 3 rolled steels changed at 300°C to produce a plot similar to the cold worked steels with a region of work hardening

2) the cold worked shape was retained at all the temperatures

3) the specimens failed consistantly within the heated zone at 400°C and above

4) the type of steel has little effect upon the strength parameters

ii) Yield or 0.2% proof stress

1) there is no significant increase or decrease in the stress up to 300°C

2) above 300°C the stress decreases rapidly with all the results converging into a narrow band

3) the yield stress is reduced to the working load stress between 500 and 560°C

iii) Ultimate tensile strength

1) the strength is similar to the room temperature value up to 300°C, followed by sharp decrease with increasing temperature

2) there is a 50% reduction in the strength between 515 and 560°C

iv) Elastic modulus

1) it is not until 300°C that there is any marked decrease in the modulus

2) there was a wide scatter of results for all the temperatures and sizes with a 50% reduction occurring between 550 and 700°C.

b) Series 2

i) General points

1) the cold worked shape changed to an elastic/plastic

shape at a temperature of between 200 and 300°C

2) the elastic/plastic shape was retained at all the temperatures

3) the type of steel affects the strength properties

ii) Yield or 0.2% proof stress

1) lower stresses were obtained for the cold worked steels at most temperatures

2) little or no reduction in the stress of the hot-rolled steels over the temperature range (4% maximum)

3) slight increase in stress for all the steels up to 400°C

4) stress reduce to the working load stress at 685°C for the 12 mm square twisted steel only

5) up to 600°C the maximum reduction for the cold worked steels was 15%

iii) Ultimate tensile strength

1) up to 500°C there is little variation from the room temperature value (-9% and +4%)

2) above 500°C the cold worked steels reduce more rapidly than the hot rolled steels

iv) Elastic modulus

1) minimal variation from the room temperature value for all the steels over the whole temperature range

2) segregation between the types of steel is only apparent for the 25 mm size steels with the cold worked steels less than the hot rolled steels

c) Series 3

Series 3A

i) General points

1) the gauges were succeptable to different heating rates

2) recorded strains corrected from series 1 pre-heating cycle results

3) all types and sizes attained equilibrium at 400°C

4) all types and sizes failed at 600°C

5) at 500°C, creep observed for 8 and 25 mm mild steel, 8 mm torbar steel and 25 mm unisteel with rates ranging from 0.001%/min to 0.035%/min for the 25 mm mild steel and unisteel respectively

Series 3B

i) General points

1) same change in shape of the recorded plots as observed for series 2

2) the majority of specimens taken to 500°C only failed within the heated zone

3) reduction in any of the strength parameters for all the sizes and types was not significant

4) only the elastic modulus for the 25 mm size steels shows any signs of segregation between the types of steel with the cold worked steels being lower than the hot rolled steels.

CHAPTER 8

Prestressing Steel Results

8.1 Introduction

A similar procedure has been adopted in this chapter to that used in Chapter 7 for the reinforcing steels. All the results from the test procedures outlined in Chapter 5 have been included in Appendix C. Although there is some confusion amongst the standards[12][13], trade literature[37] and previous work[36] as to the terminology of certain strength parameters for prestressing streels, those used for all the tensile tests were the same as for the reinforcing steels except the tensile strength is given in terms of load rather than stress. Table 8.1 shows the room temperature values (Table 6.11) obtained together with the average elongation for those specimens that failed within the 250 mm gauge length with the three main strength parameters being used to normalise in non-dimensional form the values at each temperature.

The same notation for the normalised values used in Chapter 7 is used for the prestressing steels with Y_t, U_t and E_t being the normalised 0.2% proof stress, tensile strength and elastic modulus values at $t^{o}C$ respectively.

The results from prestress 2 were obtained first and showed very little variation between the duplicate test results and therefore the tests on the other procedures were reduced to one at each temperature.

The elongation from the 7 wire strand was not recorded due to difficulties in rejoining the two fractured sections and because of the helical configuration of the wire, the markings used for the 250 mm gauge length could not be guaranteed to occur on the same wire.

Although the recorded plots are not included if was noticeable that there was no change in the shape of the stress/strain plot for any of the steels at any temperature and any loading procedure. This shape was typical for prestressing steels tested at room temperature with a long elastic zone followed by a work hardening period but without any yield point being recorded.

Since the recorded plots were uniform throughout, the test procedures have been sub-divided into the two remaining areas of interest, ie, test results and normalised figures.

8.2 Prestress 1

For use with prestress 3 results, the net expansion from the specimen and extensometer was recorded after the 30 minute soaking period and before the tensile test at the temperature was carried out.

a) test results

The results given in Table C1 of Appendix C show large reductions in the three strength parameters over the temperature range with an increase in elongation being more significant at the high temperatures. These elongations being 27.2 and 38.8% at 700°C for the mill coil and stabilised wire respectively.

b) normalised results

Using the values given in Table 8.1 and C1, the normalised results are shown in Figs. 8.1, 8.2 and 8.3 for the three strength parameters. These figures clearly show that there is no difference between the three types of steel and they all follow the general pattern of decreasing strength with increasing temperature.

The normalised proof stress shows a figure of three separate sections with an initial section up to Y_{200} showing an instant decrease in stress with a 100°C temperature increase followed by a fast decreasing section between Y_{200} and Y_{500} and then falling off at the higher temperatures. A 50% reduction in proof stress is obtained at a temperature between 370° and 420°C.

The U_t figure is of a similar shape but the strength decrease is not significant until the temperature is above 200°C. The reduction

Nominal Size mm	Type	Measured Area mm^2	0.2% proof stress N/mm^2	tensile strength kN	elastic modulus kN/mm^2	elongation %
5	Mill coil	20.53	1606.2	36.9	203.27	3.4
5	Stablilised wire	19.95	1464.8	33.5	204.12	4.6
9.3	7 wire strand	53.60	1864.5	104.0	199.54	- *

TABLE 8.1 Mean room temperature values

* No specimens failed within 250 mm gauge length

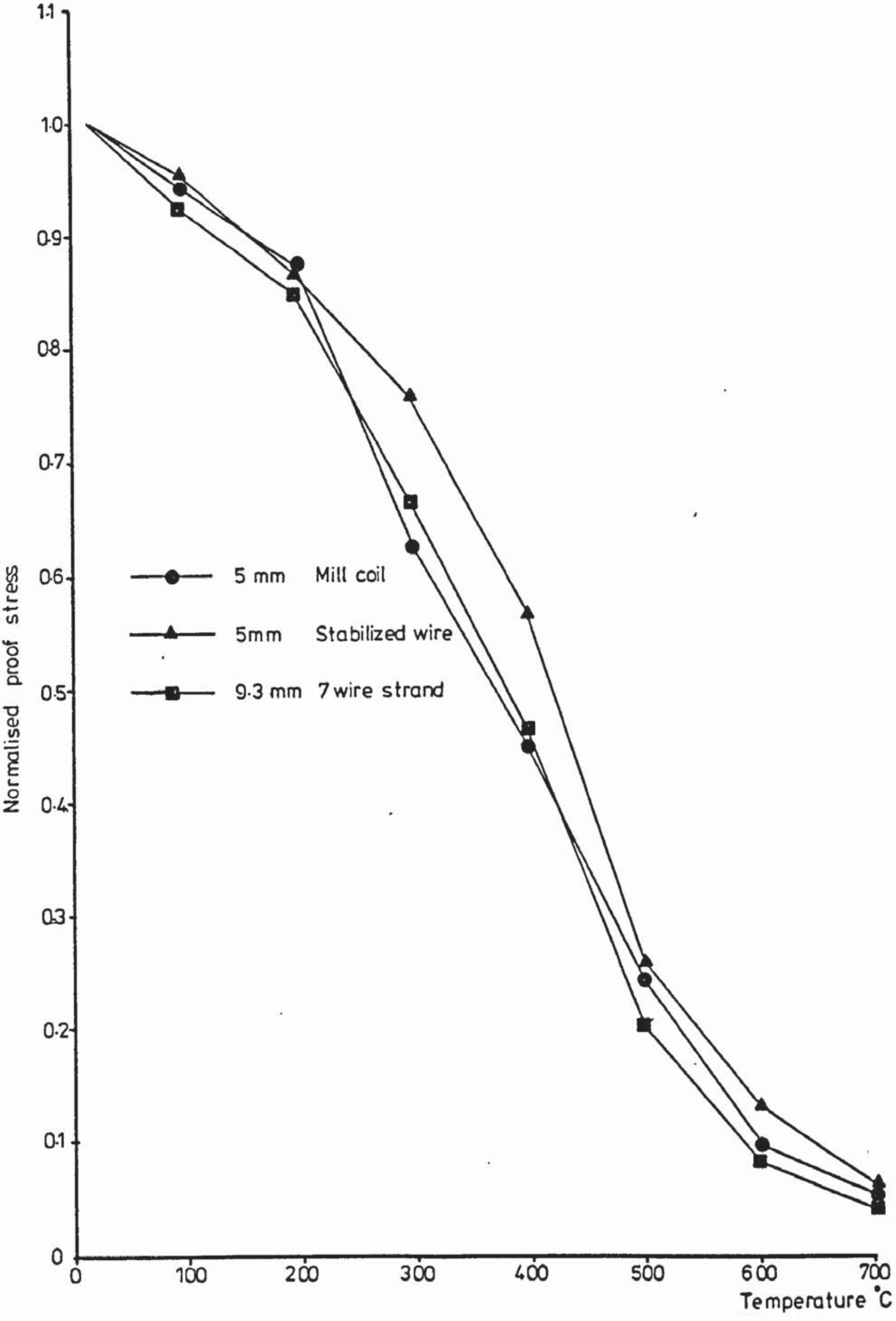


FIGURE 8.1 Normalised proofstress for prestress 1

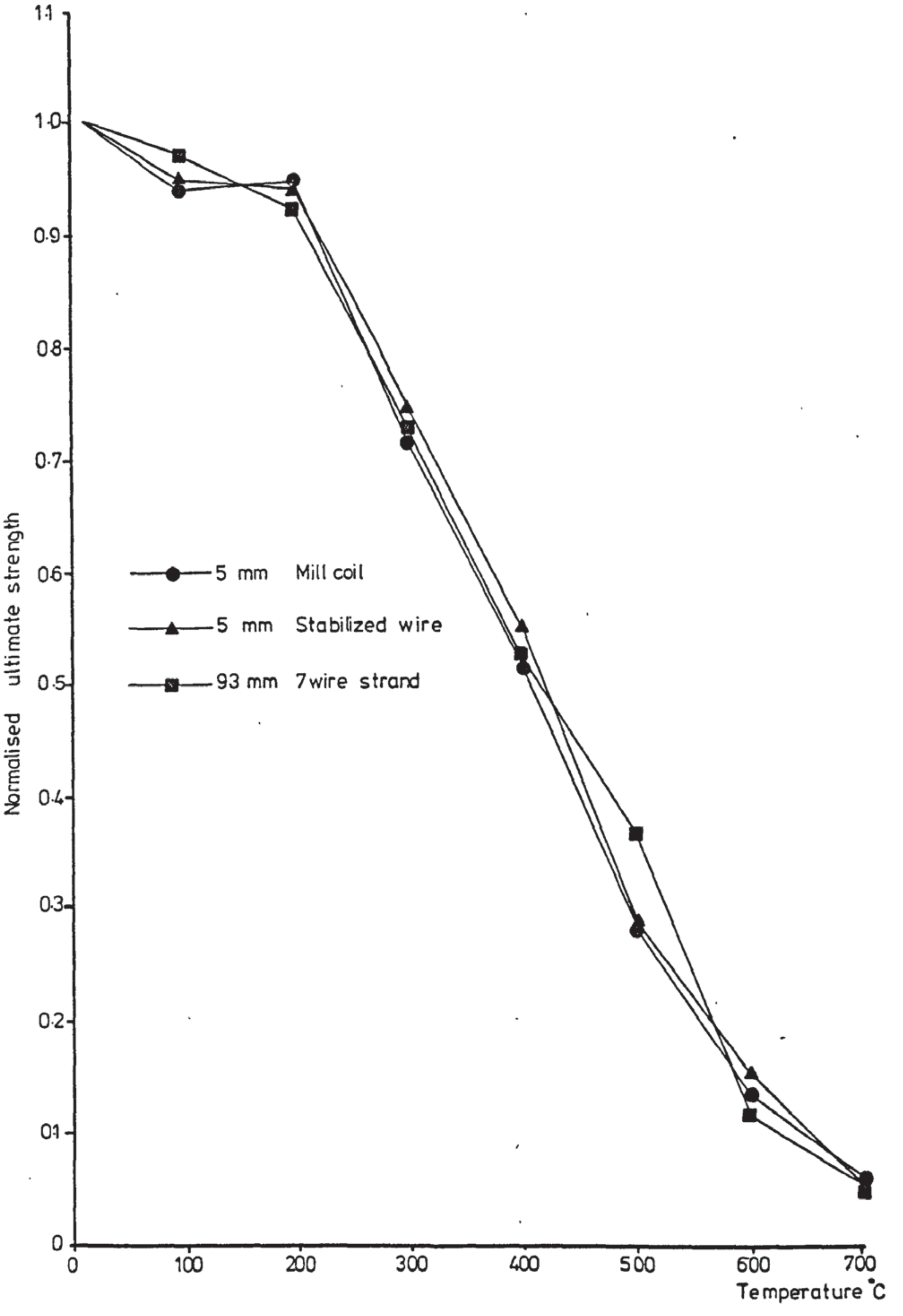


FIGURE 8.2 Normalised ultimate strength for prestress 1

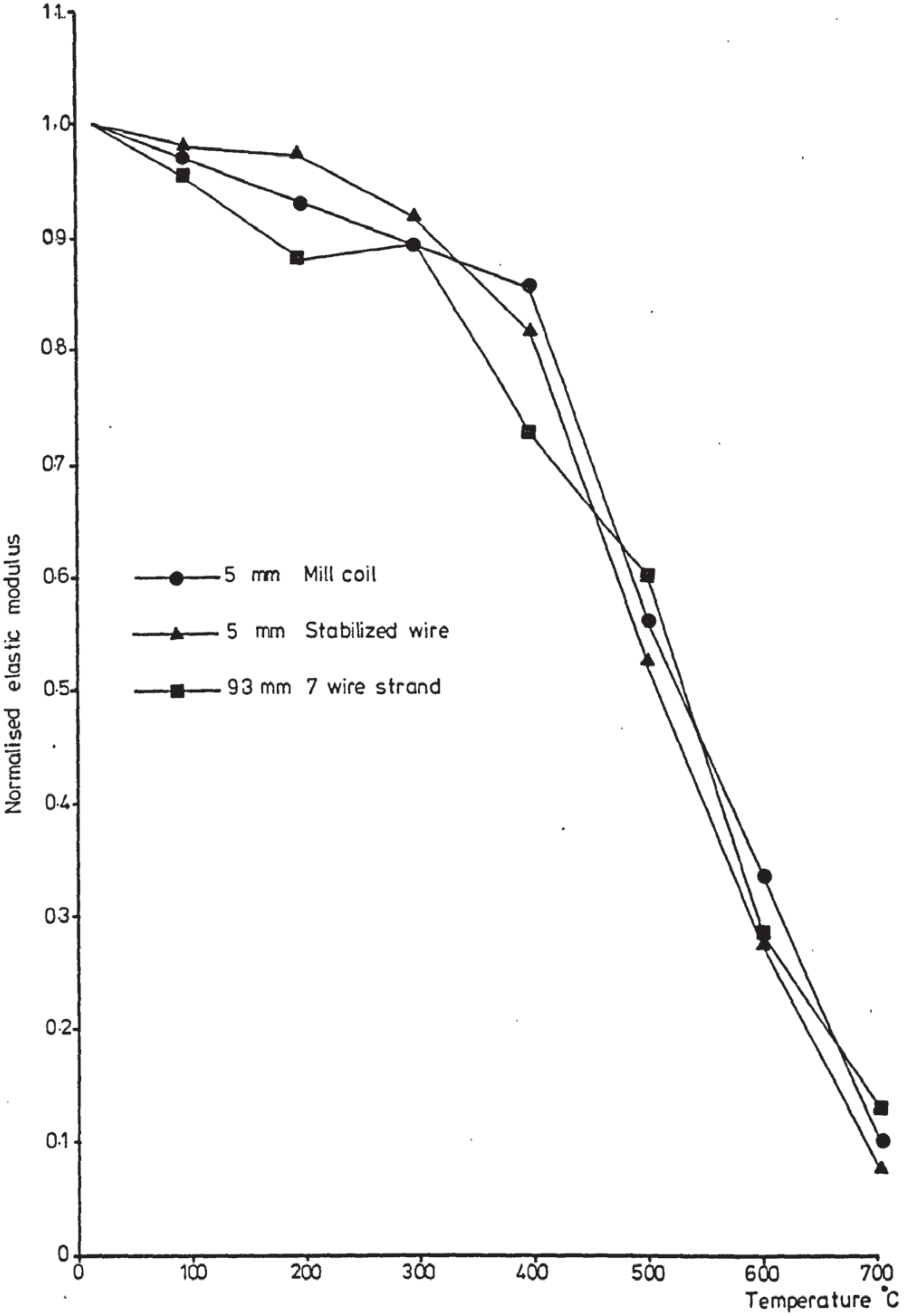


FIGURE 8.3 Normalised elastic modulus for prestress 1

in strength is such that the prestress load (70%) and the load losses (approximately 55%) is obtained at temperatures of 305 to 325°C and 385 to 400°C respectively.

The scatter of results is more noticeable from the E_t values but the general shape is of gradually decreasing values up to 400°C followed by an almost linear reduction with increasing temperature. A 50% reduction is observed at temperatures between 505 and 530°C and a 90% reduction at approximately 700°C.

8.3 Prestress 2

To ensure that all three types of steel were taken to the same temperature they were placed inside the furnace together and then tested individually when they had cooled to room temperature.

a) test results

Duplicate tests were performed at each temperature on the stabilised wire and 7 wire strand but a shortage of mill coil prevented all the tests to be duplicated. However, the results given in Table C2 of Appendix C showed very close agreement between the tests and this confirmed the decision to perform only one test of each temperature for the other procedures. Without the elongation being recorded for the 7 wire strand and those for the other two steels being erratic, no clear pattern could be observed although failure did occur within the gauge length at temperatures of 300, 400, 500 and 700°C but not 600°C.

b) normalised results

The normalised results are shown in Figs. 8.4, 8.5 and 8.6 and again the type of steel has no effect upon the general shape of the figures. The decrease in the normalised proof stress and tensile

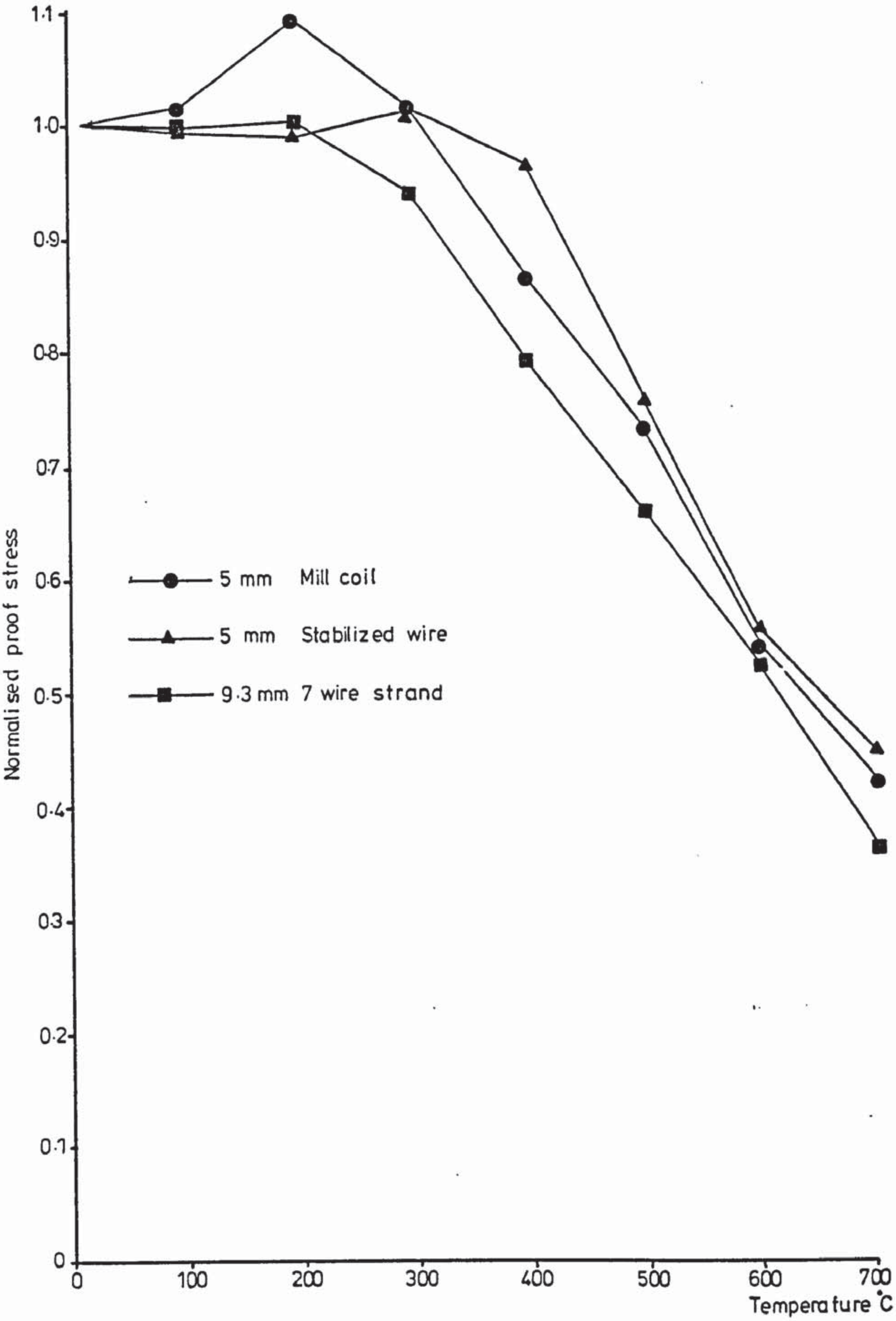


FIGURE 8.4 Normalised proof stress for prestress 2

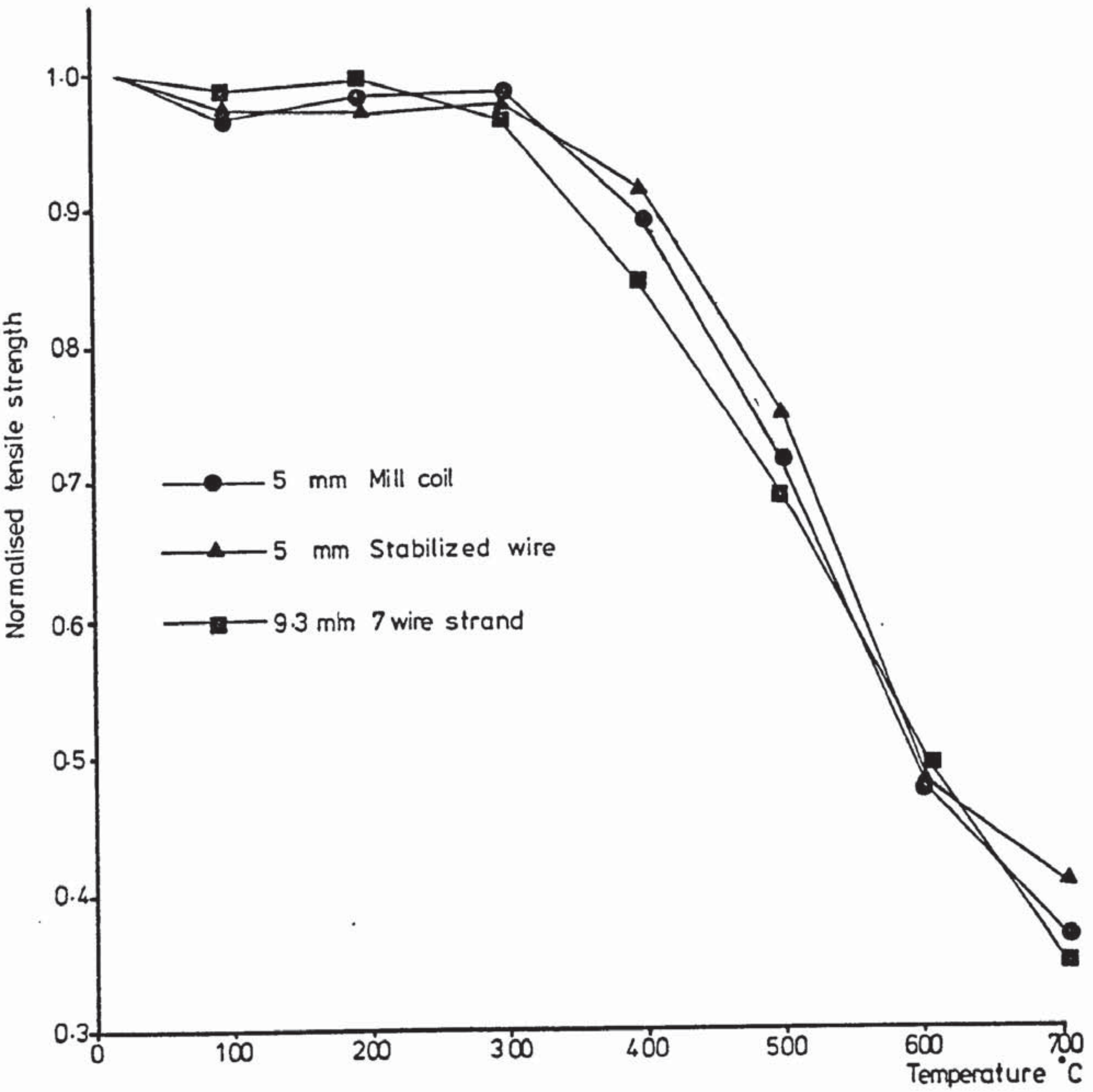


FIGURE 8.5 Normalised ultimate strength for prestress 2

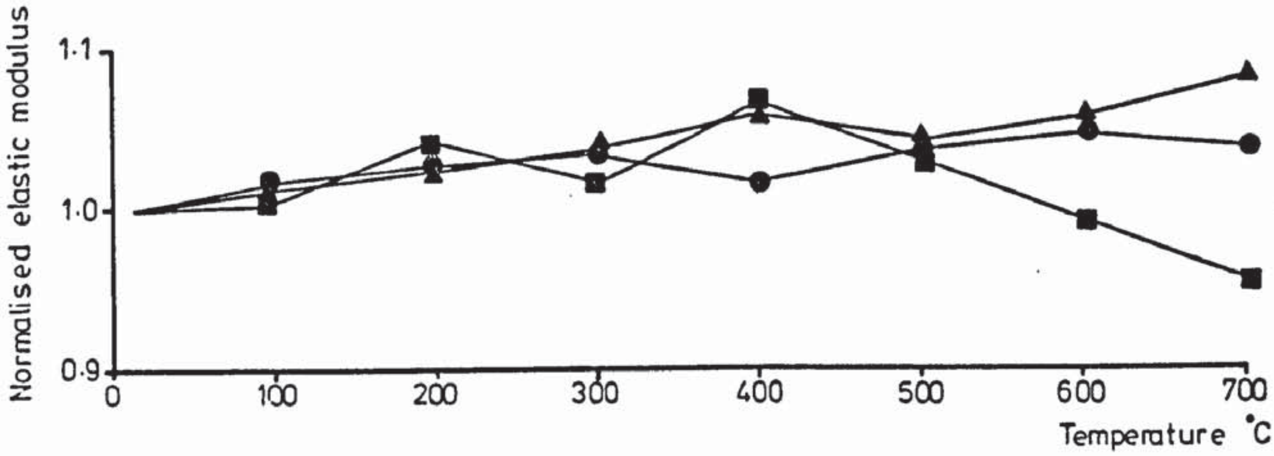


FIGURE 8.6 Normalised elastic modulus for prestress 2

strength is not significant until temperatures were above 300°C with the lower temperature producing a constant strength for both parameters except for the mill coil where a 9% increase was observed in the proof stress at 200°C. the decrease in strength is not as drastic as the prestress 1 results but a 50% reduction in proof stress was obtained between 610 and 650°C and the two stressing levels (U_t = 0.7 and 0.55) at 490 to 520°C and 570 to 575°C.

The most noticeable difference between Figs. 8.4, 8.5 and 8.6 to the figures from prestress 1 (Figs. 8.1, 8.2 and 8.3) is the shape of Fig. 8.6 for the elastic modulus and this clearly shows that temperature does not decrease the modulus values and in fact a slight overall increase can be observed.

8.4 Prestress 3

A pattern of testing similar to that used for the reinforcing steels was adopted for the prestressing steels. The test procedure was performed in two stages (prestress 3A and 3B). The working loads (70% tensile strength) applied are shown in Table 8.2 and (as with the recorded plots of the reinforcing steel for series 3A) a negative strain was recorded upon the application of temperature which became positive as the temperature reached the required level and was attributed to the differential limb expansion of the extensometer.

a) test results

The results obtained from both prestress 3A and 3B are given in Tables C3 and C4 respectively of Appendix C. The strains recorded from the heating cycle of prestress 1 and used to correct the recorded strains obtained from the prestress 3A results are given in Table 8.3 at the three temperatures used.

At the level of loading applied, all the specimens failed when the

Size mm	Type	70% tensile strength kN
5	Mill coil	25.83
5	Stablilised wire	23.45
9.3	7 wire strand	72.80

TABLE 8.2 Working loads for prestress 3A tests

Temperature °C	Net recorded strain with zero load %
100	-0.028
200	-0.015
300	0.000
400	+0.010

TABLE 8.3 Correction to recorded strain obtained from prestress 1 tests

temperature was increased to 300°C, although this temperature was not reached for any of the three series. The corrected strain, as expected, increased with temperature and the specimens either attained equilibrium at 200°C or failed before reaching 300°C.

There is no clear pattern from the prestress 3B results due to their meagre nature, although the proof stress does show signs of increase with the limited number of available values.

b) normalised results

With only two results available for each steel, the normalised values (Figs. 8.7, 8.8 and 8.9) do not show any signficant difference between the type and the room temperature values apart from the increase in proof stress for the mill coil at 300°C.

8.5 Summary of Results

Although the summary will be divided into the three test procedures, there are two factors common to all three:

1) the type of steel or temperature has no effect upon the shape of the recorded plot of stress against strain

2) the type of steel does not affect the stength properties

a) Prestress 1

1) an immediate decrease in all three stength parameters was observed with increasing temperature
2) all the specimens tested failed within the gauge length (heated zone)
3) 50% reduction in proof stress obtained between 370 and 420°C
4) 70% tensile strength obtained between 305 and 325°C
5) 55% tensile strength obtained between 385 and 400°C
6) 50% reduction in elastic modulus obtained between 505 and 530°C

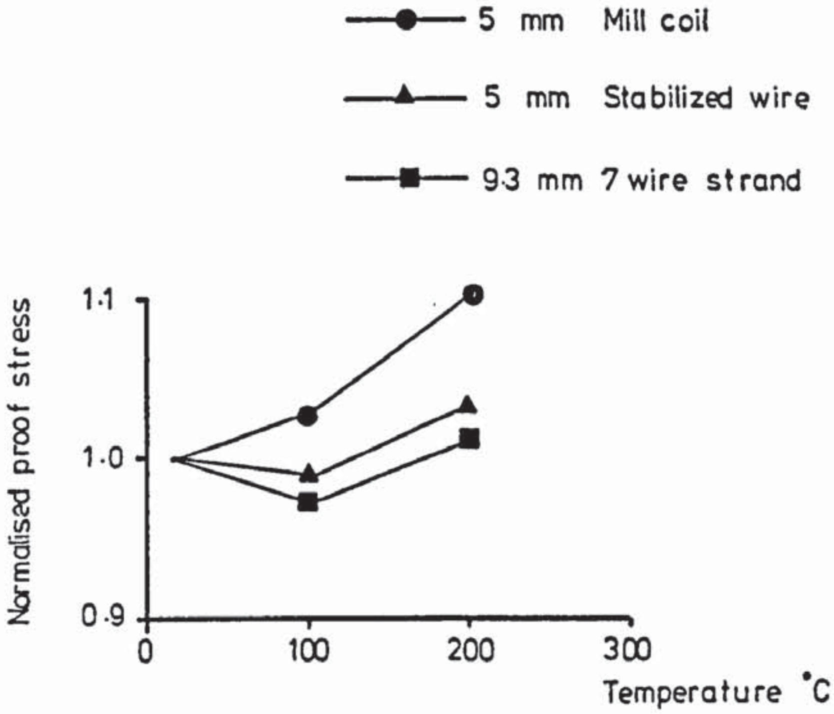


FIGURE 8.7 Normalised proof stress for prestress 3

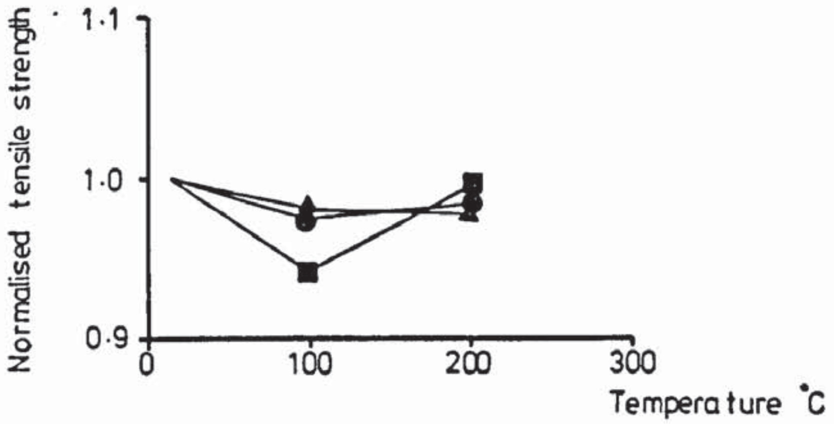


FIGURE 8.8 Normalised ultimate strength for prestress 3

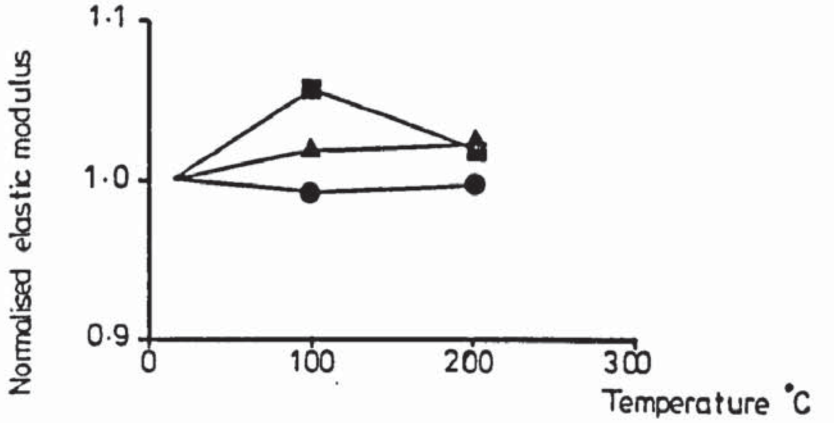


FIGURE 8.9 Normalised elastic modulus for prestress 3

b) <u>Prestress 2</u>

1) the duplicate tests gave close agreement between results
2) no clear pattern of failure over temperature range
3) decrease in proof stress and tensile strength was not significant for temperatures below and including 300°C
4) 50% reduction in proof stress obtained between 610 and 650°C
5) 70% tensile strength obtained between 490 to 520°C
6) 55% tensile strength obtained between 570 to 575°C
7) no significant increase or decrease in elastic modulus over complete temperature range

c) <u>Prestress 3</u>

1) the gauges were succeptable to different heating rates and the recorded strains were corrected from prestress 1 results
2) all specimens attained equilibrium at 200°C and failed at 300°C after 70% tensile strength applied
3) with only two results available for each type a pattern cannot be seen from the results of the tensile tests.

CHAPTER 9

Ancillary Tests

9.1 Introduction

One of the aims of the research was to be able to relate the strength parameters obtained on specimens under laboratory conditions to those of similar material in the insitu condition. It was anticipated that a portable hardness machine would be able to perform the test on the laboratory specimen and give the strength at a particular temperature as an equivalent hardness number. This machine could then be used on similar material exposed within a structure and a hardness number obtained which could then be directly related to the strength from the results obtained in the laboratory. However, this was not possible as the portable machine needed a smooth flat area of approximately 25 mm diameter for the firing head to rest on. Also the method used was similar to that of the Schmit hammer for concrete where a rebound technique is adopted. This required a solid base onto which the material is rested. However, in the insitu condition, this base would be of concrete, a material weaker than that to be tested, and this would result in a hardness number influenced by the strengths of the concrete and steel together.

Although this portable method was unsuitable, the use of hardness numbers was still thought to be the best method of determining the insitu steel strength without having to perform full tensile tests. Small samples would be required from the affected area and this would not involve extensive concrete removal as that required to obtain a suitable length of specimen for a tensile test.

The type of hardness test performed is described in this chapter with the corresponding results together with the results from a chemical analysis performed on both types of steels.

9.2 Hardness Test

It was decided to obtain the Vickers hardness number as this was the most accurate of the three standard hardness tests. Rockswell and Brinell being the other two. The samples for the test needed to have had a similar heat treatment to that expected in the insitu conditions. The series 2 and prestress 2 procedures would subject each sample to different temperatures and allow it to cool before testing. Although the samples could not be taken until the tensile test had been completed, they were removed from a section within the heated zone but away from the area of fracture to eliminate any softening due to large internal structural deformations. After all the samples had been ground, one from each type, size and temperature, and mounted in Bakelite compound except for the 25 mm size which were large enough to be held individually, they were smoothed on successively finer abrasive paper finishing with the 600 μ size.

Using a standard Vickers pyramid hardness machine, with a 20 kg loading for the reinforcing steel and 50 kg for the prestressing steel to obtain a reasonably large impression, 4 pyramid impressions were made on each sample and the average of the numbers obtained from the ocular readings determined.(Table 9.1). These values were normalised using the corresponding room temperature value in Figs. 9.1 and 9.2. The correlation between yield stress and tensile strength with Vickers number, for the prestressing steels only at each temperature, are shown in Figs. 9.3 and 9.4. The reason for this will be discussed later in this chapter.

9.3 Chemical Analysis

One sample from each batch of steel was taken for chemical analysis tests. Each one had to be either greater than 20 mm diameter or of a

Nominal Size mm	Type \ Temp	room temperature	100	200	300	400	500	600	700
		Average Vickers Pyramid Numbers							
8	Mild steel	205	203	203	207	202	218	214	209
8	Unisteel	268	276	272	266	263	261	272	258
8	Torbar	223	228	229	215	220	215	216	206
10	Square Twisted	181	190	187	193	198	193	183	184
12	Mild steel	190	183	184	190	182	202	202	202
12	Unisteel	246	254	254	243	235	236	237	215
12	Torbar	212	209	209	207	219	219	210	190
12	Square Twisted	207	211	211	218	215	224	200	198
25	Mild steel	226	217	222	228	218	222	218	203
25	Unisteel	265	275	277	273	286	275	275	237
25	Torbar	200	197	192	193	200	203	200	192
25	Square Twisted	200	212	209	213	218	210	202	190
5	Mill coil	492	541	555	531	498	428	323	260
5	Stabilised	545	502	502	495	473	410	318	277
9.3	7 wire strand	522	501	508	539	488	416	324	247

TABLE 9.1 Vickers Pyramid Numbers

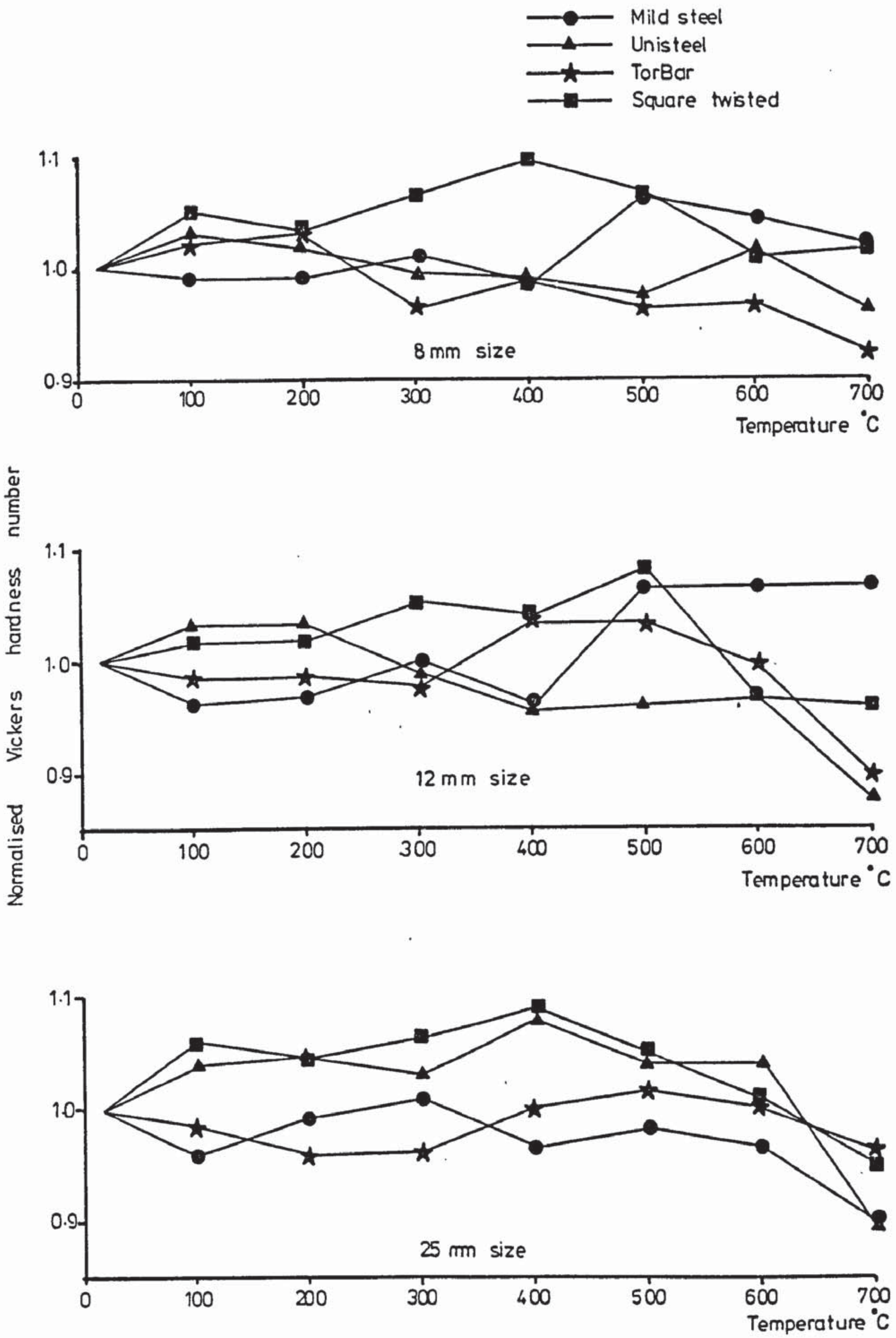


FIGURE 9·1 Normalised Vickers hardness numbers for reinforcing steels, series 2

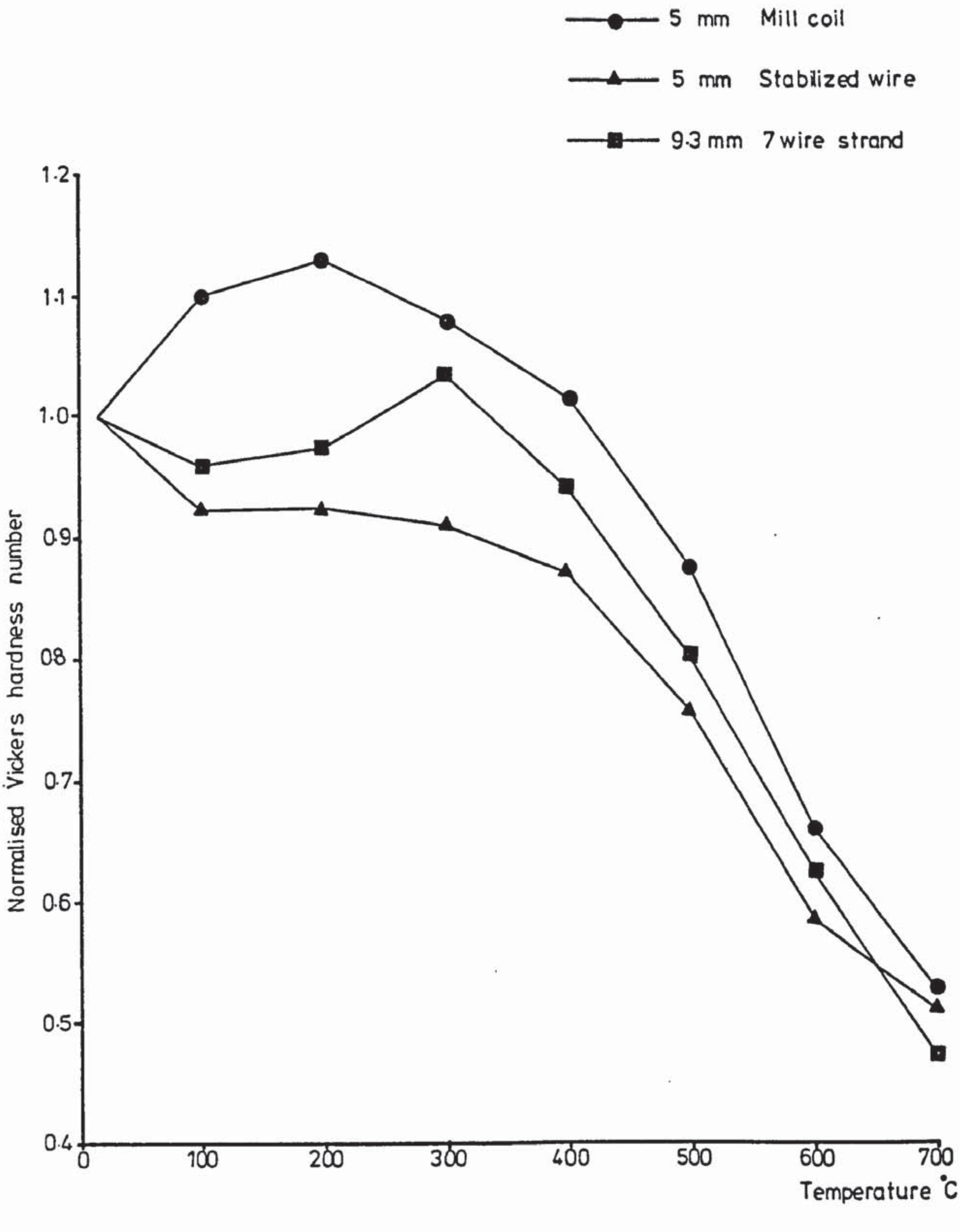


FIGURE 9·2 Normalised Vickers hardness numbers for prestressing steels, prestress 2

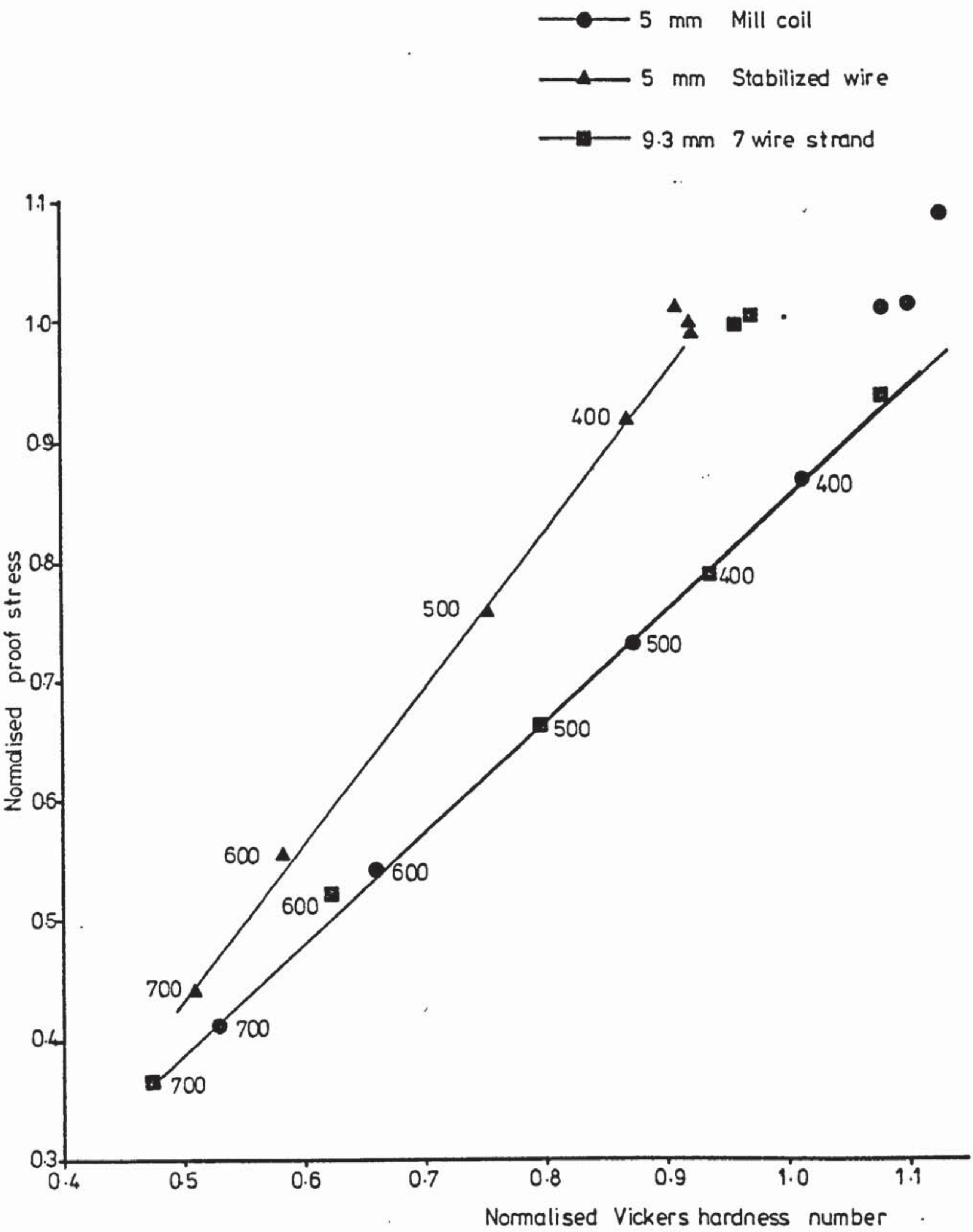


FIGURE 9·3 Correlation between normalised proof stress and Vickers hardness number for prestressing steels, prestress 2

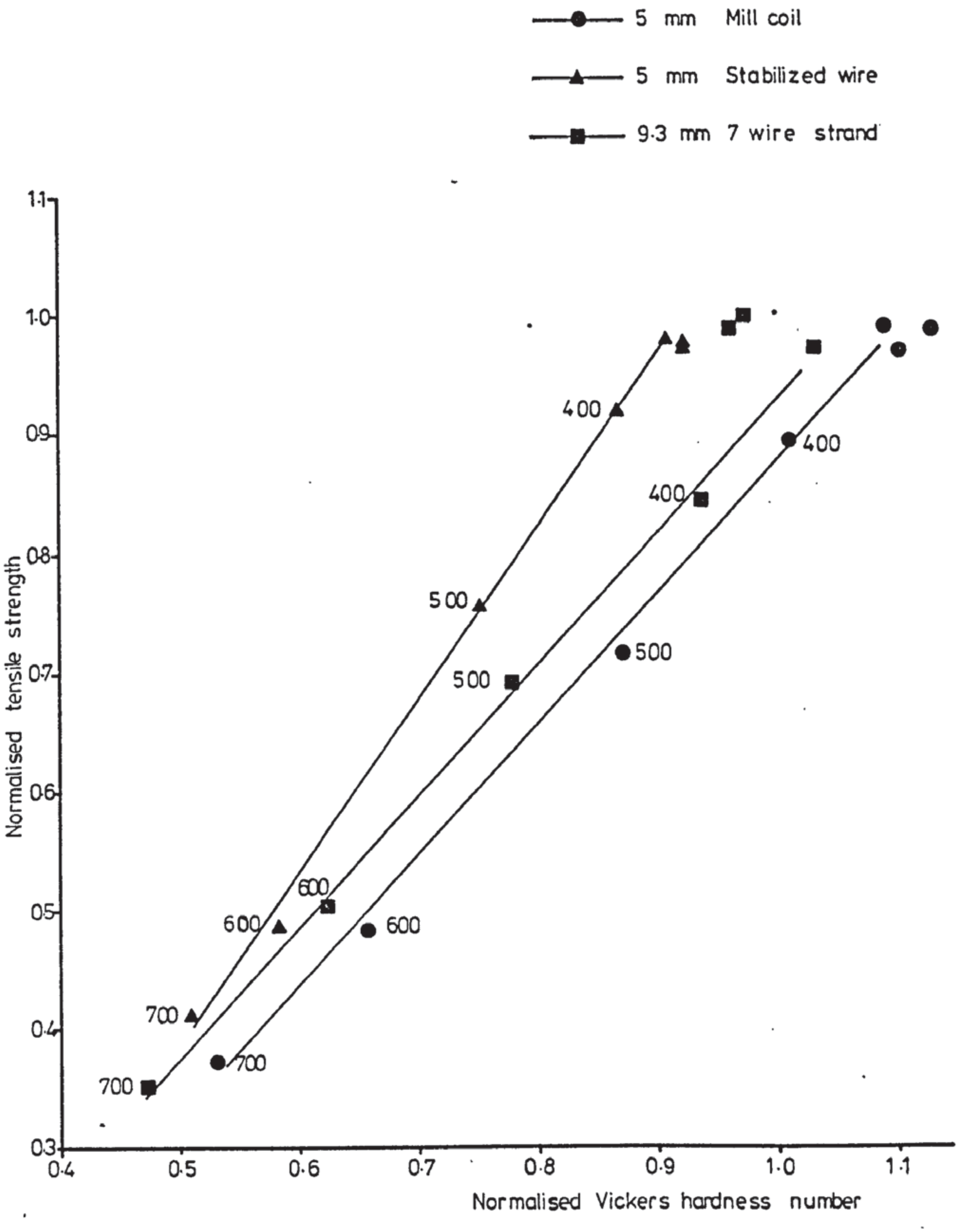


FIGURE 9·4 Correlation between normalised tensile strength and Vickers hardness number for prestressing steels, prestress 2 mass greater than 50 gm. This was so that the smaller samples could be melted in aluminium to form a button of the correct size for use in the analysis machine. The analyses were performed by GKN Technology on a Quantovac machine, as this would produce a 16 element result (13 shown in Table) in one operation rather than determine each element individually, as would be performed by the Metallurgy Department within the University.

Table 9.2 shows the full element scan for all the specimens sent and Tables 9.3 (a), (b) and (c) show the specifications for the chemical compositions given in the appropriate standards [10][11][12][13]

9.4 Discussion of Results

9.4.1 Vickers hardness numbers

Taking the four individual Vickers numbers obtained on each specimen, the values for the hot rolled steels show a good correlation between each other, however, it is not until 600°C that the values obtained on the cold worked steels at the edge and middle of the specimen have any agreement. The values on the edge of these specimens were higher than the middle values which suggests that the cold working process results in a stronger outer skin and this is not reduced until the steel has been raised to a temperature of 600°C.

It is clear from the results given in Fig. 9.1 for all three sizes of reinforcing steel that there is no significant increase or decrease in the Vickers ratio with increasing temperature. The majority of the values are contained within a 10% band of the room temperature value and the expected decrease of values at temperatures above 600°C is not marked. This is contrary to the results obtained for the yield (or 0.2% proof) stress and the tensile strength under the series 2 loading procedure. Where, although a similar pattern of

Nominal Size	Type	Batch	Elements %												
mm			C	S	Si	P	Mn	Ni	Cr	V	Mo	Co	Nb	Cu	Sn
8	Mild steel	1	.23	.046	.04	.012	.61	.03	.02					.05	.004
		2	.15	.029	.14	.018	.66	.13	.15		.03	.01		.14	.014
8	Unisteel	1	.25	.030	.28	.035	1.08	.13	.10		.01	.01	.01	.34	.040
8	Torbar	1	.21	.046	.06	.010	.80	.04	.05			.01	.01	.10	.010
		2	.14	.026	.13	.010	.62	.16	.07		.01	.01	.01	.19	.019
8	Square	1	.21	.028	.05	.021	.58	.03	.04			.01		.06	.005
10	twisted	1	.11	.018	.14	.042	.48	.01	.03					.01	.001
12	Mild steel	1	.15	.027	.11	.032	.55	.03	.03					.02	.001
		2	.20	.027	.05	.011	.64	.03	.03					.04	.002
12	Unisteel	1	.21	.031	.01	.020	1.49	.02	.04	.07				.06	.005
12	Torbar	1	.24	.044	.05	.010	.79	.04	.06					.09	.011
		2	.20	.021	.16	.020	.57	.04	.07					.11	.005
12	Square	1	.18	.042	.14	.032	.50	.12	.09		.01			.29	.031
	twisted	2	.12	.019	.14	.008	.54	.13	.08		.01	.01		.21	.016
25	Mild steel	1	.19	.039	.10	.020	.62	.12	.10		.01			.28	.024
		2	.19	.044	.16	.014	.69	.14	.14		.01			.29	.026
25	Unisteel	1	.25	.026	.18	.013	1.43	.02	.02					.05	.003
25	Torbar	1	.25	.024	.05	.015	.75	.02	.03			.01		.01	
		2	.23	.021	.02	.016	.72	.01	.02					.02	
25	Square	1	.21	.038	.14	.029	.59	.13	.10		.02			.30	.026
	twisted	2	.14	.022	.14	.010	.48	.18	.12		.02			.19	.018

TABLE 9.2 Chemical composition (reinforcing steel)

Nominal Size mm	Type	Batch	Elements %												
			C	S	Si	P	Mn	Ni	Cr	V	Mo	Co	Nb	Cu	Su
5	Mill coil	1	.77	.038	.22	.015	.57	.03	.06					.09	.010
		1	.77	.039	.22	.016	.60	.04	.07					.09	.010
5	Stabilised	1	.77	.023	.25	.017	.66	.03	.03				.01	.04	.003
	wire	1	.77	.023	.25	.017	.69	.03	.04			.01	.01	.04	.003
9.3	7 wire	1	.82	.035	.20	.032	.61	.02	.05				.01	.03	.002
	strand	1	.73	.018	.22	.033	.56	.01	.07				.01	.02	.006

TABLE 9.2 (cont) Chemical composition (Prestressing steel)

Element	Grade 250 % max	Grade 460/425 % max
Carbon (C)	.25	.40
Sulphur (S)	.060	.050
Phosphorus (P)	.060	.050

TABLE 9.3(a) Specified Chemical Composition (Hot rolled steels) (10)

Element	Grade 460/425 % max
Carbon (C)	.25
Sulphur (S)	.060
Phosphorus (P)	.060

TABLE 9.3(b) Specified Chemical Composition (Cold worked steels) (11)

Element	Minimum %	Maximum %
Carbon (C)	.60	.90
Silcon (Si)	.10	.35
Manganese (Mn)	.50	.90
Sulphur (S)	-	.050
Phosphorus (P)	-	.050

TABLE 9.3(c) Specified Chemical Composition (Prestressing steels)

scatter of results at the lower temperatures can be seen from Figs. 7.16 to 7.21, there is a significant decrease in both properties at and above 600°C being most noticeable for the two cold worked steels.

Although little could be derived from the reinforcing steel results this was not the case with the prestressing steels. Looking at these values in Table 9.1 overall, it can be seen that they reduce significantly as the temperature increases. This can be seen more clearly from Fig. 9.2 where the mill coil increases in Vickers ratio reaching a peak at 200°C and then decreasing with increasing temperature. The stabilised wire and 7 wire strand both start to decrease significantly above 300°C with the value of the Vickers number at 700°C for all three steels being approximately half the room temperature value. If the ratio given in Fig. 9.2 is plotted against the yield (or 0.2% proof) stress (Fig. 9.3) and tensile strength (Fig. 9.4) ratio's at the same temperature, it can be seen that above 300°C a linear relationship is obtained. The equations for each of these is given in Table 9.4 and it shows a close agreement between the mill coil and 7 wire strand equations with the gradients being closely related.

	5 mm Mill Coil	5 mm Stabilised wire	9.3 mm 7 wire strand
0.2% proof stress ratio	$-0.076 + 0.928v$	$-0.224 + 1.309v$	$-0.074 + 0.923v$
Tensile strength ratio	$-0.222 + 1.098v$	$-0.335 + 1.444v$	$-0.175 + 1.100v$

TABLE 9.4 Equations derived from Figs. 9.3 and 9.4

Note (i) v is normalised Vickers hardness number

(ii) these equations are only applicable for temperatures above 300°C

To use these relationships it would first be necessary to have a knowledge of the room temperature properties of one of these particular steels, ie, yield (or 0.2% proof stress) or tensile strength, depending upon which property was required, and the Vickers hardness number. Then by obtaining the Vickers hardness on the same material which had been subjected to a temperature above 300°C the residual strength property could be estimated.

These results agree favourably with other work where the use of hardness testing on prestressing wire and strand to estimate the tensile strength and exposure temperatures has been shown by Abrams and Erlin[51] to be satisfactory for temperatures above 400°C and below 720°C. Below 400°C an interpretation of the microstructure needs to be used to distinguish the exposure temperature.

9.4.2 Chemical analysis results

The chemical compositions given in Table 9.2 for all the specimens are within the specifications given in Tables 9.3(a), (b) and (c). The more noticeable points from the Tables are the high content of manganese from all three sizes of unisteel and the high carbon content of the prestressing steels, compared with those of the reinforcing steels. The high manganese must contribute towards the high yield strength of this hot rolled steel, since the mild steel, which is also a hot rolled steel, has a much lower yield stress although it has a similar chemical composition except for the manganese percentage.

The high carbon content of the prestressing steels gives this material the very high tensile strength (approximately three times for the equivalent size of reinforcing steel) and low elongation properties.

9.5 Conclusions

The results contained within this chapter show that there is no correlation between the strength properties of the reinforcing steels and the Vickers hardness number at different temperatures. However, the opposite is true for the prestressing steels at temperatures above 300°C where a linear relationship exists. It is not suggested that the equations obtained should be used for all types of prestressing steels but the results do give a basis for further work and clearly advocates the use of Vickers hardness testing for the determination of the strength properties of prestressing steels.

The chemical analysis was only intended to give a general appraisal of the compositions of each of the materials being used and check that the percentage of each element was within the specifications defined in the standards. The analysis did show that the material was produced to the standards and the high strength of the unisteel could be partly attributed to the high manganese content of the steel.

CHAPTER 10

Discussion and Conclusions

10.1 General Discussion of Results

The results from the preliminary and ancillary tests, Chapters 6 and 9 respectively, have already been discussed and the main points arising are given in the main conclusions (section 10.2). The main test results, Chapters 7 and 8, have been described previously and a detailed summary of the results given (sections 7.5 and 8.5). Rather than give a detailed comparison with the results from previous work reviewed in Chapter 3, the areas of general agreement and disagreement are discussed.

At one time or another individual researchers have agreed with the majority of the results obtained but there has not been a specific report that completely covers all the points raised from this research.

Bannister[6] and Corson[7] have agreed with the results on the reinforcing steels, noticing the difference between hot rolled and cold worked steels when cooled before testing. The increase in strength when tested between 150 and 300°C that has been given in several documents[6,7,39,46] and the joint report[4] has not been supported by the results to such a large degree.

The area where full agreement has been made is that a 50% reduction in both yield stress and ultimate strength occurs between 500 and 600°C[4,6,7,39,40,41,45] when tested at elevated temperature, although tighter limits of 520 to 580°C are obtained.

The working load tests have shown that failure does not occur at 400°C as reported by Woodman and Copeland[42] but between 500 and 600°C. Also none of the results showed a difference between size of specimen as was reported by Cunningham[40].

Several reports[36,38,43,46,49] gave a 50% reduction in the strength of prestressing steel between 400 and 500°C, although the range actually obtained was 370 to 420°C. The permanent reduction in strength after cooling from 300°C and above has been corroborated by several results[4,36,48,50,51].

Some of the reports described in Chapter 3 on previous work has been primarily intended for internal circulation within an organisation or so specialised that it has little relevance to the Engineer. The Engineer may require the strength properties at a certain temperature or the temperature at which a particular reduction occurs. Rather than use tabulated data for this, charts can give the two sets of information from one diagram. To do this for all the results obtained from Chapters 7 and 8 would only produce a mass of lines which would be of little use to anyone. To give a general indication of the effect temperature has on the strength of the steels tested, a representative value, taken as the mid-point of the scatter of results, is used and these are given in Figs. 10.1, 10.2 and 10.3 for the three loading conditions used. A clearer picture of the extent of scatter that was obtained can be seen from Figs. 7.12, 7.13 and 7.14. Wherever possible, parameters that have given similar results have been combined to produce a single line, eg, the elastic modulus for all the steels was similar when tested at ambient temperature after being cooled from elevated temperatures and one line instead of three is used. Also, when there was a difference between the type of steels separate plots are given.

The curves from the most recent design chart[65] is included in Fig.10.1 and it can be seen that in the mid-range of temperatures good agreement is obtained but at the upper and lower temperatures the design curves are on the unsafe side of the results. Also, since there is a 10% variation at most temperatures with the representative results, the design curves should be placed on the safe side of these values.

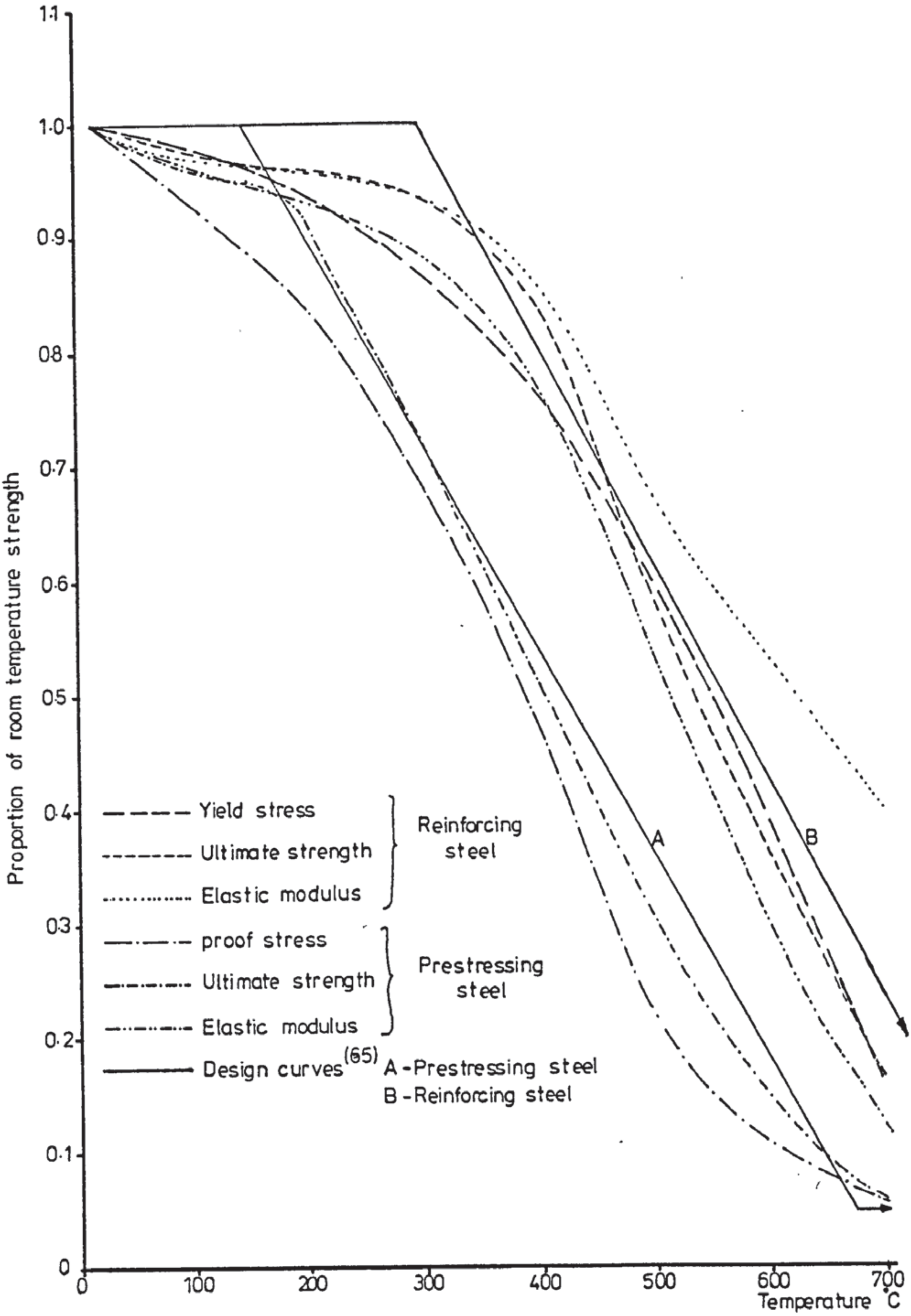


FIGURE 10.1 Typical strength properties of reinforcing and prestressing steels tested at elevated temperature

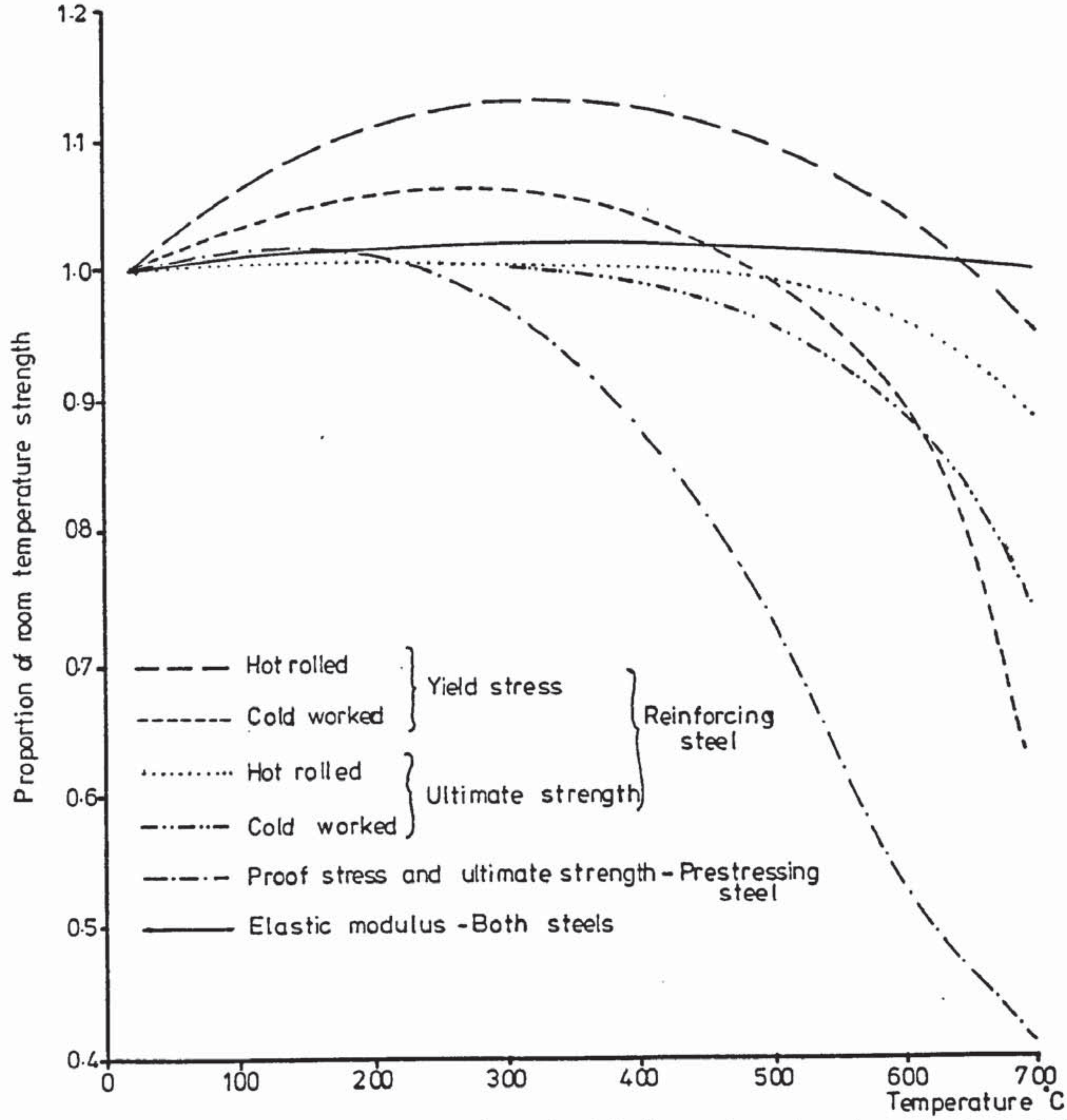


FIGURE 10.2 Typical strength properties of reinforcing and prestressing steels tested at room temperature after heating to an elevated temperature

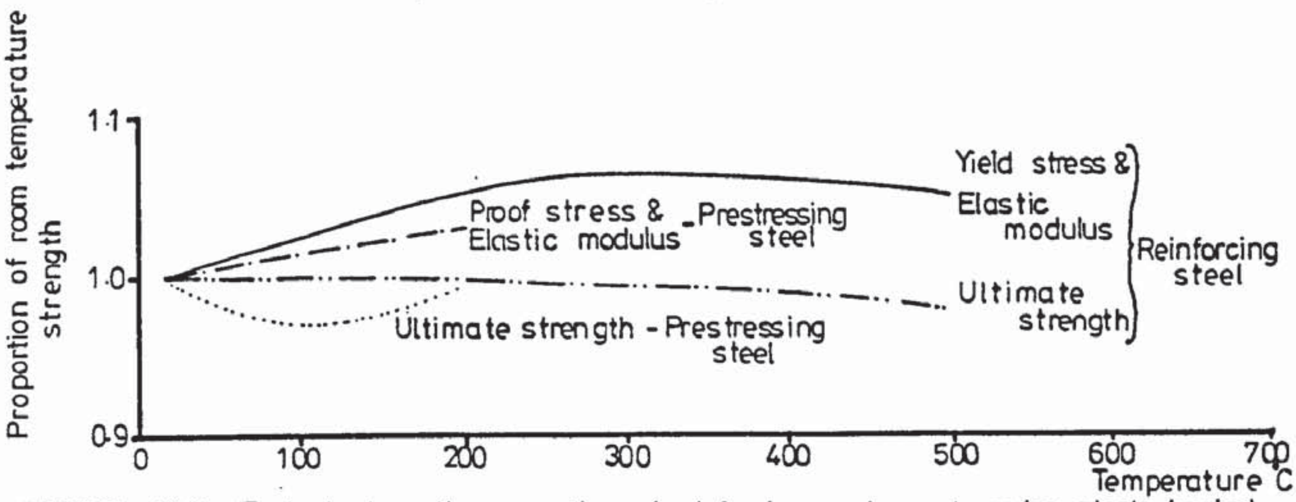


FIGURE 10.3 Typical strength properties of reinforcing and prestressing steels tested at room temperature after having a working load applied during heating

Apart from these general points a detailed set of conclusions on the complete research, including comments about the equipment and test procedures are made in the next section.

10.2 Main Conclusions

10.2.1 Introduction

The basic aims of the research were to provide authentic and comprehensive experimental data on the effects of elevated temperatures on the strength of reinforcing and prestressing steels. The test programme allowed for the deterioration in strength of a structure during a fire and its residual strength at ambient temperature after a fire to be considered.

The results that were obtained gave information on the three major strength parameters, ie, yield strength, ultimate strength and elastic modulus, at elevated temperatures and by comparing them with the room temperature values, transformed them into an acceptable form for use with any type and size of steel. Due to problems with the testing equipment, it was not possible to perform a set of relaxation tests on the prestressing steels. However, this was the only omission from the original testing programme.

An area where it was hoped to provide new ideas was the insitu non-destructive testing of the steel. This proved to be unpractical with the equipment available together with the results being obtained from the reinforcing steel. Nevertheless by using a hardness test on small samples of prestressing steel a correlation was obtained between the strength and hardness number at 400°C and above.

The main points arising from the major sections are given below.

10.2.2 Equipment

10.2.2.1 Test Machine (Section 4.2)

The test machine, although basic in its design and concept, performed all the tests, apart from some minor exceptions, without too much difficulty. These exceptions included the limited ram travel, the influence of friction and the inability to obtain a reduction in the applied load with constant strain (relaxation). The use of servo-hydraulics could have solved the relaxation problem but this was discovered too late to be put into practice.

10.2.2.2 Specimen Anchorage (Section 4.3)

The use of wedge grips for the three sizes of reinforcing steel proved very successful and the large, heavily deformed bars (torbar and square twisted) were securely held without major slippages occurring. Using a wedge block arrangement allowed for the prestressing anchorages to be positioned on the underside of special wedges whereby the steel was not gripped along the length of the wedge. Rotation of the block permitted centralisation of the specimens about the axis of the machine.

10.2.2.3 Instrumentation (Section 4.4)

The furnaces performed well although initially the control of the temperature proved difficult. It was not until the control was changed to the top zone that the temperature gradient was kept to a minimum, ie, $\pm 5^{\circ}C$ of the required value. Using two furnaces allowed for each furnace, if necessary, to be repaired without stopping the tests completely. The method of twisting the Chromel-Alumel thermo-couple onto the specimen provided quick assembly of the specimens into the furnace. However, after two cycles of loading to $700^{\circ}C$, the insulation of the wires was destroyed.

The extensometers used allowed various positions of the transducers to be chosen so that different gauge lengths could be attained. Although the use of nimonic limbs caused differential limb extension it did bestow the gauges with a certain amount of robustness which would not have been obtained with quartz.

The load was measured from pressure transducers attached to the loading ram which needed changing from one to the other when loads above 200 kN were to be applied. The arrangement worked satisfactory although a load cell would have been a better option.

A continuous plot of two variables, usually load and strain, were measured continuously on an X-Y recorder and this enabled yield points to be observed with greater accuracy than if discrete values had been used.

10.2.3 Test Procedures (Chapter 5)

The three test procedures were designed to allow the subsequent results to be directly related to the typical fire situation. Wherever possible standard loading rates and procedures[16,17] were adopted. This provided uniformity throughout the tests which allows for one set of results to be compared with another.

The series 1 and prestress 1 procedure, where the steels were tested at elevated temperature, allowed for the performance at each temperature to be obtained.

Series 2 and prestress 2, which was when the specimens were cooled to ambient temperature before testing, simulated the condition after a fire had occurred and a knowledge of the residual properties was required.

Finally, series 3 and prestress 3, where a simultaneous load and temperature was applied, would copy the effect upon the steel of a structure stressed to its design load and then subjected to a fire situation.

10.2.4 Preliminary Tests (Chapter 6)

The calibrations performed on the test machine and instrumentation showed that its performance withstood the requirements of the testing programme. The calibration procedures were considered reliable and uncomplicated without being inaccurate and the error in recording the applied load easily rectified by adjusting the measured value by a predetermined amount.

The specimen identification used was successful and enabled the samples to be distinguished at all times.

The density tests proved inconclusive and a standard value of 7.85 Mg/m^3 used to obtain the cross-sectional area.

The analysis of the room temperature test results produced a variation in strength parameters which was presented in terms of confidence limits with resulting coefficients of variance. The largest value, 9.4%, occurring for the elastic modulus from the 12 mm unisteel. The mean values for all the types and sizes of steel tests were used to normalise the results from the elevated temperature tests.

10.2.5 Main Test Results (Chapters 7 and 8)

The normalised test results from the reinforcing and prestressing steels at elevated temperature under the various test conditions have been summarised in the relevant chapters and a few detailed conclusions are given below.

The factor that was consistent throughout the results was that size of section has little influence upon the final value. With reference to the type of steel tested, the hot rolled steels, one high yield, performed equally as well as each other, the two cold worked steels could not be distinguished and the three prestressing steels gave identical results once they were all normalised. The prestressing steels did not perform as well as the reinforcing steels when subjected to the same testing condition. They also did not produce a change in the shape of the stress/strain plot at any temperature or under different loading conditions.

10.2.5.1 Series 1 and Prestress 1

The type of reinforcing bar did not have any effect upon the normalised results although a change in the hot rolled stress/strain was observed above 300°C. For the reinforcing bars, there was no significant change in the normalised yield stress, ultimate strength or elastic modulus below 300°C but as soon as the temperature was raised to 100°C a reduction was observed for the prestressing steels.

A 50% reduction in both the yield stress and ultimate strength was obtained between 520 and 580°C and between 540 and 700°C for the elastic modulus for the reinforcing steels. A similar reduction was found from the prestressing steels when the temperature was between 370 and 420°C for the proof stress and ultimate strength and between 510 and 530°C for the elastic modulus.

10.2.5.2 Series 2 and Prestress 2

The representative results from all the steels after having been cooled to ambient temperature before being tested (Fig.10.2) showed that the elastic modulus remained practically unaltered over the temperature range.

Segregation between the two types of reinforcing bars was observed, where the hot rolled yield stress increased by as much as +12½% at 400°C before having a final value of -5% at 700°C. The cold worked steels also exhibited an increase (6% at 300°C) but at 700°C the loss was 37%. The ultimate strength values for the two steels were similar up to 500°C but at 700°C the hot rolled steels had a 12% reduction compared with a 26% reduction for the cold worked steels.

At 300°C and above the prestressing steels showed a marked decrease in both the proof stress and tensile strength, with a 50% reduction occurring between 590 and 650°C.

10.2.5.3 Series 3 and Prestress 3

All the prestressing steels failed at 300°C with a 70% ultimate load being maintained. It was felt that this loading was too high and possibly a value of between 50 and 60% ultimate would have been more representative of the true prestressing force in the steel after the member had been in service for some time.

None of the reinforcing steels failed at 400°C with the working load (yield stress/1.8) applied, but at 600°C they all failed. At 500°C they either obtained equilibrium, failed, or after three hours of testing continued to creep. There was no clear pattern at this temperature for any of the steels.

Upon cooling and subsequent retesting to failure there was no reduction in all three strength parameters from the available samples.

10.2.6 Ancillary Tests (Chapter 9)

As was commented in the introduction, the Vickers hardness tests were only productive from the prestressing steels after having been tested to 400°C and above under prestress 2 loading conditions. For these temperatures a direct correlation between strength and hardness number could be made.

The chemical tests were only intended for information purposes and the results were not investigated further.

10.2.7 Design Charts

The representative results obtained from the tests show a close agreement with those given in the most recent publication on the design of concrete structures for fire resistance[65].

The charts, however, are only limited to the yield strength of reinforcing steels and tensile strength of prestressing steels tested at elevated temperatures. The data now available gives the changes in all three strength parameters under different temperature and loading conditions.

10.3 The Significance of the Test Results on Structural Analysis

Some studies performed by Holmes and Anchor(68) on the load bearing capacity of reinforced concrete beams at elevated temperatures indicate that the 'catenary action' proposed by some designers(65) would not occur as the top steel would not have a large enough increase in temperature and hence the 'cantilever action' postulated below (which requires relatively small central deflections) would occur in preference to catenary action (which requires relatively high central deflections).

If the two 'type' structures, ie, statically determinate and indeterminated, are considered, the failure condition can be determined under a given loading and exposed temperature. If, for the indeterminate case, the rise in temperature is such that the yield strength of the bottom steel is reduced to pratically zero (780°C from interpolation of Fig.10.1), then the beam will function as two cantilevers. The failure condition can be derived from statics and will be independent of the order in which the temperature and load are applied.

Deflections will also occur and will depend upon the order of application of the load and the temperature if the applied stress is in the plastic range at that particular temperature. If the temperature increase is only sufficient to cause elastic effects at this stress level, the determination of the deflection would be independent upon the order of application.

If the temperature rise is not high enough to cause failure, the yield strength of the bottom steel can be considered to be reduced to a given value, depending upon the load/temperature application. The maximum tensile force which then can be developed in this steel is the area times reduced yield stress. This could then be regarded as the bottom steel having a reduced area but with the original yield stress. This procedure could also be applied to simply supported beams.

The simulated reduced area would also have the effect of changing the distribution of moments. The extent to which the moments are redistributed are not only dependent upon the change of yield stress but also on the change in elastic modulus at elevated temperature. This change can be seen from Fig.10.1 whereby a significant reduction occurs above 300°C.

Using the same analogy as used for the yield stress reduction, the elastic property of the bottom steel could be regarded as the elastic modulus remaining constant but having a reduced area. The strains due to thermal expansion would need to be considered together with the length of exposure at the elevated temperature. In a short term fire exposure the creep strains could be ignored but in a long term exposure they would need to be incorporated in the reduction factors.

Therefore, two different effective reduced areas need to be considered for the bottom steel when carrying out an analysis of this nature, with the elastic property being dependent upon the circumstances to be considered.

After returning to ambient temperature a similar procedure can be adopted, as long as the section and the bond can be assumed to be in tact. However, this time the analysis can be made easier by the elastic modulus being relatively unaffected after returning from elevated to ambient temperature (Fig.10.2). The yield stress reduction factor in this case would be greater than 1.0 for hot rolled steels cooled from 600°C and 500°C for cold worked steels (Fig.10.2).

A similar consideration can be used for the prestressing steels. The initial prestressing force and the greater reduction in ultimate strength at prestressing steels at elevated temperatures than that for the yield stress of reinforcement (Fig.10.1) needs to be taken into account. Also, upon cooling from temperature above 300°C to ambient, the prestressing steel has a noticeably marked decrease in strength although the elastic modulus remains unaltered up to 700°C. Again bond is a major factor but by using unbonded tendons this problem could be alleviated.

10.4 Recommendations for Future Work

The data obtained from this research should provide the Engineer with the necessary information, for design purposes, on the mechanical properties of common British produced reinforcing and prestressing steels at elevated temperature. However, it is felt that more work needs to be performed on different levels of sustained load with increasing temperature. This will be of particular relevance to prestressing steels where the applied prestressing force is not constant throughout the lifetime of a structural member.

The performance of concrete under fire conditions is reasonably well documented, although the use of various lightweight aggregates, changes in the basic constituents, ie, additives, and different applications of the material make it necessary for work to continue in this field.

The area in which the main emphasis of work should be directed is the concept of bond. As yet, little is known of the nature and mechanics of bond at high temperatures. Cracking around the reinforcement would have a significant effect on the bond, being particularly relevant to the flexural behaviour at elevated temperatures. An extension to this work could be an investigation into the shear failure of beams with a view towards the effect upon the aggregate interlock and dowl action, the major influences upon the shear capacity of beams.

The use of computers in heat transfer calculations and mathematical models of the structural behaviour for single components are already feasible but composite structures are not easy to analyse. This therefore makes this an area for future improvement.

Finally, the analysis and design for use in predicting fire behaviour and the introduction of an accepted fire design philosophy are of paramount importance. The subsequent inclusion into a recognised code of practice are the main objectives of this type of work.

APPENDICES

APPENDIX A - Design of test rig

After the basic shape of the test rig was decided upon, each element was designed to withstand the maximum design load together with the self weight of the test rig itself.

This design load was based upon the expected tensile strength for 25 mm high yield reinforcement and was taken to be 15% greater than the characteristic strength. Allowing for a factor of safety of 2 and variation in the manufacturers value, a design load of 500 kN was arrived at.

The design of the loading plattens was based upon the work of Dr J D Davis[(69)] in which a finite element method of analysis was used for the determination of the deflection and moment values in the rectangular plattens supported at the four corners. The subsequent stresses were then checked against the allowable stresses from BS 449.

For the upper frame, where a 0.6 m column spacing was used, a 75 mm thick plate with a loading of 500 kN produced an applied bending stress of 153.05 N/mm^2 with a central deflection of 0.91 mm and required the use of grade 50 steel.

For the lower frame, a 1.0 m column spacing was used with 75 mm thick plate and a loading of 510 kN to allow for the weight of the upper frame and loading ram. This produced a bending stress of 155.24 N/mm^2 with a central deflection of 2.55 mm and again required the use of grade 50 steel.

The columns for the upper frame were in tension with each taking a load of 125 kN. Taking a 50 mm diameter bar with a M48 thread and the roof diameter taken as 40 mm, an applied tensile stress of 99.45 N/mm^2 was obtained. This allowed for either grade 43 or 50 steel to be used.

The lower frame columns were in compression with an overall length of 2.0 m between plates. A reduced threaded section of the columns would pass through the plates with a nut attached after assembly. With this arrangement, the effective height was taken to be 1.5 L. Using an applied load of 150 kN to each column, an applied compressive stress of 34 N/mm^2 was obtained for a 75 mm diameter section. Again either grade 43 or 50 steel could be used. For continuity between every section, grade 50 steels were used for both sets of columns.

The full loading force would be taken by the locating pin. The applied stresses for a 50 mm diameter section in grade 55 steel was checked for double shear and simple bearing and the wedge block, made of grade 50 steel, checked for tensile stress and enclosed bearing. The resultant stresses were below the allowable stresses and the section adopted. A minimum of 50 mm bearing on either side of the wedge block was allowed for, together with an edge distance of 85 mm for the wedge itself.

After deciding upon the shape of the wedges, the upper section of the wedge block was checked for applied bending and shear stress at the critical section from an applied load of 500 kN resolved into the perpendicular forces due to a wedge angle of 9^o. At the critical section, which was 45 mm thick and 100 mm long, an applied bending stress of 173.8 N/mm^2 and a shear stress of 109.7 N/mm^2 was obtained. These were within the allowable stresses for a grade 50 steel.

APPENDIX B

REINFORCING STEEL RESULTS

APPENDIX B - Reinforcing Steel Results

The test results reproduced in this appendix have been obtained from the recorded plots of load against strain and temperature against strain from the procedures outlined in Chapter 5 and used in Chapter 7.

There are three test procedures with four types and three sizes of steel being used, with duplicate tests being performed on the 8 and 12 mm sizes.

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	51.59	358.6	443.9	205.50	-
		51.77	357.3	452.0	195.09	-
	200	51.77	353.5	450.1	-	-
		51.24	359.1	456.7	197.11	-
	300	51.01	290.1	447.0	189.18	-
		51.87	295.0	443.4	188.00	-
	400	51.87	266.0	393.3	184.11	13.0
		51.58	263.6	426.4	168.67	16.0
	500	51.88	221.7	304.5	118.54	16.2
		51.13	230.8	326.6	139.84	15.8
	600	51.79	135.2	162.2	110.06	25.6
		51.82	135.1	162.1	115.79	26.0
	700	51.23	80.0	70.3	95.65	27.6
		51.91	65.5	82.8	78.02	27.6
Unisteel	100	50.39	466.4	654.9	210.36	11.4
		50.37	498.3	671.0	211.44	-
	200	50.35	500.5	671.3	202.58	-
		50.22	539.6	665.1	204.10	-
	300	50.43	479.9	672.2	283.56	-
		50.33	476.9	661.6	269.22	-
	400	50.45	446.0	590.7	193.26	8.6
		50.45	432.1	584.7	255.70	7.8
	500	49.81	357.4	461.8	185.71	3.6
		49.85	312.9	419.3	145.44	4.2
	600	49.87	220.4	260.4	107.17	6.8
		49.92	234.4	278.4	105.17	9.2
	700	49.92	94.2	104.2	50.08	33.6
		49.92	104.2	118.2	75.12	20.4
TorBar	100	48.74	508.8	578.6	209.27	-
		48.68	511.5	581.3	207.48	-
	200	48.74	504.7	576.5	208.25	-
		48.68	503.3	583.4	200.29	-
	300	48.70	460.0	581.1	179.67	12.6
		48.72	470.0	582.9	199.10	-
	400	48.69	421.0	464.2	174.57	-
		48.72	426.9	476.2	201.15	12.0
	500	48.75	317.9	342.6	152.82	6.0
		48.61	310.6	355.9	125.49	5.8
	600	48.74	188.8	203.1	94.38	11.0
		48.81	180.3	219.2	106.54	9.6
	700	48.73	63.6	73.9	71.82	24.2
		48.72	53.3	73.9	102.63	27.6

contd.

10 mm Square twisted	100	76.96	431.4	479.5	212.45	5.0
		77.26	427.1	456.9	203.86	4.0
	200	77.00	431.2	475.3	198.05	-
		77.00	428.4	472.3	196.13	-
	300	77.06	408.8	484.0	193.36	-
		77.50	400.0	458.1	196.13	-
	400	77.50	361.3	428.4	162.58	9.8
		77.30	368.7	429.5	168.82	8.6
	500	76.94	250.8	292.4	120.22	14.2
		77.41	235.1	281.6	121.43	12.4
	600	77.01	163.6	171.4	98.04	14.6
		77.11	163.4	171.2	105.69	14.6
	700	77.40	49.1	69.8	91.09	36.0
		77.03	57.1	76.6	68.16	23.0

TABLE B1 8 mm Series 1 Results

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	116.14	318.6	423.6	201.48	-
		116.15	-	419.3	-	-
	200	116.15	280.7	421.9	195.87	-
		115.58	282.9	418.8	192.51	-
	300	115.37	294.7	400.5	192.00	-
		115.76	259.2	419.0	194.80	-
	400	115.56	226.7	340.9	180.43	12.0
		115.48	235.5	379.3	181.85	20.6
	500	115.68	190.2	242.0	153.44	17.2
		116.05	172.3	250.8	146.50	18.0
	600	116.36	98.0	140.9	117.74	30.0
		116.26	106.7	145.4	110.96	23.2
	700	115.58	53.6	68.4	77.87	52.0
		107.77	53.8	70.5	76.09	40.8
Unisteel	100	114.39	448.5	584.8	228.17	12.2
		113.64	444.4	586.9	217.79	12.2
	200	114.58	442.5	577.8	218.62	-
		114.22	450.9	570.0	189.55	-
	300	112.84	452.9	577.8	189.21	-
		113.04	463.6	584.8	192.40	-
	400	112.28	398.1	507.7	158.09	15.2
		112.36	396.9	502.8	173.55	12.0
	500	112.17	303.1	396.7	146.21	12.4
		112.16	303.1	389.6	147.11	13.2
	600	112.17	194.3	247.8	130.16	17.6
		111.49	180.3	249.3	139.92	18.2
	700	112.48	110.2	124.5	56.01	24.2
		114.98	97.4	116.5	80.01	24.6
TorBar	100	114.21	523.6	593.6	232.03	-
		114.21	516.6	596.3	232.90	-
	200	114.22	527.1	595.4	218.90	-
		114.20	521.0	597.1	212.33	-
	300	113.63	471.7	581.7	202.41	-
		113.72	452.0	578.6	191.26	-
	400	113.71	418.6	502.1	186.86	10.4
		113.72	426.5	505.6	190.38	12.2
	500	113.71	329.8	375.5	129.70	7.4
		113.82	335.6	376.0	134.42	8.6
	600	113.73	177.6	207.5	78.26	12.0
		114.02	187.7	219.3	93.84	12.2
	700	113.55	82.8	93.4	87.19	21.8

contd.

Square twisted	100	115.34	521.9	574.0	203.74	-
		115.29	516.1	572.5	210.34	-
	200	115.27	499.7	574.3	203.00	-
		115.35	497.6	572.2	207.56	-
	300	115.39	456.7	573.7	187.62	-
		114.90	464.8	577.0	187.99	-
	400	115.46	421.8	472.9	181.88	9.0
		115.29	422.4	477.1	185.19	8.6
	500	115.27	316.6	319.3	148.35	3.6
		115.24	298.5	341.0	144.05	6.0
	600	115.37	169.9	185.5	101.41	7.8
		116.92	142.0	179.6	93.23	11.0
	700	115.26	46.0	71.1	112.35	49.0
		115.35	50.3	73.7	109.67	34.0

TABLE B2 12 mm Series 1

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	492.43	288.3	470.1	189.87	-
	200	492.32	278.3	478.3	188.90	-
	300	492.63	236.5	460.8	209.08	-
	400	492.60	194.88	421.2	167.48	13.8
	500	493.18	177.42	313.3	155.62	12.2
	600	493.57	116.50	183.4	137.77	22.8
	700	492.90	73.0	87.2	100.43	26.0
Unisteel	100	487.58	533.2	664.5	203.04	12.8
	200	486.76	460.2	661.5	183.87	-
	300	488.29	454.6	682.0	192.51	12.0
	400	488.45	415.6	613.2	193.47	11.4
	500	484.71	327.0	428.1	136.16	9.6
	600	485.93	208.9	262.4	107.01	11.6
	700	495.25	119.1	145.4	63.60	17.4
TorBar	100	480.57	459.9	554.1	196.64	-
	200	480.69	472.2	548.2	216.36	-
	300	472.23	455.3	555.9	185.29	-
	400	473.71	400.2	490.2	182.11	6.8
	500	477.95	297.1	354.6	170.52	5.2
	600	478.14	154.8	207.1	100.91	16.0
	700	481.07	58.2	87.3	84.19	31.2
Square twisted	100	486.80	451.9	531.0	199.26	-
	200	486.53	446.0	539.5	207.59	-
	300	486.71	402.7	537.3	195.19	-
	400	486.81	373.9	448.8	208.50	7.4
	500	486.44	296.0	333.0	149.04	4.2
	600	485.93	186.2	205.8	101.87	9.4
	700	486.36	84.3	99.7	88.4	18.8

TABLE B3 25 mm Series 1

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	51.77	382.5	457.8	207.65	-
		51.87	368.2	470.4	203.39	-
	200	51.03	413.5	464.4	185.19	-
		51.82	405.2	472.8	183.33	-
	300	31.91	400.7	468.1	211.91	-
		51.82	409.1	468.9	217.10	-
	400	51.32	411.1	471.6	213.37	-
		51.62	408.8	464.9	217.94	-
	500	51.77	380.5	461.7	212.48	20.0
		51.05	383.9	462.3	211.56	16.0
	600	51.87	368.2	453.1	207.25	20.8
		51.81	359.0	447.8	209.42	22.0
	700	51.91	333.3	418.0	212.87	24.2
		51.09	336.7	416.9	206.50	24.4
Unisteel	100	49.85	515.5	714.1	202.61	-
		49.83	495.7	718.4	210.72	-
	200	49.81	598.3	716.7	214.82	-
		49.91	577.0	705.3	225.41	-
	300	50.06	577.3	717.1	217.24	-
		49.91	609.1	719.3	225.41	-
	400	50.49	570.4	687.3	223.81	-
		50.33	602.0	695.4	223.52	-
	500	50.49	560.5	671.4	212.91	-
		50.41	541.6	686.4	223.17	-
	600	49.95	556.6	706.8	205.23	-
		49.94	574.6	716.8	238.26	-
	700	49.91	541.0	643.2	218.39	11.2
		49.89	509.1	625.4	215.47	9.8
TorBar	100	48.74	535.5	592.9	204.14	-
		48.75	535.4	586.7	215.38	-
	200	48.74	541.6	590.9	216.45	-
		48.73	543.8	589.0	207.26	-
	300	48.77	529.0	582.3	209.14	8.0
		48.73	533.6	584.9	208.29	8.8
	400	48.81	501.9	559.3	203.85	8.4
		48.73	513.0	564.3	212.39	10.2
	500	48.82	508.0	536.7	217.12	11.6
		48.78	508.4	535.1	207.05	11.2
	600	48.80	454.9	508.2	200.82	13.6
		48.78	453.1	508.4	210.13	13.2
	700	48.76	293.3	414.3	217.39	19.8
		48.76	297.4	416.3	214.32	19.8

contd.

10 mm Square twisted	100	77.01	458.4	516.8	212.30	-
		77.01	454.5	511.6	211.01	-
	200	77.30	465.7	490.3	214.75	-
		77.00	474.0	514.3	222.08	-
	300	77.01	471.4	507.7	218.15	-
		77.50	456.8	489.0	225.81	-
	400	77.09	460.5	498.1	212.09	9.8
		76.96	457.4	502.9	216.35	9.8
	500	77.01	432.4	480.5	214.26	12.6
		77.42	413.3	459.8	219.58	13.0
	600	77.11	398.1	451.3	210.74	13.2
		77.36	369.7	439.5	219.75	14.2
	700	77.37	224.9	329.6	198.40	25.4
		77.44	277.6	396.4	210.49	25.4

TABLE B4 8 mm Series 2

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	115.47	321.3	428.7	208.71	-
		115.57	328.8	423.1	204.21	-
	200	116.55	372.4	432.4	217.93	-
		116.05	344.7	422.2	211.12	-
	300	116.15	328.0	419.3	213.52	-
		116.12	340.2	426.3	215.29	-
	400	116.45	349.5	423.4	209.10	-
		116.12	327.2	423.7	209.27	-
	500	116.64	302.6	420.1	195.90	27.6
		116.55	320.9	452.2	208.92	24.5
	600	116.43	282.6	418.3	188.95	23.3
		116.25	279.6	419.8	201.29	27.7
	700	116.05	272.3	396.4	202.50	24.4
		116.64	287.2	402.9	210.91	24.1
Unisteel	100	113.47	490.9	642.5	209.31	-
		113.12	492.4	655.9	212.16	-
	200	113.28	527.0	642.7	215.40	-
		112.91	524.3	641.2	209.46	-
	300	111.83	505.2	621.5	227.13	-
		111.82	501.7	609.0	207.90	-
	400	111.83	507.9	613.4	208.80	-
		112.21	517.8	611.4	207.20	-
	500	112.30	472.0	605.5	201.25	16.3
		112.50	504.0	610.7	199.56	-
	600	113.07	487.3	611.1	213.58	13.7
		113.08	482.8	605.8	208.70	17.3
	700	114.90	428.2	511.7	206.70	15.8
		114.99	421.8	509.6	208.71	15.6
TorBar	100	113.44	527.2	488.0	212.45	-
		113.63	523.6	589.6	211.21	-
	200	114.22	547.2	579.6	211.00	-
		114.30	535.4	587.1	214.35	-
	300	114.30	540.7	587.1	216.10	-
		114.31	538.9	588.7	218.70	-
	400	113.82	550.0	601.8	212.18	-
		114.01	546.4	597.3	214.89	-
	500	113.91	512.7	592.6	212.89	10.0
		114.02	497.3	587.6	207.42	9.2
	600	113.90	482.9	557.5	212.91	12.0
		114.01	469.3	557.0	199.54	12.6
	700	114.02	315.7	444.7	199.53	16.0
		114.01	311.4	445.6	212.26	16.4

contd.

Square twisted	100	115.28	509.2	589.0	211.60	-
		115.28	509.2	588.1	214.69	9.8
	200	115.37	334.8	588.5	208.89	-
		117.02	525.6	575.1	208.51	-
	300	115.28	529.1	584.7	212.96	10.6
		115.30	527.3	583.7	210.32	10.8
	400	115.39	524.3	575.4	214.92	10.4
		117.01	515.3	564.1	209.38	10.4
	500	115.46	496.3	547.4	212.19	12.4
		116.91	487.6	536.3	211.70	12.4
	600	115.28	445.0	500.5	216.00	12.0
		115.39	454.1	499.2	207.12	12.0
	700	116.94	239.4	384.0	220.20	25.2
		115.24	244.7	389.6	209.13	26.6

TABLE B5 12 mm Series 2

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	493.09	319.4	478.6	204.83	21.6
	200	492.78	330.8	490.1	208.00	27.8
	300	492.99	330.6	492.9	212.99	29.0
	400	492.78	324.7	491.1	210.03	19.2
	500	492.60	324.8	491.3	213.15	27.6
	600	492.81	334.8	488.0	214.08	25.2
	700	492.90	317.5	449.4	211.00	25.2
Unisteel	100	487.11	560.4	709.3	207.34	16.2
	200	487.48	561.0	712.8	214.37	-
	300	485.01	571.1	726.8	213.40	15.6
	400	488.29	579.6	738.3	210.94	-
	500	487.32	554.1	704.9	221.62	15.6
	600	488.53	556.8	699.0	211.86	15.6
	700	494.83	453.7	602.2	204.11	6.8
TorBar	100	481.03	478.1	571.7	213.08	-
	200	483.16	484.3	568.1	209.04	-
	300	482.41	501.6	570.1	222.84	-
	400	481.95	506.3	572.7	217.86	-
	500	481.95	484.5	558.1	220.98	12.0
	600	478.55	410.2	503.5	225.62	14.0
	700	479.14	292.2	446.6	225.40	16.8
Square twisted	100	486.23	450.4	552.2	213.89	12.0
	200	486.53	467.6	549.8	212.73	-
	300	486.90	467.2	552.5	212.57	11.8
	400	486.90	462.1	544.3	209.49	14.0
	500	486.79	464.3	525.9	210.56	15.6
	600	486.32	434.9	497.6	212.82	15.4
	700	486.61	355.5	434.6	213.72	-

TABLE B6 25 mm Series 2

Type	Temp °C	Length of Test min	Time at Temp min	Net strain including correction %	Other Notes
Mild steel	100	65	30	0.012	
		50	30	0.012	
	200	70	35	0.038	
		65	35	0.023	
	300	70	35	0.086	
		65	35	0.106	
	400	65	25	0.181	
		60	25	0.210	
	500	145	115		$\dot{\epsilon}$ const. 0.002%/min
		115	80		$\dot{\epsilon}$ const. 0.002%/min
	600	60	20		Failed
		65	20		Failed
Unisteel	100	70	55	0.038	
		75	60	0.037	
	200	65	45	0.033	
		55	30	0.074	
	300	60	30	0.068	
		75	40	0.060	
	400	90	55	0.162	
		75	40	0.117	
	500	205	160		Failed
		135	90		Failed
TorBar	100	55	35	0.024	
		55	30	0.022	
	200	60	35	0.029	
		60	35	0.037	
	300	55	35	0.061	
		50	25	0.076	
	400	55	25	0.126	
		50	20	0.134	
	500	220	190		$\dot{\epsilon}$ const. 0.004%/min
		230	195		$\dot{\epsilon}$ const. 0.009%/min
	600	36	-		Failed, max temp 575°C
		40	-		Failed, max temp 560°C
Square twisted	100	55	30	0.009	
		50	30	0.026	
	200	65	30	0.040	
		70	40	0.040	
	300	70	45	0.058	
		65	35	0.077	
	400	60	30	0.145	
		60	35	0.162	
	500	135	100		Failed
		180	145		Failed

TABLE B7 8 mm Series 3A Results

Type	Temp °C	Length of Test min	Time at Temp min	Net strain including correction %	Other Notes
Mild steel	100	300	240	0.026	
		210	195	0.026	
	200	240	180	0.036	
		45	30	0.021	
	300	195	180	0.176	
		60	30	0.257	
	400	75	40	0.300	
		65	30	0.288	
	500	90	60	1.460	
		90	60	2.080	
	600	45	15		Failed
		45	15		Failed
Unisteel	100	90	75	0.026	
		75	60	0.022	
	200	100	75	0.051	
		65	45	0.040	
	300	70	40	0.037	
		75	45	0.054	
	400	80	35	0.102	
		75	40	0.075	
	500	110	60	0.516	
		90	45	0.408	
	600	60	15		Failed
		60	15		Failed
TorBar	100	80	60	0.028	
		75	55	0.029	
	200	120	95	0.055	
		75	45	0.040	
	300	95	70	0.073	
		80	50	0.065	
	400	75	40	0.110	
		50	35	0.130	
	500	105	75	1.131	
		100	70	1.126	
	600	30	-		Failed,max temp 590°C
		30	-		Failed,max temp 595°C
Square twisted	100	65	50	0.024	
		80	60	0.019	
	200	55	40	0.034	
		55	30	0.029	
	300	80	50	0.044	
		70	45	0.049	
	400	65	35	0.134	
		70	35	0.106	
	500	100	65	0.646	
		100	60	0.660	
	600	40	-		Failed,max temp 590°C
		35	-		Failed,max temp 580°C

TABLE B8 12 mm Series 3A Results

Type	Temp °C	Length of Test min	Time at Temp min	Net strain including correction %	Other Notes
Mild steel	100	85	65	0.008	
		95	75	0.005	
	200	80	55	- 0.006	
		100	70	- 0.002	
	300	105	65	0.059	
		80	40	0.130	
	400	75	40	0.160	
		90	40	0.128	
	500	140			$\dot{\epsilon}$ const. 0.001%/min
		130	85		$\dot{\epsilon}$ const. 0.003%/min
	600	68	-	18.4	Failed, max temp 590°C
		57	5	21.4	Failed
Unisteel	100	75	55	0.004	
		70	40	0.001	
	200	80	50	- 0.002	
		80	45	0.005	
	300	85	50	0.012	
		75	40	0.015	
	400	90	45	0.096	
		80	40	0.116	
	500	180	145		$\dot{\epsilon}$ const. 0.034%/min
		150	115		$\dot{\epsilon}$ const. 0.035%/min
	600	44	-	12.4	Failed, max temp 575°C
		47	-	11.2	Failed, max temp 575°C
TorBar	100	65	45	0.002	
		70	55	0.023	
	200	75	25	0.022	
		70	40	0.025	
	300	85	55	0.036	
		65	35	0.032	
	400	85	50	0.137	
		60	25	0.117	
	500	111	64	22.4	Failed
		58	20	23.2	Failed
Square twisted	100	70	50	0.016	
		60	40	0.027	
	200	70	30	0.023	
		70	35	0.018	
	300	75	40	0.021	
		75	45	0.024	
	400	90	45	0.062	
		95	50	0.154	
	500	290	245	2.6	Failed
		149	112	2.6	Failed

TABLE B9 25 mm Series 3A Results

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	50.51	322.7	459.3	245.50	-
		50.12	313.2	450.9	215.48	14.1
	200	48.76	356.8	473.7	225.59	-
		50.90	400.8	485.2	221.02	-
	300	49.93	374.5	476.7	219.22	-
		50.41	341.2	450.4	217.22	-
	400	49.89	336.7	447.0	212.47	14.4
		48.63	370.1	479.1	202.55	-
	500	50.27	358.1	483.4	219.81	18.0
		49.79	361.5	474.0	224.94	-
Unisteel	100	49.87	577.5	711.9	223.58	-
		49.82	511.8	716.6	228.82	11.2
	200	49.92	548.8	707.1	-	-
		49.93	564.8	695.0	275.41	-
	300	50.26	600.9	690.4	216.87	-
		50.37	549.9	698.8	219.38	-
	400	50.43	567.1	703.9	216.14	9.8
		50.41	583.2	698.3	218.21	-
TorBar	100	47.56	532.0	614.0	226.03	-
		49.11	484.6	570.1	225.01	-
	200	47.18	521.4	612.5	217.25	-
		47.95	519.3	592.3	205.42	-
	300	48.53	529.6	589.3	209.15	-
		48.15	552.4	614.7	213.91	-
	400	49.11	521.3	594.6	209.73	-
		45.82	-	591.4	-	-
	500	47.18	461.0	519.3	226.80	7.0
		49.60	429.4	475.8	205.14	6.4
10 mm Square twisted	100	49.60	500.0	588.7	206.65	-
		48.73	492.5	595.1	210.34	-
	200	49.99	518.1	578.1	220.04	-
		49.11	513.1	580.3	218.90	-
	300	48.82	517.2	575.6	218.15	-
		49.70	501.0	559.4	210.26	-
	400	48.63	531.6	596.3	237.51	-
		49.60	530.2	584.7	224.29	8.4

TABLE B10   8 mm Series 3B Results

Type	Temp °C	Area mm²	Yield or 0.2% proof stress N/mm²	ultimate tensile strength N/mm²	elastic modulus kN/mm²	elongation %
Mild steel	100	108.75	326.4	450.6	209.66	22.4
		108.86	306.8	441.9	206.69	26.4
	200	108.29	309.4	440.5	226.24	26.4
		107.74	317.4	455.7	219.51	26.4
	300	108.73	300.7	442.4	246.02	29.4
		108.66	303.7	437.1	236.52	-
	400	107.34	319.5	428.5	246.88	-
		107.37	301.8	428.4	214.21	31.6
	500	107.43	327.7	423.5	237.36	-
		107.43	330.4	428.2	225.72	22.0
Unisteel	100	111.91	470.9	633.5	180.95	-
		111.53	489.6	641.1	187.39	-
	200	112.15	519.8	646.5	204.19	-
		112.19	514.3	646.2	210.80	-
	300	112.30	523.6	651.8	194.57	-
		112.28	561.1	649.3	214.64	-
	400	111.69	527.4	649.1	221.15	-
		111.43	535.8	652.4	246.34	-
	500	111.86	512.2	645.4	207.85	15.7
		111.94	512.0	613.7	218.94	-
TorBar	100	111.34	468.2	558.7	207.84	-
		110.49	474.3	557.5	203.89	-
	200	111.38	487.5	560.2	203.96	-
		108.76	501.8	578.3	209.30	
	300	108.18	496.7	577.7	208.68	-
		108.04	503.4	574.8	205.03	-
	400	112.25	495.4	561.2	206.99	-
		111.16	485.0	560.5	203.94	-
	500	107.99	460.9	545.4	210.36	12.4
		Specimen damaged during series 3A tests				
Square twisted	100	99.15	551.4	652.5	198.87	-
		99.56	542.5	647.9	208.64	7.8
	200	99.81	575.1	650.2	207.04	-
		99.58	565.1	643.7	203.87	-
	300	99.71	567.2	651.9	204.77	-
		99.21	553.0	653.2	202.08	-
	400	99.56	566.2	639.8	206.84	9.4
		99.18	572.1	643.3	206.03	10.0
	500	99.73	543.5	606.6	206.93	11.2
		98.72	542.3	606.8	205.66	9.2

TABLE B11 12 mm Series 3B Results

Type	Temp °C	Area mm^2	Yield or 0.2% proof stress N/mm^2	ultimate tensile strength N/mm^2	elastic modulus kN/mm^2	elongation %
Mild steel	100	508.58	320.5	471.9	216.29	24.0
	200	512.26	339.7	491.9	212.78	28.0
	300	508.58	324.4	471.9	219.24	30.2
	400	509.36	329.8	469.2	227.74	22.6
	500	508.39	350.1	473.1	221.29	18.0
Unisteel	100	488.60	552.6	707.1	212.85	12.0
	200	487.95	554.4	708.1	209.04	16.0
	300	487.45	558.0	708.8	216.43	-
	400	488.23	561.2	706.6	210.97	-
	500	489.21	596.9	711.4	197.26	8.6
TorBar	100	502.20	454.0	559.4	240.94	-
	200	505.29	461.1	562.1	205.82	-
	300	501.41	458.7	532.5	212.40	-
	400	497.53	468.3	548.7	208.03	-
Square twisted	100	475.55	438.4	552.0	213.44	12.6
	200	490.86	513.4	613.2	207.80	-
	300	486.01	493.8	567.9	210.90	-
	400	493.86	500.1	576.1	209.57	11.8

TABLE B12 25 mm Series 3B Results

APPENDIX C

PRESTRESSING STEEL RESULTS

APPENDIX C - Prestressing Steel Results

The test results reproduced in this appendix have been obtained in a similar manner to those given in Appendix B from the same three test procedures given in Chapter 5 and have been used Chapter 8.

For the three test procedures, three types of prestressing steel have been used on each, with duplicate tests being performed on most of the prestress 2 tests.

Size and Type	Temp °C	Area mm^2	0.2% proof stress N/mm^2	tensile strength kN	elastic modulus kN/mm^2	elongation %
5 mm Mill coil	100	20.53	1510.0	34.7	196.79	3.4
	200	20.53	1398.0	34.8	188.99	8.2
	300	20.63	998.5	26.6	181.29	7.4
	400	20.63	717.4	19.2	173.53	6.6
	500	20.52	389.4	10.4	114.04	15.2
	600	20.53	160.7	5.1	67.22	14.8
	700	20.52	87.7	2.3	21.44	27.2
5 mm Stabilised wire	100	19.91	1391.3	31.6	199.90	4.0
	200	19.96	1262.5	31.5	198.40	7.2
	300	19.94	1103.3	24.9	186.56	7.2
	400	19.97	826.2	18.4	165.50	7.6
	500	19.88	380.4	9.7	106.11	9.4
	600	20.00	200.0	5.2	56.00	21.4
	700	19.96	90.2	2.0	16.03	38.8
9.3 mm 7 Wire strand	100	53.62	1734.4	100.9	190.23	unable to measure gauge length due to configuration of fracture
	200	53.67	1576.3	96.0	175.14	
	300	53.63	1232.5	75.5	177.84	
	400	53.47	860.3	54.4	144.38	
	500	53.61	380.5	38.1	119.38	
	600	53.65	158.4	12.3	56.67	
	700	53.67	78.3	6.1	26.46	

TABLE C1 Prestress 1 Results

Size and Type	Temp °C	Area mm²	0.2% proof stress N/mm²	tensile strength kN	elastic modulus kN/mm²	elongation %
5 mm Mill coil	100	20.63	1604.5	35.5	204.56	-
		20.53	1646.4	36.1	208.48	-
	200	20.53	1753.5	36.4	207.50	-
		20.53	1748.7	36.3	210.42	-
	300	20.53	1622.0	36.5	210.42	5.4
	400	20.53	1383.3	32.9	206.53	5.2
	500	20.53	1169.0	26.4	210.42	4.8
	600	20.52	867.4	17.8	212.48	-
	700	20.52	662.8	13.7	210.53	8.4
5 mm Stabilised wire	100	19.95	1453.6	32.6	207.52	-
		20.01	1454.3	32.6	206.90	-
	200	19.95	1448.6	32.6	208.52	-
		19.97	1447.2	32.5	209.31	-
	300	19.94	1474.4	32.6	208.63	4.8
		19.95	1483.7	32.8	215.54	-
	400	19.96	1337.7	30.7	213.43	4.4
		19.96	1337.7	30.7	218.44	4.8
	500	19.93	1103.9	25.1	212.74	4.0
		19.96	1112.2	25.3	212.42	5.0
	600	19.97	821.2	16.4	215.32	-
		19.93	802.8	16.0	215.76	-
	700	19.93	652.3	13.7	220.77	12.0
		20.03	644.0	13.7	220.67	12.4
9.3 mm 7 wire strand	100	53.68	1857.3	102.7	197.47	-
		53.58	1853.3	102.6	203.06	-
	200	53.64	1860.6	103.7	206.56	-
		53.56	1872.7	103.3	209.11	-
	300	53.63	1752.8	100.9	201.38	-
		53.60	1738.8	100.3	204.48	-
	400	53.49	1471.3	87.4	210.13	-
		53.56	1471.2	87.4	215.46	-
	500	53.60	1231.3	71.5	205.22	-
		53.68	-	71.7	-	-
	600	53.64	971.3	52.1	201.34	-
		53.64	971.3	52.1	194.26	-
	700	53.58	677.5	36.3	188.88	-
		53.71	685.2	36.8	191.03	-

TABLE C2 Prestress 2 Results

Size and Type	Temp ^{o}C	Length of Test min	Time at Temp min	Net strain including correction %	Other Notes
5 mm Mill coil	100	55	35	0.203	
	200	90	70	0.867	
	300	30	-		Failed, elongation 6.8%, max temp 295°C
5 mm Stabilised wire	100	45	30	0.044	
	200	65	50	0.295	
	300	30	-		Failed, elongation 4.4%, max temp 298°C
9.3 mm 7 wire strand	100	65	50	0.073	
	200	150	120	0.425	
	300	27	-		Failed, max temp 295°C

TABLE C3 Prestress 3A Results

Size and Type	Area mm^2	Test Temp °C	0.2% proof stress N/mm^2	tensile strength kN	elastic modulus kN/mm^2	elongation %
5 mm Mill coil	20.63	100	1648.1	36.2	201.65	-
	20.53	200	1768.1	36.3	202.63	-
5 mm Stabilised wire	19.99	100	1445.7	32.8	208.10	-
	19.99	200	1515.8	32.8	208.10	-
9.3 mm 7 wire strand	53.57	100	1810.7	98.1	210.57	-
	53.58	200	1885.0	103.5	203.06	-

TABLE C4 Prestress 3B Results

NB No specimen test fractured within 250 mm gauge length

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