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T. N. W. Akroyd, MScTech,
LLB(Hons), CEng, FIStructE
Barrister-at-Law

Secretary
C. D. Morgan, OBE, FCIS

All editorial inquiries
should be addressed to:
The Structural Engineer
11 Upper Belgrave Street
London SW1X 8BH
Telephone: 01-235 4535

Editor
R. J. W. Milne, BSc

Assistant Editor
Barry Scanes, BA

Copies of Notes for authors
available on request

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Structural engineering is the science and art of designing and making, with economy and elegance, buildings, bridges, frameworks, and other similar structures so that they can safely resist the forces to which they may be subjected

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The effects of elevated temperatures on the strength properties of reinforcing and prestressing steels

M. Holmes, PhD, DSc, CEng, FIStructE, FICE
Department of Civil Engineering, University of Aston

R. D. Anchor, BSc, CEng, FIStructE, FICE
University of Aston and R. D. Anchor Consultants

G. M. E. Cook, BSc, CEng, MIMechE, MICE, FIFireE
Fire Research Station, BRE

R. N. Crook, BSc, PhD
Cement & Concrete Association

Synopsis

The effect of elevated temperatures on the strength and stiffness properties of four reinforcing and three prestressing steels of varying size, manufactured to British Standard specifications, has been investigated. To simulate the temperatures likely to be experienced by the steel during a fire, a temperature range of 20° to 700° was adopted. The steels were tested in their 'as manufactured' condition in a purpose-built, tensile testing machine with tube furnaces and associated recording instrumentation. The test programme was designed to provide data on three major strength parameters—yield (or 0·2 % proof) stress, ultimate strength, and elastic modulus. Using the data it is possible to assess the deterioration in strength of a structure during a fire and its residual strength at ambient temperature after a fire.

Introduction

Estimates of the resistance of structures to fire exposure are currently obtained by exposing structural elements to a standard fire (BS 476[1] ASTME[2] and ISO 834[3]). The fully-loaded structural element under test is exposed to the standard fire and the time measured until collapse takes place. Traditionally, in the UK the structural fire resistance of a member is decided by applying rules concerning concrete cover, minimum member size, and protection offered by surface finishes.

The joint report by The Concrete Society and The Institution of Structural Engineers[4] suggests that a more rational design approach for fire resistance should be adopted using limit state philosophy. Such an approach would involve consideration of the total structure response to fire, rather than consideration of the behaviour of isolated structural elements. The report also makes clear that, before limit state principles can be adopted for fire resistance, much additional information and data needs to be acquired, including the behaviour of steel reinforcement at elevated temperature.

This paper describes an extensive study of the behaviour of reinforcing and prestressing steel at elevated temperatures and various applied stress conditions. The data obtained may be used in formulating the limit state design procedures for fire resistance mentioned above.

Types of steel investigated

For the investigation, four types of reinforcement and three types of prestressing steel were selected to represent the wide range of steels currently available to the construction industry. For the reinforcing steels, three nominal diameters were chosen, i.e. 8 mm, 12 mm, and 25 mm. This would 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 seven-wire strand.

Table 1 gives the type of steel to be used, its trade name, and supplier.

The recent introduction of the Torbar type of cold-worked, high yield steel, with much improved bond characteristics, has led to ceased production of the square twisted type of cold-worked steel. However, since the latter type of steel has been widely used in the construction industry, the tests were still considered necessary so that an assessment of the performance and residual properties of existing concrete structures damaged by fire can be made.

The manufacture of the various types of reinforcement was in accordance with BS 4449[5] and BS 4461[6] with prestressing steels covered by BS 2691[7] and BS 3617[8]. These standards lay down specific requirements for chemical composition, characteristic strength (yield or proof), ultimate tensile strength, etc. Although these standards give values that are acceptable for general usage, it was decided to obtain as many of the properties given in the standards from the actual delivered steel.

Testing equipment

A tensile testing machine with the versatility to accommodate the size and length of specimen and deformation under load and capable of operating at elevated temperature, was not available commercially. Therefore, a special purpose machine, working on the basic concept of two load plattens moving apart, was designed and built. A schematic diagram is shown in Fig 1. The loading mechanism had a maximum extension of 150 mm, but this was extended to 300 mm by the use of a spacer inserted between the ram and top loading platten, while the ram core was retracted.

The steel was to be tested in its 'as rolled' condition and this required the use of serrated mechanical wedges so as to grip the reinforcement and enable the load to be transferred to it. Proprietary prestressing anchorages and smooth wedges were used for loading the prestressing steel specimens.

TABLE 1—Steel types and suppliers

Type of steel	Proprietary name or generic description	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 Engineering Co Stafford
Prestressing wire	Mill Coil	GKN (Somerset Wire) Ltd., Cardiff
	Stabilised wire	
Prestressing strand	seven wire strand	

To heat the specimens a cylindrical tube furnace having an inner silicon heating tube of 87·5 mm diameter, with a maximum operating temperature of 1000°C, was used. The silicon tube was protected in a large diameter, stainless steel tube with the void filled with insulating material. Because of heat losses through the ends of the furnace, which was reduced by Meckenchnie ceramic wool fibre, and the need to obtain a low temperature gradient over the heated length, the furnace was split into three, 150 mm zones. These zones were controlled independently by Eurotherm thyrister units from a preselected digital temperature display. Temperature measurement was obtained from fibreglass-insulated Chromel-Alumel thermocouples fixed to the specimen. The thermocouples were used to monitor the specimen temperature over the three zones, record the gauge length temperature, and control the thyrister units.

Since the gauge length was confined within the furnace and would be subjected to a temperature up to 700°C the choice of a strain measurement device was limited. Ideally, quartz extensometers, having extremely low thermal expansion properties giving accurate results, should be used. However, the fragile nature of quartz ruled out its use and Nimonic 80A alloy steel, having low creep properties, was chosen instead. The susceptibility of this material to thermal expansion meant that, whenever steady-state temperatures were not present, the results needed to be corrected for the thermal expansion of the strain gauge. Two transducers, with an operating range of ± 12·5 mm and temperature range of −10°C to +50°C, used in conjunction with detachable collets and mounted outside the furnace, allowed for all sizes of specimen with differing gauge lengths to be accommodated on one extensometer. Calibration of the transducers was obtained using metric micrometers placed under the transducers.

Load measurement was obtained from two pressure transducers attached to the loading ram. For accuracy, one measured up to 200 kN and the other above 200 kN. Outputs from the pressure tranducers, extensometer transducers and thermocouples were amplified and input into a Bryans X-Yt 29000 series recorder. A continuous plot of two of the inputs was obtained and the scales were adjusted to give the maximum range of values required.

Objectives of the test programme

The test programme outlined below was designed to provide the essential experimental data on the effects of high temperature on the strength and stiffness properties of reinforcing and prestressing steel. In designing the programme, attention was paid to the deterioration in strength of a structure during a fire and its residual strength at ambient temperature after a fire. The three test procedures subsequently derived were common to both types of steel (reinforcing and prestressing).

Test procedures

At least two room-temperature tensile tests were performed on all the different types and sizes of steel before the elevated temperature tests commenced. Separate specimens were used for each test and two nominally identical tests were performed at each temperature increment of 100°C.

The cross-sectional area of each specimen was determined by the method given in BS 4449[5] and BS 4461[6] and for each size of specimen a convenient gauge length based on $5{\cdot}65\sqrt{S_o}$ (where S_o is the cross-sectional area) was used. Tests, wherever possible, were performed in accordance with BS 18[9] and BS 3688[10]. However, it was not practical, with the positioning of the equipment, to perform the tests under 'strain rate control'. As an alternative, an equivalent loading rate based on the recommended strain rate of between 0·001 and 0·003/min up to yield or proof stress and the physical characteristics of the specimens, was used.

To ensure that the whole cross-section of the specimen had reached the specified temperature, a standard soaking time of ½ h was used. This was based on the minimum fire resistance time given in CP 110[11] and would also allow the extensometers and other gauges to reach a steady state before the test commenced.

The following test procedures (series 1 to 3) are shown diagrammatically in Fig 2.

Series 1

A specimen with extensometers 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. The inputs to the X-Y plotter were set and the furnace was switched on. With the aid of the digital thermometer the furnace control was adjusted until all three zones on the specimen were within ±5°C of the specified temperature (700°C maximum) and the half-hour soaking period was commenced. At the end of this period the strain due to the expansion of the specimen and extensometers was 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.

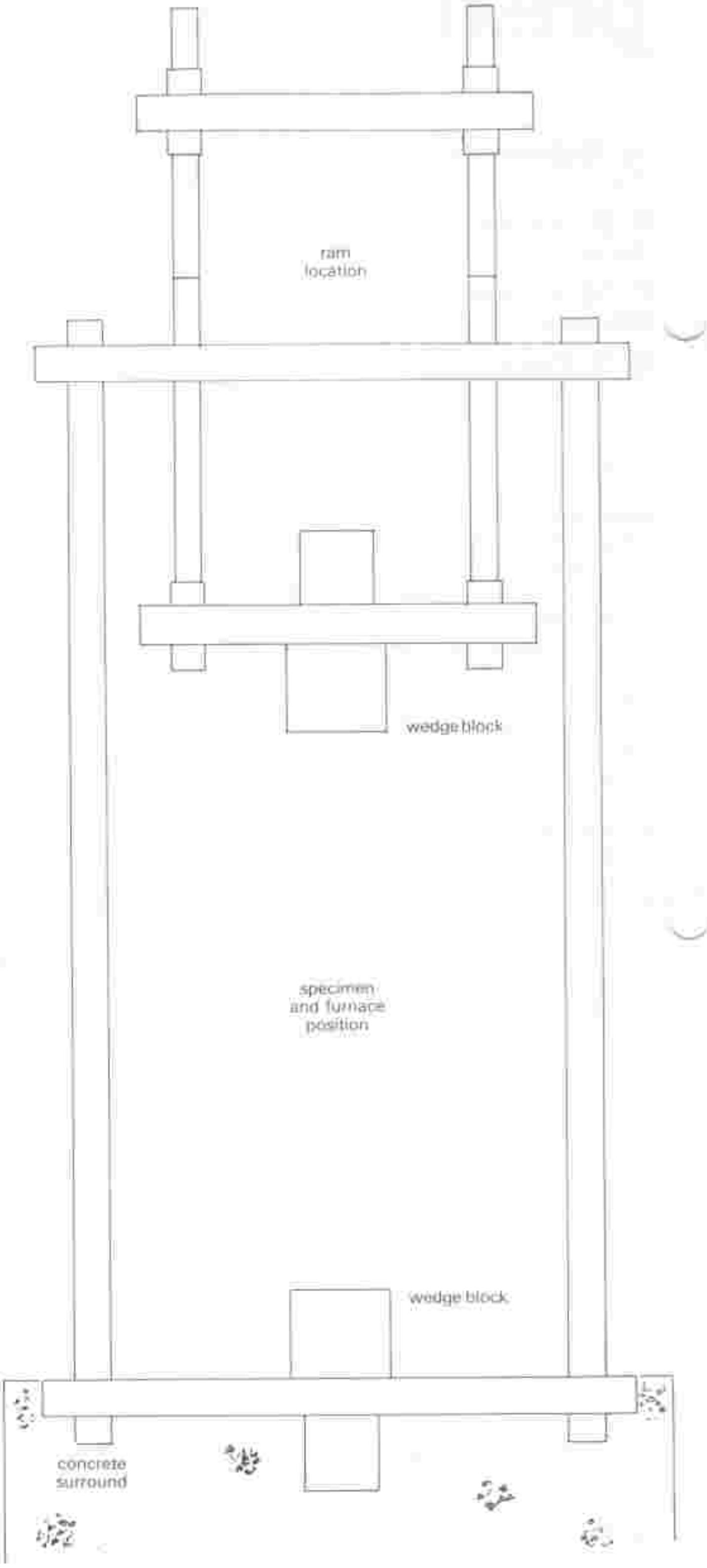

Fig 1. Test frame arrangement

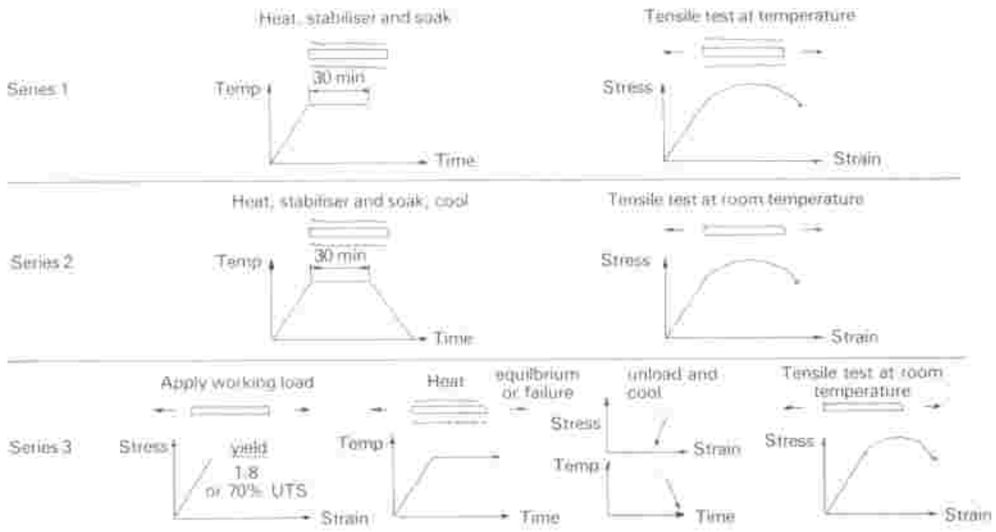

Fig 2. Test procedures

The results from this type of test are applicable to 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.

Series 2

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

Specimens, usually four, one of each type for a specific size with the thermo-couples 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, and a tensile test performed at room temperature to failure.

Series 3

The procedure for arranging the specimen and gauges in the furnace and test rig was identical with that described for series 1. However, instead of raising the temperature of an unloaded specimen, a load was applied equivalent to the working stress for the steel. This was equivalent to yield or 0·2 % proof stress divided by 1·8 for the reinforcing and to 70 % ultimate tensile strength for the prestressing steels. These strength parameters were obtained from the room-temperature control tests on samples of similar size and type. This part of series 3 is referred to as series 3A.

For each specified temperature the strain, temperature, and time were recorded, and the test was terminated either when the strain rate became very small (usually taken as 0·0004/min) or if the test had been running for over 3 h and the strain was non-uniform, or the specimen had failed. If failure had not occurred, the specimen was unloaded, cooled to room temperature and a tensile test performed on it in the test rig. This part of series 3 is referred to as series 3B.

This procedure gives the information necessary to determine the performance of the steels when they had been subjected simultaneously 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 being subjected to a fire.

Test results

Room temperature results

The room-temperature control test results were obtained from the tests performed in an Avery Denison testing machine and the specially-built test rig. To complete all the tests on the reinforcing steels two batches were required, with batch 1 steels being used for series 3 and batch 2 for series 1 and 2. Enough 8 mm unisteel was available to complete the tests from batch 1. Whenever possible, samples for use in both machines were cut from the same length.

Tables 2, 3, 4, and 5 show the 95 % confidence limits and the coefficient of variance for the tests performed. Each of the values recorded in these tables is based on a minimum of five test results.

These two parameters show the spread of results obtained from the tests. The strength parameters of yield (or 0·2% proof) stress, ultimate strength, and elastic modulus obtained from the room-temperature tests would be used to normalise the corresponding values obtained from the specimens tested at, or after being cooled from, an elevated temperature.

TABLE 2—8 mm room-temperature results

Type of steel	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 2	337·7 ± 43·6 369·0 ± 15·4	6·5 2·1	467·3 ± 65·5 487·0 ± 39·1	7·1 4·1	211·56 ± 18·31 203·13 ± 11·17	4·4 2·8
Unisteel	1	491·5 ± 3·0	0·3	711·1 ± 13·4	1·0	208·66 ± 28·79	7·0
Torbar	1 2	485·1 ± 25·9 499·1 ± 27·8	2·7 2·8	586·7 ± 36·8 596·4 ± 30·8	3·2 2·6	205·32 ± 8·56 210·64 ± 13·30	2·1 3·2
Square twisted	1 2 (10 mm)	471·0 ± 34·9 448·9 ± 8·6	3·8 1·0	569·8 ± 54·9 511·1 ± 27·1	4·9 2·7	206·76 ± 5·17 208·57 ± 5·37	1·3 1·3

TABLE 3—12 mm room-temperature results

Type of steel	Batch no.	Yield or 0·2% proof stress		Ultimate tensile strength		Elastic modulus	
		95% confidence limits (N/mm²)	Coefficient of variance (%)	95% confidence limits (N/mm²)	c/v (%)	95% confidence limits (kN/mm²)	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 4—25 mm room-temperature results

Type of steel	Batch no.	Yield or 0·2% proof stress		Ultimate tensile strength		Elastic modulus	
		95% confidence limits (N/mm²)	Coefficient of variance (%)	95% confidence limits (N/mm²)	c/v (%)	95% confidence limits (kN/mm²)	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 5—Prestressing steel room-temperature results

Type of steel	Yield or 0·2% proof stress		Tensile strength		Elastic modulus	
	95% confidence limits (N/mm²)	Coefficient of variance (%)	95% confidence limits (kN/mm²)	c/v (%)	95% confidence limits (kN/mm²)	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 stablised wire	1464·8 ± 23·4	0·8	33·5 ± 1·2	1·8	204·12 ± 33·36	8·3
9·3 mm seven wire strand	1864·5 ± 38·0	1·0	104·0 ± 0·4	0·2	199·54 ± 6·04	1·5

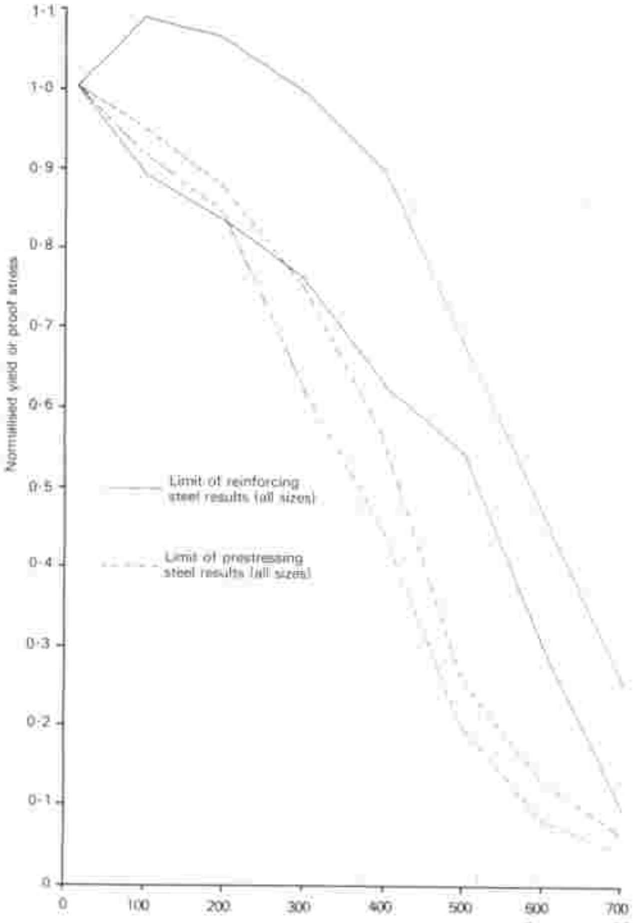

Fig 3. Total spread of all results from series 1—normalised yield or proof stress results

From all the mean values given in Tables 2 to 5 the only one to fall below the characteristic strength was for 10 mm square twisted steel, which had a mean 0·2 % proof stress of 448·9 N/mm². The individual results from this batch of steel did not comply with section 20 of BS 4461[6]: all the 0·2 % proof stress values fell below the characteristic strength.

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 caused the scatter of results, rather than any error in testing 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 the characteristic strength of 250 N/mm². 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 British Standards[5, 6].

The elastic modulus was obtained from the slope of the linear portion of the stress/strain plot. However, some of the plots, usually from the cold worked steels, had little or no linear portion as they became non-linear either as soon as the load was applied or at low load values. In these cases the initial tangent modulus was measured from the experimental stress/strain plot.

The factor that was consistent throughout the results from series 1, 2 and 3 was that size of section had little influence on the property measured. With reference to the type of steel tested, the hot rolled steels (including 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.

Series 1 results

Although the individual stress/strain plots of the tensile tests have not been included, it was noticeable that, for each of the three series, there was a change in the shape of the plots for certain types of reinforcing steel but not from the prestressing steels[12].

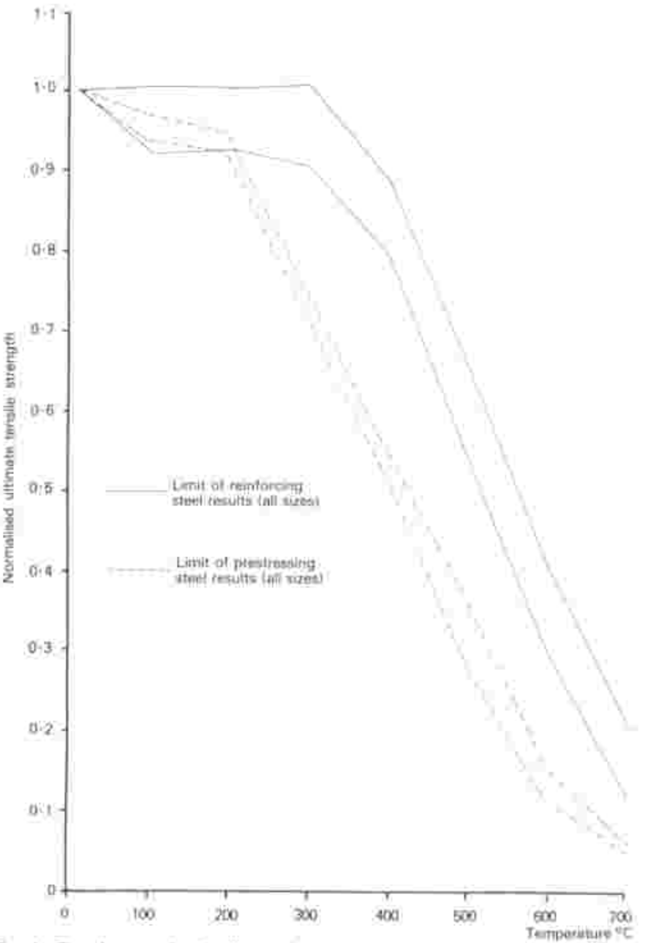

Fig 4. Total spread of all results from series 1—normalised ultimate tensile strength results

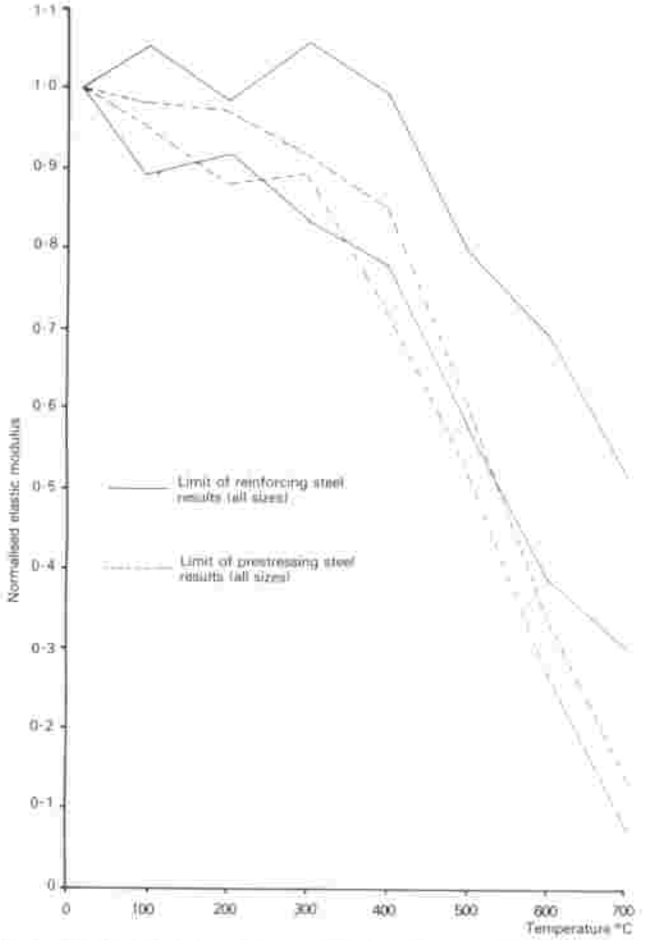

Fig 5. Total spread of all results from series 1—normalised elastic modulus results

The three sizes of Torbar and square twisted type steels, and also the 8 and 12 mm unisteel type, retained the typical 'cold worked' shape of a linear section, followed by a non-linear portion with no distinctive yield point and continued 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 without a distinctive yield point. It was therefore necessary to adopt the offset method usually used for the 'cold worked' steels to obtain the 0·2 % proof stress for temperatures of 300°C and above. The normalised results for the yield stress, ultimate strength and elastic modulus for all sizes and types (including the prestressing steels) are shown in Figs 3, 4, and 5.

These figures show that, for the reinforcing bars, there was no significant change in the normalised values below 300°C, but as soon as the temperature of the prestressing steels was raised to 100°C there was a noticeable reduction in these values.

A 50 % reduction in both the yield stress (Fig 3) and ultimate strength (Fig 4) was obtained between 520°C and 580°C and between 540°C and 700°C for the elastic modulus (Fig 5) for the reinforcing steels. A similar reduction was found from the prestressing steels when the temperature was between 370°C and 420°C for the proof stress (Fig 3) and ultimate strength (Fig 4) and between 510°C and 530°C for the elastic modulus (Fig 5). For the prestressing steels the temperature at which the ultimate tensile strength reduced to 70 % of its original value was between 305°C and 325°C (Fig 4).

A representative value taken as the midpoint of the scatter of results shown in Figs 3, 4 and 5 is given in Fig 6 for both reinforcing and prestressing steels. The curves from the most recent design chart[13] are included in Fig 6, and it can be seen that in the midrange of temperatures good agreement is obtained, but at the upper and lower temperatures the design curves do not form the lower bound limit.

Series 2 results

From the series 2 tests the recorded plots obtained again showed a change in shape for some of the reinforcing steels[12], although this was completely opposite to that obtained from series 1 tests. Here, those steels exhibiting a ductile behaviour (all mild steel plus 25 mm unisteel) retained it over the whole temperature range, but those steels producing the typical 'cold worked' stress/strain characteristic (all Torbar and square twisted plus 8 and 12 mm unisteel) changed the shape of their plot between 200°Cand 300°C.

Fig 7 shows the variation in ultimate strength, 0·2 % proof, stress and elastic modulus with temperature for 12 mm square twisted steel illustrating a decrease in strength with increasing temperature. The variation between nominally identical tests (Fig 7) was small for the proof stress and tensile strength, but was larger for the elastic modulus, while still being within the extremes of the values obtained from the room-temperature tests.

When normalised the strength parameters again showed that the size of steel had little effect on the general shape of the graphs[12]. However, the manufacturing process for the reinforcing steel does have an effect on the yield and tensile strength, with the 'cold worked' steels having a greatly reduced strength with increasing temperature compared with the 'hot rolled' steels. As observed with series 1, the type of prestressing steel had no effect on the normalised values.

The decrease in the normalised proof stress and tensile strength for the prestressing steels was not significant, until the temperature exceeded 300°C. Below this temperature a constant strength was obtained for both parameters, except for the mill coil where a 9 % increase in proof stress was observed at 200°C[12]. The decrease in strength was not as drastic as the series 1 results, but a 50 % reduction in proof stress was obtained between 610°C and 650°C. For the two stressing levels of 70 % and 55 % ultimate tensile strength a temperature range of 490°C to 520°C and 570°C to 575°C, respectively, was observed[12]. The elastic modulus for both reinforcing and prestressing steels remained unaltered over the

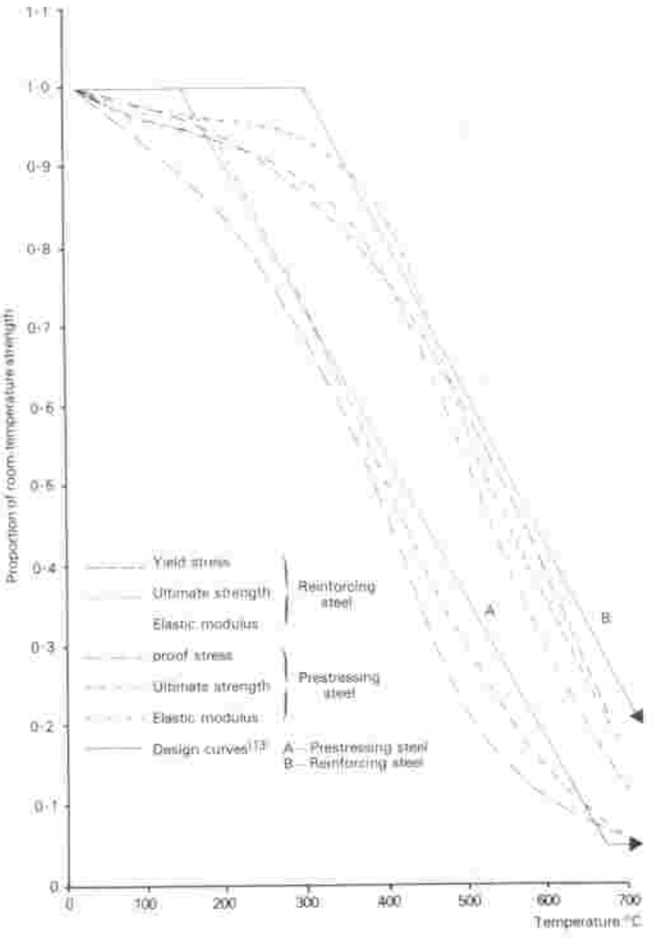

Fig 6. *Typical strength properties of reinforcing and prestressing steels tested at elevated temperatures (series 1)*

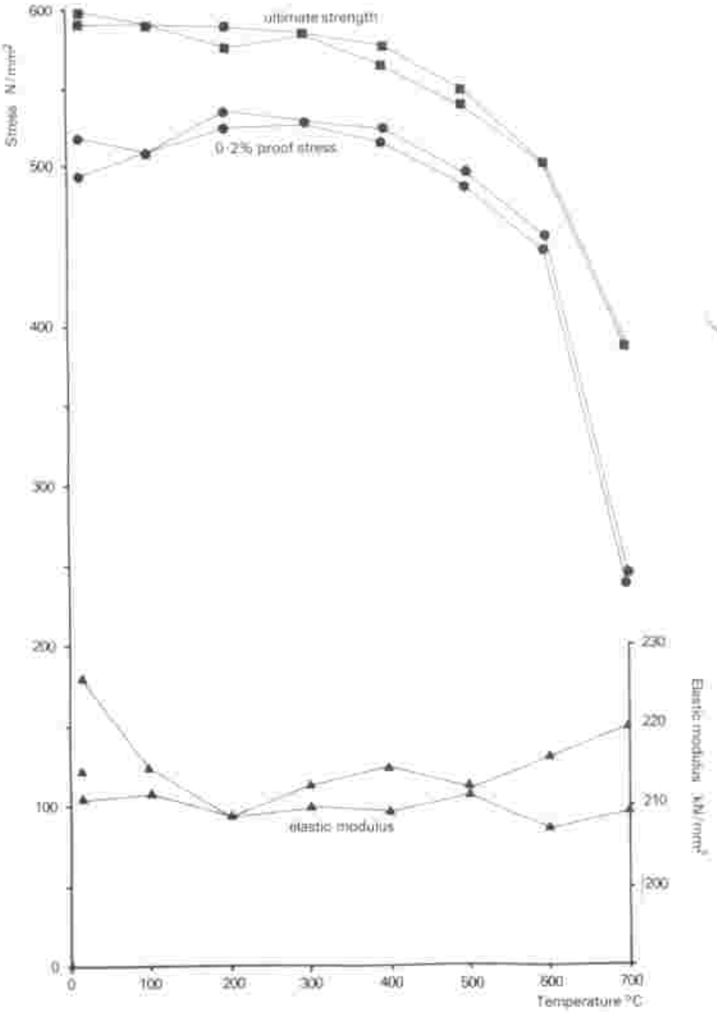

Fig 7. *Full range of test results for 12 mm square twisted steel (series 2)*

whole temperature range.

Differences between the two types of reinforcing bar were observed. The hot rolled yield stress increased by as much as 12·5 % at 400°C before reducing to 95 % of the original 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[12]. Fig 8, a representative plot of all the results obtained from this series, shows the difference between the performance of the 'hot rolled' and 'cold worked' reinforcing steels and the prestressing steels after being subjected to an elevated temperature.

Series 3 results

All the prestressing steels failed at 300°C when subjected to 70 % ultimate load being maintained[12]. In retrospect 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 3 h of testing continued to creep. There was no clear pattern at this temperature for any of the steels[12].

On cooling and subsequent retesting to failure, there was no reduction in any of the three strength parameters from the available samples for the reinforcing steels, although a slight decrease was obtained for the ultimate tensile strength of the prestressing steels (Fig 9).

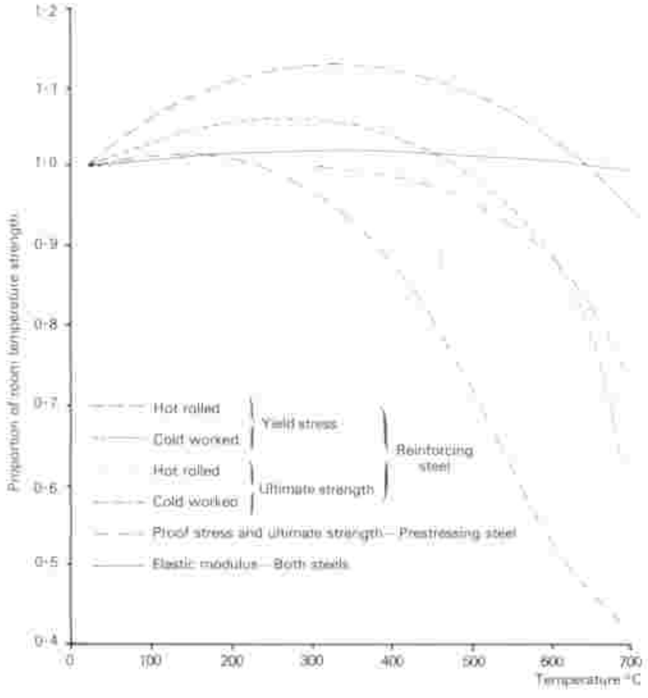

Fig 8. Typical strength properties of reinforcing and prestressing steels tested at room temperature after heating to an elevated temperature (series 2)

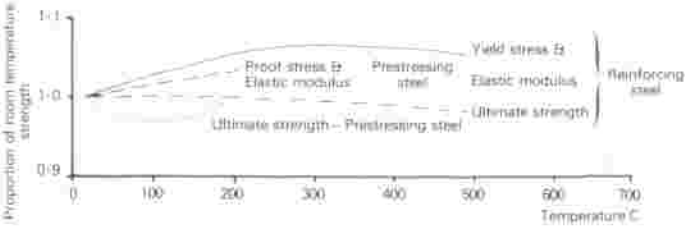

Fig 9. Typical strength properties of reinforcing and prestressing steels tested at room temperature after having a working load applied during heating (series 3)

Conclusions

The paper provides, for the first time, comprehensive data on the performance of reinforcing and prestressing steels in their 'as rolled' condition before, during and after exposure to elevated temperatures likely to be reached in a fire. It is expected that the data will be of use in Codes of Practice and other guidance documents which encourage the design of fire resisting structures using basic material properties.

In a fuller description[12] of the work reported in this paper a more detailed comparison is made between the comprehensive study described here and previous *ad hoc* work on elevated temperature properties of steel.

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