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The stress-strain behaviour of carbon steel at high temperatures is essentially different from that at ambient temperature, without a clear yield plateau but strain hardening occurring all the way in the plastic range. Figure 6 shows the stress-strain curves of grade 43A (i.e. S275) steel at elevated temperature, plotted from British Steel data (Kirby & Preston 1988). British Steel Corporation (now named as Corus) carried out an extensive small-scale tensile test programme in 1980s on BS4360: Grades 43A and 50B steels to provide elevated temperature data for structural fire engineering design applications. To represent the behaviour of beams and columns in large scale tests, the heating rates were set at the range 5 to 20°C/min. The stress-strain curves shown in Figure 1 were derived from the transient-state tests on grade 43A steel with a heating rate of 10°C/min.

The test results show that carbon steel begins to lose strength at temperatures above 300°C and reduces in strength at a steady rate up to 800°C. The well defined yield plateau at 20°C is replaced by a gradual increase of strength with increasing strain (or strain-hardening) at high temperatures. Such characteristics make it very difficult to define the strength of steel at high temperatures which is an important parameter in fire structural design. Instead of fixing a single strain limit for yield strength at elevated temperatures (such as the 0.2% proof strength at 20°C), BS5950-8 (2003) suggests three strain limits of 0.5%, 1.5% and 2% according to the member types (see Table 1).

For a given strain, the reduced strength of steel at a particular temperature can be determined from the experimental stress-strain curve at that temperature. For instance, the reduced steel strengths of approximate 171, 208 and 213 N/mm2 corresponding to the strain limits of 0.5%, 1.5% and 2% respectively have been obtained from the stress-strain curve of steel at 500°C in Figure 1. The strength reduction factors (i.e. the ratio of the steel strength at a temperature relative to its yield strength at 20°C) can then be calculated. Figure 2 presents the strength reduction factors of Grade 43A steel with increasing temperature at the three strain limits, as recommended by BS5950-8.

The use of the British Steel data in BS5950-8 was justified by large scale beam and column tests. The loaded fire tests on bare steel beams showed that high strains in excess of 3% were developed. Excluding the thermally-induced curvature, the stress-related strains were of the order of 2 to 3%. Thus a conservative strain limit of 1.5% has been selected for the fire design of steel beams (Lawson & Newman 1990). Consequently, the strain limit was increased to 2% in composite beams design because higher strains were normally developed in composite beams than in steel beams at a given deflection, due to the composite action of the slabs supported by the beams. For columns and structural members protected with fire protection materials of poor stickability, a strain limit of 0.5% was considered to be appropriate.

Based on the British Steel data, EN1993-1.2 derives the reduction factors for effective yield strength, proportional limit and slope of linear elastic range as given in Table 2. The effective yield strength is related to 2% strain limit. Figure 3 illustrates the variation of the reduction factors with temperature. The strength reduction factor at 2% strain of BS5950-8 is also plotted for comparison.

The definitions of effective yield strength, proportional limit and slope of linear elastic range are established on the basic characteristic of the stress-strain model for steel at high temperatures proposed by EN1993-1.2. Figure 4 shows that the first part of the curve is a linear line progressing up to the proportional limit $f_{p,\theta}$ and the elastic modulus $E_{a,\theta}$ is equal to the slope of this straight-line segment. The second part of the curve depicts the transition from the elastic to the plastic range. This region is formulated by an elliptical progression up to the effective yield strength $f_{y,\theta}$. The third part of the curve is a flat yield plateau up to a limiting strain for yield strength. The last part of the curve is characterised by a linear line decreasing to zero stress at the ultimate strain.

Basically, the slope of linear elastic range governs the steel stiffness, whereas the effective yield strength governs the strength. Comparing their reduction factors at elevated temperatures, it can be seen that the stiffness of steel reduces earlier and more rapid than the strength. This indicates that the failure mode of steel members may change at elevated temperatures. For instance, a steel beam made of slender I-section, which is designed to plastic-hinge failure under ultimate load at ambient temperature, may experience the premature failure of web buckling at elevated temperatures.

EN1993-1-2 provides detailed mathematical formulae of stress-strain relationships of steel at elevated temperatures as shown in Figure 4. The effect of creep is implicitly considered and the material models are applicable for heating between 2 and 50 K/min.

Based on the mathematical formulae provided by EN1993-1-2, a series of stress-strain curves at elevated temperatures have been constructed for S273 steel as shown in Figure 5. The original British Steel data are also included for comparison. Although the formulae cannot provide perfect fitting with the test data at all temperatures, the correlation at temperatures above 400°C is in good agreement. Generally, the lack of accuracy at low temperatures below 400°C will not hinder the accurate prediction of fire resistance of steel structures in practice. This is because the actual loads applied to most buildings are commonly below 60% of the ultimate loads they are designed for at ambient temperature. That means the structures will generally have a minimum inherent fire resistance of 500°C.

EN1993-1-2 further extends the stress-strain relationship to include strain-hardening for steel temperatures below 400°C, providing local or overall buckling does not lead to premature collapse. In this case, the mathematical formulae in Figure 4 need to be modified according to Figure 6. Figure 7 shows the stress-strain relationships for S275 steel at elevated temperatures, allowing for strain hardening.