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An Introduction to the Mechanical Properties of Structural Steel at Elevated Temperatures

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SUMMARY

This paper presents data on the elevated-temperature mechanical properties of hot rolled structural steel used in buildings and explains their physical meaning. The properties include Poisson's ratio, thermal expansion and phase transformation, stress–strain relationships, and elastic modulus. Some room temperature data are given as benchmarks. It also attempts to explain some anomalies in elastic modulus measurements and the difficulties in idealizing stress–strain data.

1. POISSON'S RATIO

1.1. General

When a body is pulled, it becomes longer and thinner; when compressed, shorter and thicker. Poisson's ratio ν quantifies this phenomenon and is defined as

$$\frac{\text{lateral strain}}{\text{longitudinal strain}}$$

Most values given in the literature for Poisson's ratio for mild steel have been derived from separate determinations of elastic modulus E and shear modulus G using the relationship

$$\nu = \frac{E}{2G} - 1$$

Woolman and Mottram [1] point out that values so determined are subject to considerable errors, since slight errors in either E or G are magnified in the subsequent estimation of ν. For example, if E were measured 2% high and G 2% low, the calculated value of ν would be in error by 18%. The authors reinforce the generally held view that the values of the elastic constants, E and G, are not sensitive to the structure or composition of the steel, and they say that the best estimates of ν for the family of low alloy steels (of which structural steel is a member) are all between 0.27 and 0.30. BS 5950: Part 1: 1985 [2], which deals with the room temperature design of steel structures, recommends that a value of $\nu = 0.30$ should be used.

If a rectangular block is subjected to tensile stresses σ_x and σ_y, then the strains will be as follows:

$$e_x = \frac{\sigma_x}{E} - \frac{\nu\sigma_y}{E}$$

$$e_y = \frac{\sigma_y}{E} - \frac{\nu\sigma_x}{E}$$

$$e_z = -\frac{\nu\sigma_x}{E} - \frac{\nu\sigma_y}{E}$$

Equations of this kind are used in the constitutive relations in two-dimensional finite element elastic theories [3]. Hence the need to know ν.

1.2. Variation of ν with temperature

There appears to be a paucity of data on the variation of Poisson's ratio with temperature. Clarke [4] has reported values up to a temperature of 650 °C for a mild steel (En 2) containing 0.15% C, 0.46% Mn and 0.28% Si, and the variation is not great, as shown in Table 1.

Stirland of the British Steel Corporation (BSC)* has reported [5] a value of $\nu = 0.34$ at 1000 °C, which is in line with the trend indicated in Table 2, and has recommended that a value of 0.30 should be used for calculation purposes for all structural steel grades. This value has been adopted in the draft BS 5950: Part 8 [6] which deals with fire protection of structural steel.

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*In this paper BSC means BSC Swinden Laboratories or, formerly, BSC Teesside Laboratories.

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TABLE 1

Variation of Poisson's ratio of steel with temperature

Temperature (°C)	Elastic modulus (lb/in^2) × 10^{-6}	Shear modulus (lb/in^2) × 10^{-6}	Poisson's ratio
20	30.8	11.9	0.288
95	30.3	11.7	0.290
205	29.2	11.2	0.293
425	26.7	10.2	0.300
595	24.1	9.2	0.306
650	22.8	8.75	0.311

2. THERMAL EXPANSION AND PHASE TRANSFORMATION

2.1. General

To predict the thermal movement of structures in fire, it is necessary to know the thermal expansion properties of structural materials and composites. There are precise data for metals, but for complex materials, such as concretes employing different aggregates, the data tend to be scarce and subject to much variation. The amount of thermal movement will depend not only on the coefficient of linear expansion, which is determined in tests under stress-free conditions, but also on the restraint imposed by adjoining construction. With metals this does not present a problem in the elastic range because metals are Hookean materials; that is, stress is proportional to strain. With inorganic composite materials, such as concrete, Hookean behaviour cannot be assumed due to cracking and phenomena associated with loss of water and phase changes in the cement matrix and aggregate upon heating.

When a solid material is heated it increases in length according to the equation:

$$L_t = L_0(1 + \alpha T + \alpha_1 T^2 + \alpha_2 T^3)$$

where L_0 = length at the initial temperature, and L_t = length after a temperature rise of T.

For pure metals, the constants α, α_1 and α_2 have values of the order of 10^{-5}, 10^{-11} and 10^{-14} respectively. Because α_1 and α_2 are small compared with α, the following relation is adequate for most purposes:

$$L_t = L_0(1 + \alpha T)$$

where α is the coefficient of linear thermal expansion. BS 5950: Part 1: 1985 [2] gives a value of $\alpha = 12 \times 10^{-6}$/°C.

2.2. Variation of thermal expansion with temperature, and phase transformation

Precise determinations of the thermal movement of 22 different steels at elevated temperatures were reported [7] in 1952 by the National Physical Laboratory for the British Iron and Steel Research Association. Data for three steels with markedly different carbon contents (annealed at 930 °C) are reproduced in Table 2 which is taken from Table IVA of ref. 7. Steels 1, 2 and 3 had carbon contents of 0.06%, 0.23% and 0.415%, respectively. Structural steel is nearest to steel 2 in chemical composition for which α varies from a mean value of 12.18×10^{-6}/°C in the range 0 - 100 °C to 14.81×10^{-6}/°C in the range 0 - 1200 °C. Over the range 0 - 550 °C, the mean value is 14.17×10^{-6}/°C. Since this is the temperature range of main interest concerning the behaviour of structural steel in fire, it appears that a nominal value of 14×10^{-6}/°C is a sensible choice. This is the value adopted in a comprehensive set of recommendations [8] by the European Convention for Constructional Steelwork for the design of steel structures exposed to the standard fire (called the ECCS Recommendation in this paper). This is also the value adopted in the draft BS 5950: Part 8. The data in Table 2 apply only to mild steel:

TABLE 2

Mean coefficients of thermal expansion of carbon steels over different temperature ranges

Steel	Mean coefficient of expansion (×10^{-6}/°C) over temperature ranges (°C)											
	0 - 100	0 - 200	0 - 300	0 - 400	0 - 500	0 - 600	0 - 700	0 - 800	0 - 900	0 - 1000	0 - 1100	0 - 1200
1	12.62	13.08	13.46	13.83	14.25	14.65	15.00	14.72	12.89	13.79	14.65	15.37
2	12.18	12.66	13.08	13.47	13.92	14.41	14.88	12.64	12.41	13.37	14.16	14.81
3	11.21	12.14	13.00	13.58	14.05	14.58	14.85	11.84	12.65	13.59	14.36	15.00

for a high alloy steel, α is higher and varies, for instance, from 13.88 to 19.59×10^{-6}/°C over temperature ranges of 0 - 50 °C and 0 - 1200 °C, respectively, for a stainless steel (18% chromium/8% nickel).

Table 2 also shows that α gradually increases as the temperature increases up to approximately 700 °C and then temporarily reduces with further increase in temperature. This is caused by a phenomenon called phase transformation. The temporary sudden shrinkage is caused by a transformation of pearlite to austenite, and is accompanied by a rearrangement in the atomic structure from the body-centred cubic structure to the face-centred cubic structure. The phenomenon is explained by Walker [9] and Kennedy *et al.* [10]. The temporary shrinkage is roughly 15% of the expansion for a temperature range of 20 - 700 °C. The reverse occurs upon cooling but not at the same temperature (see below), but this is of no importance in fire engineering analyses.

Some typical thermal expansion–temperature curves in the phase transformation range are shown in Fig. 1. These are taken from ref. 7 and apply to steels of low and medium carbon content. The shapes of the curves are clearly dependent on carbon content: the magnitude of the dip varies, and while the 0.43% C and 0.23% C steels commence their phase transformation at around 720 °C, the 0.06% C steel does not until around 800 °C. These and other data in ref. 7 suggest that the temperatures at which phase transformation begin and end vary markedly with chemical composition.

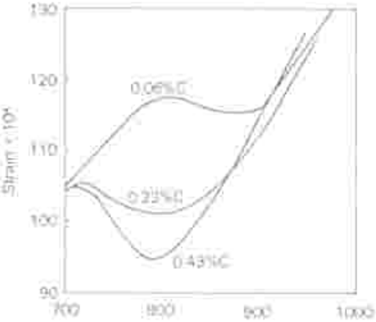

Fig. 1. Thermal expansion–temperature curves for low and medium carbon steels in the phase transformation range.

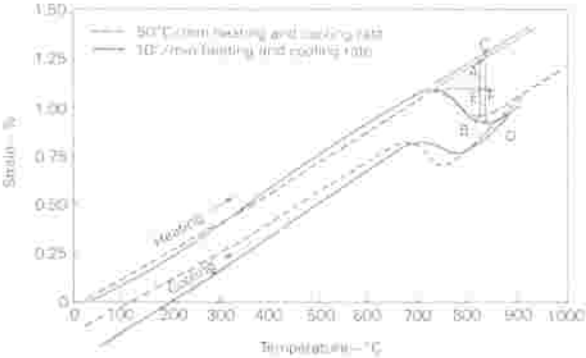

Fig. 2. Dilatometer curves for a mild steel showing effect of different heating and cooling rates.

In real fires and standard furnace tests (for example, ISO 834), steel members are heated at different rates. To determine if variation of heating rate would affect the magnitude of shrinkage and temperature of onset of phase transformation, BSC was commissioned to conduct tests using its high precision MMC High Speed Vacuum Dilatometer. Two specimens were taken from the same piece of structural steel containing 0.28% C and 0.67% Mn. One was tested at a heating/cooling rate of 10 °C/min, the other at 50 °C/min. Figure 2 shows these data. During heating, marked contraction commenced at approximately 730 °C and ceased at approximately 830 °C, irrespective of heating rate. The magnitude of contraction is, referring to Fig. 2, distance EB and distance FD, for the two heating rates: this is 0.15% and 0.2% strain for the heating rates of 50 °C/min and 10 °C/min, respectively. It is also clear from Fig. 2 that ignorance of phase transformation would lead to an overestimate of strain at temperatures above 830 °C of 0.30% and 0.38% for heating rates of 50 and 10 °C/min respectively (derived from lengths AB and CD).

The question may be asked "Is phase transformation an important factor affecting the behaviour of structural steel?" Cooke has reported [11] the structural response of model steel I-section beams and columns heated along one flange when subjected to various load conditions. The measured central displacement–time curve for a non-loaded, one-third-scale beam (nominally 1500 mm long × 100 mm deep) in Fig. 3 clearly exhibits a temporary reduction in rate of increase of displacement when the heated flange temperature enters the phase transformation range. However, in practice, a steel beam in a

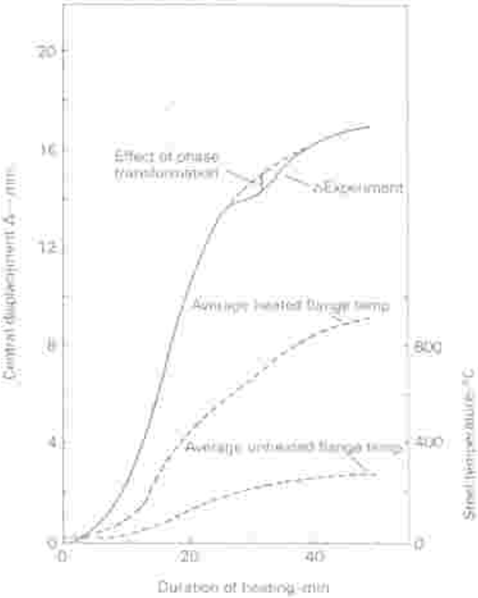

Fig. 3. Central displacement of a non-loaded steel beam heated along one flange showing effect of phase transformation.

building is likely to be carrying its maximum permissible load and would normally yield and fail by excessive displacement before reaching the phase transformation temperature.

3. ELASTIC–PLASTIC BEHAVIOUR

3.1. Stress–strain at room temperature

If a bar of homogeneous material, such as steel, of cross-sectional area A and gauge length L is mounted in a tensile testing machine and a load P is applied, the bar will elongate by an amount δ. If, on removal of the load, the elongation disappears, the material is said to be elastic. If, on the other hand, there is residual elongation, the material is said to have passed the elastic limit and become plastic. Figure 4 shows the typical behaviour of mild steel when tensile-tested at room temperature [12]. The elastic limit is reached at a strain (elongation/original length) which is small, roughly 0.15%. Up to the elastic limit, it is found that stress (direct tensile load/cross-sectional area) is proportional to strain, and this is shown by the constant slope of the stress–strain curve up to point A in Fig. 4. At point A (the yield point), the material is said to have yielded and the corresponding stress is the yield stress. It is clear from Fig. 4 that the strain at the elastic limit, typically 0.15%, is a very small portion of the total strain to failure, which can be 30% at room temperature.

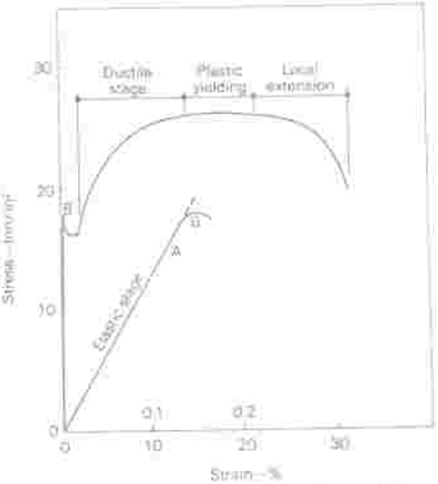

Fig. 4. Stress–strain curve for mild steel taken to failure at 20 °C.

The elastic modulus E, also called Young's modulus, is the ratio of stress to the strain it produces, i.e., $E = \sigma/e$ and for the bar of material $E = PL/A\delta$. It represents the stress required to produce unit strain. This linear relation between stress and strain up to the elastic limit has a profound simplifying effect upon structural analyses, and analyses are often classified as elastic or plastic.

3.2. Stress–strain at elevated temperatures

As steel is heated above a temperature of about 150 °C, its strength reduces, the strain increases for a given stress, and the slope of the initial part of the stress–strain graph reduces. Therefore the elastic modulus (the initial slope) reduces with increasing temperature. Figure 5 shows a family of stress–strain curves for mild steel at different temperatures given by Harmathy [13].

At elevated temperatures, the clearly defined yield point vanishes and the concept of yield stress is invalid. An alternative is to adopt the proof stress concept. Figure 6 shows a curved stress–strain diagram. If a tangent to the curve at the origin is drawn (OA) and a line BC is drawn parallel to line OA such that distance OB is 0.2%, then the stress at point C is called the 0.2% proof stress. In other words the 0.2% proof stress is the stress required to produce a permanent strain of 0.2%.

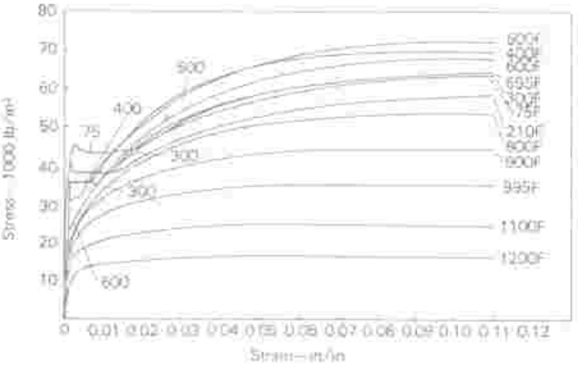

Fig. 5. Stress–strain curves for an ASTM A36 steel at different elevated temperatures.

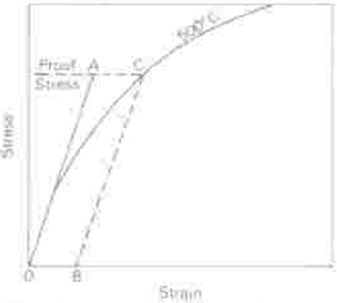

Fig. 6. Concept of proof stress.

3.3. Anomalies in elastic modulus data at elevated temperatures

A comparison of elevated temperature elastic modulus data quoted in international literature reveals that there is little agreement for steel grades within the family of structural steels. There may be several reasons for this and some, relevant to the tensile test method (static test), are listed below.

(1) Different tensile test machines have different accuracies for measuring very small strains and for achieving a uniform and accurately known temperature over the entire gauge length.

(2) Inaccuracy in strain measurements will mean that the shape of the stress–strain curve is affected and, of major importance, the shape of the curve near the origin. This can make it very difficult to plot a tangent to the curve and, since the slope of the tangent at the origin is the elastic modulus, inaccuracies in tangent plotting produce inaccuracies in E.

(3) Most static testing has adopted the isothermal test method in which the specimen is taken up to, and maintained thereafter at, a constant temperature (i.e., isothermally). When the specimen has achieved the prescribed temperature over the entire gauge length, which usually requires a soaking period, the machine is programmed to apply a constant rate of strain and the corresponding stress is measured. However, there is an alternative test method — the anisothermal test — in which the stress is maintained constant while the temperature is increased at a prescribed rate and the corresponding strains are measured.

In practice, the isothermal test is relevant to a structure in which the temperature is constant and the stress fluctuates, as in a steel boiler for instance. In building structures subjected to fire, it is argued that the applied load is constant (as on a floor above the fire, for instance) while the temperature varies, so that anisothermal data should be used in an analysis. There are situations, however, where the load and temperature vary with time (for instance, in a lightly loaded continuous beam with temperature gradients across the section such as to cause thermal bowing and varying restraint forces at the supports) and it is then not clear whether isothermal or anisothermal data should be used.

Graphs of strain versus temperature are obtained from anisothermal tests, and graphs of stress versus strain from isothermal tests, and it is therefore clear by which method the data have been obtained. However, isothermal and anisothermal data can be used to produce elastic modulus data (see later), and the problem is that the test method used may not be mentioned.

(4) The researcher may not have subtracted the thermal strain from the measured strain before plotting the stress–strain curve. Deducting the thermal strain results in higher derived E values; this can only affect the interpretation of anisothermal tests. However, it is most unlikely that such a fundamental factor would be overlooked.

(5) Differences in chemical composition of test specimens can affect the strain. For instance, small amounts of aluminium added to give improved notch toughness can result in larger plastic strains.

(6) At high temperatures, the soaking period prior to application of stress in an isothermal test can relieve residual stresses

and regularize the grain structure, causing grains elongated in the hot rolling process to return to their original shape, which could result in shrinkage such that the measured strain in a tensile test is reduced.

(7) Different researchers may have adopted different rates of strain. A fast rate of strain in the isothermal test would be expected to result in higher measured stresses than a slow rate. It should be noted that BS 3688: Part 1: 1963 [14], which deals with tensile testing of metals at elevated temperatures, prescribes a rate of strain within the range of 0.001 - 0.003 per minute near the elastic limit, but other countries may adopt different rates.

There is, however, yet another important reason for the differences in reported *E* values. There is, in addition to the static test described above, a dynamic test. In the static test, the measured strain in the specimen includes thermal strain and elastic strain and also, depending upon the stress level and temperature, plastic and creep strains. In the dynamic test, the specimen is usually a wire caused to vibrate, and *E* is determined from the measured frequency of vibration at each temperature. The stress reversals are sufficiently rapid to prevent plastic and creep strains from occurring and this is the principal reason why, for a given steel at a given temperature, the dynamically derived *E* value is greater than the statically derived value.

It is also possible that researchers concerned with structural analyses will adopt an *E* versus temperature relationship which, though falling within the scatterband of experimentally determined *E* values, is chosen so that it best correlates with benchmark data, such as flexural displacement, for the experiment. In other words, the *E* values used are those which provide the best correlation of theory and experiment for the member (e.g., beam or column) under consideration.

From the foregoing discussion it is clear that *E* can be determined from dynamic tests and from isothermal or anisothermal static tests. If *E* is defined as the initial slope of the stress–strain curve then, in principle, there should be no difference between the *E* values obtained by each of the test methods for a given temperature.

3.4. Review of elevated temperature stress–strain data

The first major British work on the elevated tensile properties of steels up to 800 °C was reported by Woolman and Mottram in 1964 [1]. A comprehensive study was made by Skinner *et al.* [15] in 1972 at the Australian Broken Hill Proprietary (BHP) Company Ltd. Other studies have been reported by Witteveen [16, 17], Anderberg [18], and Harmathy and Stanzak [13]. A comprehensive review [19] has been made by Anderberg for Rilem Committee 44-PHT.

Crook has examined, among other British steels, the tensile strength properties of hot rolled mild steel reinforcing bars, of grade similar to the BS 4360 grade 43 structural steels, up to 700 °C under isothermal test conditions. Lengths of full-size bars were tested by heating the specimen up to the test temperature, leaving it to soak for 30 minutes, then loading at a rate of 0.001 - 0.003 strain per minute according to BS 3688. Figure 7 (consolidating Figs. 7.8, 7.9 and 7.10 of ref. 20) shows the variation of *E* with temperature: *E* at 550 °C has reduced to about 65% of the room temperature value, and there is some scatter in the results. A summary of the tests has been reported by Holmes *et al.* [21].

The ECCS Recommendations [8] include a recommendation for the variation of *E* with

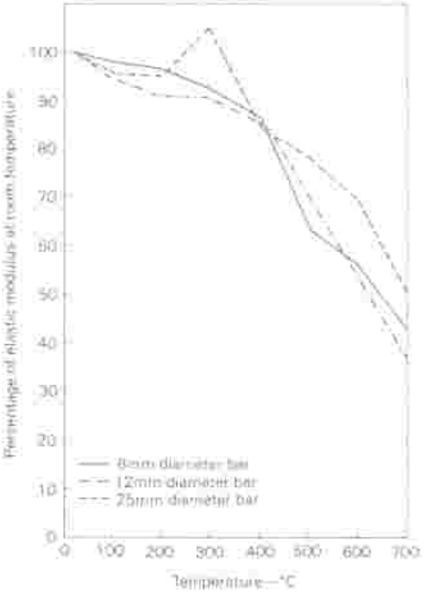

Fig. 7. Elastic modulus–temperature curves for hot rolled mild steel reinforcing bars, Crook data.

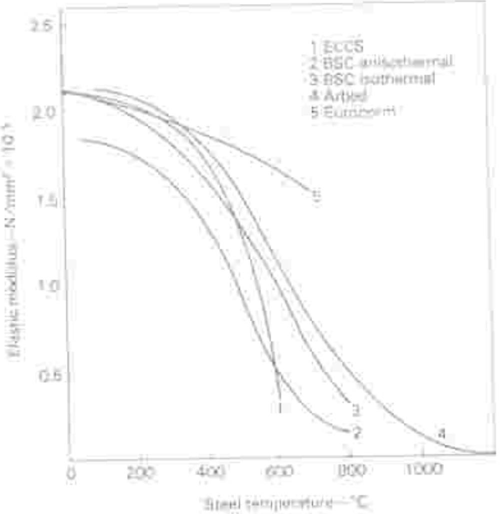

Fig. 8. Variation of elastic modulus with temperature.

temperature for use in analytical studies of structural steel. The curve (Fig. r-3 in ref. 8) is shown in Fig. 8. The comment accompanying the ECCS recommendation states that E is the tangent modulus for $\sigma \rightarrow 0$ and is not defined for temperatures above 600 °C because the effect of creep has to be analysed explicitly for such temperatures.

BSC considered that the ECCS elastic modulus data were too conservative when compared with the results of an international survey it had made in 1980 [22]. Included in this survey were many dynamically and some statically derived data for different grades (FE310, 360, 430 and 510) of Euronorm 25-1972 structural steel, which the writer has averaged to obtain the curve also shown in Fig. 8. Subsequently, Kirby [23] produced isothermal E data, Fig. 8.

A further E versus temperature relation (curve 4, Fig. 8) was reported in 1986 by Schliech [24] of the Luxembourg steel company Arbed. This is used in Arbed's finite element computer program (CEFICOSS) for analysing the behaviour in fire of composite I-section steel/concrete beams and columns.

Jerath *et al.* of BSC reported [25] in 1980 a study of the isothermal tensile properties of about 15 different low carbon steels which fell between grades 43A and 50D of BS4360: 1979, the specification for weldable structural steels [26]. (Note that this edition of the BS stipulates that grade 43 has a tensile strength in the range 430 - 510 N/mm^2 and a minimum yield strength of 255 N/mm^2, while grade 50 has a tensile strength in the range 490 - 620 N/mm^2 and a minimum yield strength of 355 N/mm^2, both for a steel thickness less than 16 mm — some of these values have changed in the 1986 edition.) An important objective was to establish a relationship between 1% proof stress and temperature since the authors had observed that full-size unprotected steel beams heated on three sides and exposed to the standard fire were at the point of failure (mid-span deflection > span/30 according to BS 476: Part 8: 1972 [27]) when the plastic strain exceeded 1%. Some stress–strain curves were also presented and Fig. 9 (Fig. 20 in ref. 27) illustrates data for a grade 43A steel.

The BSC test programme was extended to provide anisothermal test data for structural steels. The test variables were chemical composition and strength for different grades of steel, heating rate, and level of applied stress. Preliminary results by Kirby [28] showed moderate agreement with the data derived by BHP [15] for the 1% total strain temperature, Table 3.

BSC's anisothermal test work was taken further and completed in 1983. Kirby [29]

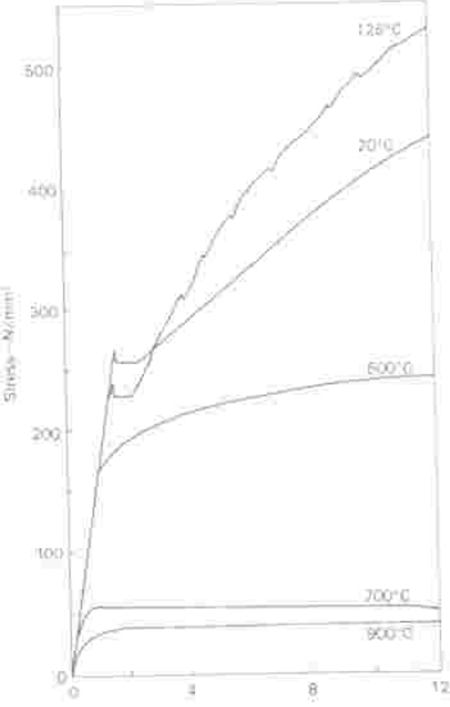

Fig. 9. Elevated temperature stress–strain curves for BS 4360: grade 43A steel.

TABLE 3

1% total strain temperatures for different stress levels for structural steels

$\frac{\sigma_{\text{applied}}}{\sigma_{\text{yield at 20 °C}}}$	Temperature (°C) at 1% strain (Heating rate 10 °C/min)	
	BHP data	BSC data
0.66	571 - 574	545
0.33	670 - 676	644
0.17	745	721

has reported the results. Grades 43A and 50B of BS 4360: 1979 steel were tested. These are said to represent 98% of the structural steel sections manufactured by BSC, and have room temperature properties corresponding approximately to Euronorm 25-72: FE 430 and Fe 510, respectively. The heating rates were 20, 10, 5 and sometimes 2.5 °C/min, corresponding to failure times in the range of 0.5 - 4 hours in the BS 476: Part 8: 1972 fire resistance test for steel beams, assuming a limiting (failure) temperature of approximately 600 °C. The applied stress, which was maintained constant in each test, varied from 15 to 250 N/mm^2 for grade 43A and from 15 to 400 N/mm^2 for grade 50B and, wherever possible, each test was continued to 5% strain. A typical family of strain–temperature curves taken from ref. 29 is shown in Fig. 10. These curves are for a grade 43A steel heated at 10 °C/min having a measured room-temperature yield stress of 267 N/mm^2. The strains are the sum of the elastic and plastic components, the thermal strains having been previously deducted. They show several important features:

(1) the occurrence of large initial strains at relatively low temperature when the stress level is high and yielding occurs. For instance, a strain of 0.5% occurs at a temperature of roughly 200 °C for a stress of 250 N/mm^2 corresponding to a stress level of 0.936;

(2) the onset of large rates of strain for little increase in temperature, sometimes called 'runaway displacement' in beam tests;

(3) the effect of phase transformation which shows itself at temperatures around 720 °C for the lowest stress.

From the strain–temperature curves, such as those shown in Fig. 10, it is possible to produce stress–strain relationships and thus elastic modulus–temperature curves. Each stress–strain relationship is produced for the relevant temperature in the following way. Assume the stress–strain curve for 500 °C is required. Using Fig. 10, a vertical line is drawn at 500 °C and the strain at A noted corresponding to a stress of 25 N/mm^2. Similarly, the strain at B is read off corresponding to 50 N/mm^2, and so on for points C to E. If, instead of stress, the ratio of applied stress to room-temperature yield stress is required, then a family of strength reduction factor versus strain curves can be derived. Using this procedure and the data reported by Kirby and Preston [30], the anisothermal E–temperature curve in Fig. 8 was produced.

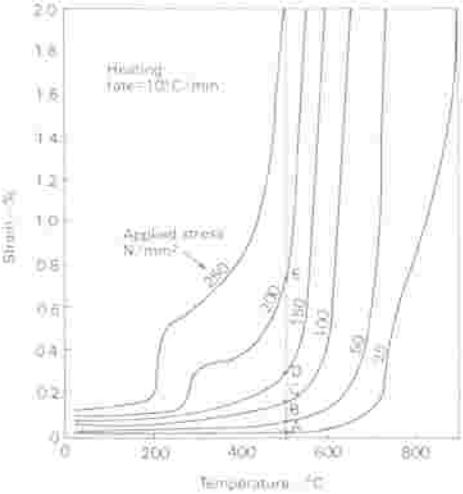

Fig. 10. Elevated temperature anisothermal strain–temperature curves for BS 4360: grade 43A steel.

3.4. *Idealized stress–strain data at elevated temperatures*

Many finite element computer programs require input of the stress–strain curves as bi-linear or multi-linear idealizations for each temperature. The program then linearly interpolates values of stress and strain for intermediate temperatures.

Making the idealizations is not easy if the elastic and plastic domains are to be idealized bi-linearly, that is, using one straight line to represent the elastic modulus and another to represent the plastic modulus. The difficulty can be appreciated from Fig. 11 which shows a single stress–strain curve corresponding to a particular temperature — in this example an isothermal curve for 500 °C. Two extreme,

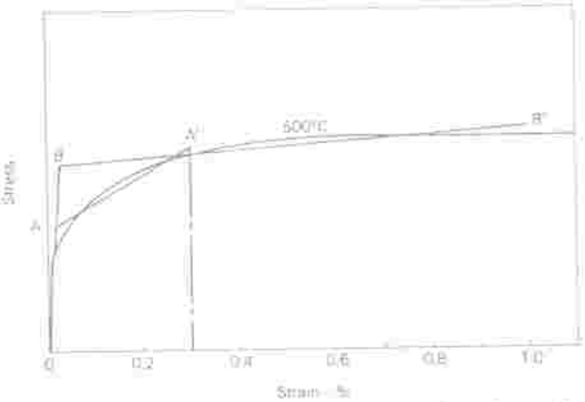

Fig. 11. Possible alternative bi-linear idealizations of a stress–strain curve used for computing purposes.

but plausible alternative bi-linear idealizations, are shown by OAA' and OBB'. It will be apparent that OAA' may be appropriate for strains up to 0.3% but will overestimate the stress at higher strains. OBB', on the other hand, is a good fit for large strains but greatly overstates the stress at the knee, B. Another problem is that small increases in stress above the knee cause large increases in strain and this could result in many computer iterations if the load steps are not small.

The problem of choosing a best-fit bi-linear curve is clearly made easier if the strain range can be minimized. Alternatively, the problem can be minimized using multi-linear idealizations.

CONCLUSIONS

This paper has given a brief survey and explanation of the mechanical properties of structural steel at elevated temperatures. It has shown that values of Poisson's ratio and coefficient of linear thermal expansion of 0.3 and $14 \times 10^{-6}/°C$, respectively, are generally accepted for fire analyses.

Phase transformation, particularly the temperature of onset and magnitude of dip, appears to be sensitive to chemical composition. For a composition typical of a BS 4360: grade 43 steel, different rates of heating (10 °C/min and 50 °C/min) have little effect upon the phase transformation curve during heating. Phase transformation is only likely to appear in displacement data for members operating under a low stress level; for high levels typical of those normally adopted in building design, failure of a member by yielding and large displacement will precede and obscure the effects of phase transformation.

There is not, within Europe at least, a widely accepted model of the variation of elastic modulus with temperature (Fig. 8), but attempts to rectify this situation are being made by the European Convention for Constructional Steelwork Fire Committee. Some reasons for differences in measured values of elastic modulus derived isothermally or anisothermally have been given. However, since steel members such as beams and columns exposed to fire fail in the plastic domain, when the plastic strain is usually many times greater than the elastic strain, differences, even large differences, in elastic modulus may not be important. The more important task is to reach uniformity in a material model for stress–strain curves for a range of temperatures for use in computer programs.

ACKNOWLEDGEMENT

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LIST OF SYMBOLS

A	cross-sectional area
e	strain
E	elastic modulus
L	length
L_0	initial length
L_f	final length
P	force
T	temperature, temperature rise
α	coefficient of thermal expansion
Δ	displacement
δ	elongation
ν	Poisson's ratio
σ	stress

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