1.6 Steel structures subjected to fire

In this section a brief review of aspects of structural steel work subjected to fire is given. The strength of all engineering materials reduces as their temperature increases. Steel is no exception. However, a major advantage of steel is that it is incombustible and it can fully recover its strength following a fire, most of the times. During the fire steel absorbs a significant amount of thermal energy. After this exposure to fire, steel returns to a stable condition after cooling to ambient temperature. During this cycle of heating and cooling, individual steel members may become slightly bent or damaged, generally without affecting the stability of the whole structure. From the point of view of economy, a significant number of steel members may be salvaged following a post-fire review of a fire affected steel structure. Using the principle " If the member is straight after exposure to fire – the steel is O.K", many steel members could be left undisturbed for the rest of their service life. Steel members which have slight distortions may be made dimensionally reusable by simple straightening methods and the member may be put to continued use with full expectancy of performance with its specified mechanical properties. The members which have become unusable due to excessive deformation may simply be scrapped. In effect, it is easy to retrofit steel structures after fire. On the other hand concrete exposed to fire beyond say 600oC, may undergo an irreversible degradation in mechanical strength and spolling However it is useful to know the behaviour of steel at higher temperatures and methods available to protect it from damage done to fire. Provisions related to fire protections are given in section 16 of the IS 800 code.

1.6.1 Fire loads and fire resistance

Table 1.5 Fire load on steel structures

Examples of fire load in various structures	
Type of steel structure	Kg wood / m^2
School	15
Hospital	20
Hotel	25

Office	35
Departmental store	35
Textile mill show room	>200

The term 'fire load' in a compartment of a structure is the maximum heat that can be theoretically generated by the combustible items and contents of the structure. The fire load could be measured as the weight of the combustible material multiplied by the calorific value per unit weight. Fire load is conveniently expressed in terms of the floor space as MJ/m^2 or $Mcal/m^2$. More often it would be expressed in terms of equivalent quantity of wood and expressed as Kg wood / m^2 (1 Kg wood = 18MJ). The commonly encountered fire loads are presented in Table 1.5. The values are just an indication of the amount of fire load and the values may change from one environment to the other and also from country to country.

The fire ratings of steel structures are expressed in units of time ½, 1, 2, 3 and 4 hours etc. The specified time neither represents the time duration of the real fire nor the time required for the occupants to escape. The time parameters are basically a convenient way of comparative grading of buildings with respect to fire safety. Basically they represent the endurance of structural steel elements under standard laboratory conditions. Fig. 1.18 represents the performance of protected and unprotected steel in a laboratory condition of fire. The rate of heating of the unprotected steel is obviously quite high as compared to the fire-protected steel. We shall see in the following sections that these two types of fire behaviour of steel structure give rise to two different philosophies of fire design. The time equivalence of fire resistance for steel structures or the fire rating could be calculated as

$$T_{eq}\,(\text{Minutes}) = CWQ_f \qquad \textbf{\textit{(1.4)}}$$

Where Qf is the fire load MJ/m^2 which is dependent on the amount of combustible material, 'W' is the ventilation factor relating to the area and height and width of doors and windows and 'C' is a coefficient related to the thermal properties of the walls, floors and ceiling. As an illustration, the "W" value for a building with large openings could be chosen as 1.5 and for highly insulating materials "C" value could be chosen as 0.09.

We need to know about the mechanical properties of steel at elevated temperatures in the case of fire resistant design of structural steel work. The variations of the non-dimensional modulus of elasticity, yield strength and coefficient of thermal expansion with respect to temperature are shown in Fig1.19. The corresponding equations are given below (Cl.16.5). The variation of modulus of elasticity ratio $\bar{E}$ with respect to the corresponding value at 20^oC, with respect to temperature is given by

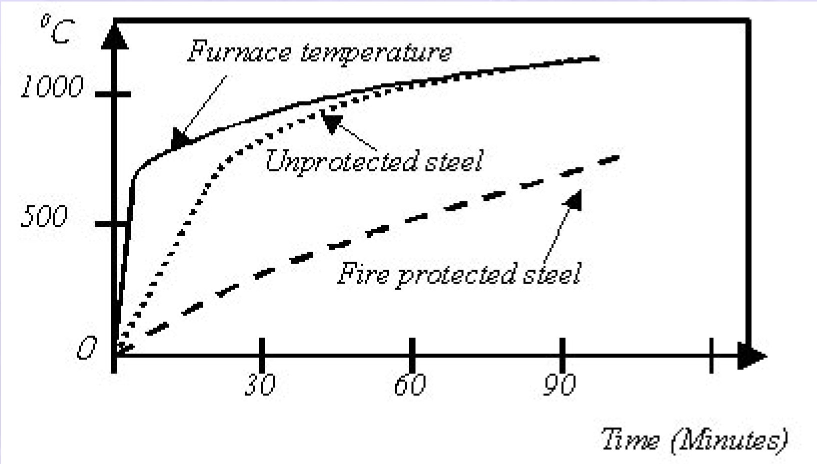

Fig 1.18 Rate of heating of structural steel work

$$\bar{E} = \frac{E(T)}{E(20^0C)} = 1.0 + \frac{T}{2000\ln\left[\frac{T}{1100}\right]} \text{ for } 0^0C < T < 600^0C \qquad \textbf{(1.5)}$$

$$= \frac{690\left(1.0 - \frac{T}{1000}\right)}{T - 53.5} \text{ for } 600^0C < T < 1000^0C$$

The yield stress of steel remains unchanged up to a temperature of about 215^oC and then loses its strength gradually. The yield stress ratio $\bar{f}$ (with respect to yield stress at 20^oC) vs. temperature relation is given by

$$\bar{f} = \frac{f_{y(T)}}{f_y(20)} = 1.0 \qquad 0^0C < T < 215^0C$$

$$= \frac{905 - T}{690} \qquad 215^0C < T < 905^0C \qquad \textbf{(1.6)}$$

Similarly the coefficient of thermal expansion also varies with temperature by a simple relation

$$\alpha(T) = \left(12.0 + \frac{T}{100}\right) x10^{-6} \quad \left({}^{0}C\right)^{-1} \qquad \textbf{(1.7)}$$

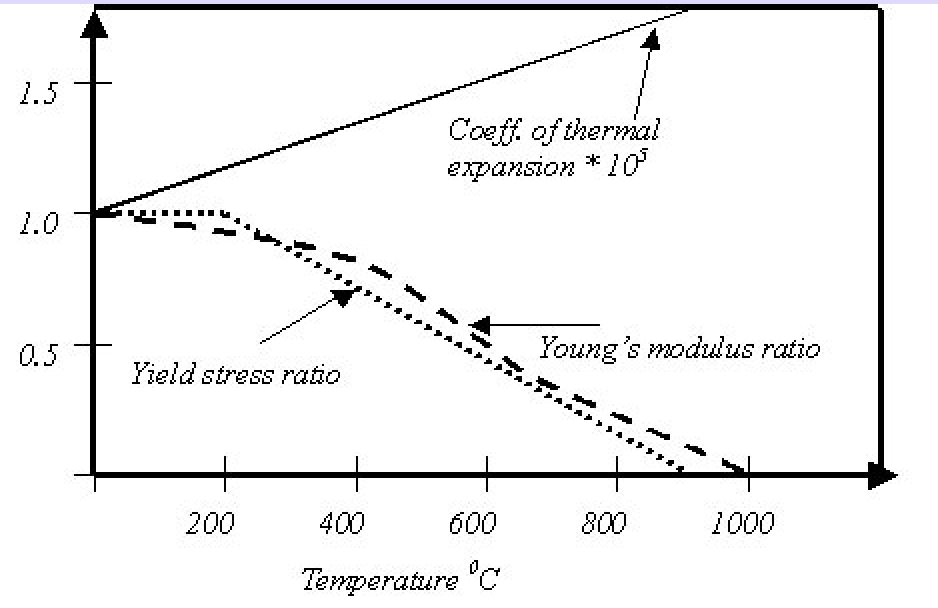

Fig 1.19 Mechanical properties of steel at elevated temperatures

These equations are very useful when one is interested in the analysis of steel structures subjected to fire.

In the codes of practice for steel structures subjected to fire, strength curves are generally provided for structural steel work at elevated temperatures. In these curves the strain at which the strength is assessed in an important parameter. For example the BS: 5950 part 8 has used 1.5% strain as the strain limit as against 2% for Eurocode 3 Part10. A lower strain of 0.5% may be used for columns or components with brittle fire protection materials.

Fire resistant steel

Fire safety in steel structures could also be brought about by the use of certain types of steel, which are called 'Fire Resistant Steels (FRS)'. These steels are basically thermo-mechanically treated (TMT) steels which perform much better structurally under fire than the ordinary structural steels. These steels have the ferrite – pearlite microstructure of ordinary structural steels but the presence of Molybdenum and Chromium stabilises the microstructure even at 600^{o}C. The composition of fire resistant steel is presented in Table.1.2

Table 1.5 Chemical composition of fire resistant steel

C		Mn	Si	S	P	Mo + Cr
FRS	≤0.20%	≤1.50%	≤0.50%	≤0.040%	≤0.040%	≤1.00%
Mild Steel	≤0.23%	≤1.50%	≤0.40%	≤0.050%	≤0.050%	-

The fire resistant steels exhibit a minimum of two thirds of its yield strength at room temperature when subjected to a heating of about 600^{o}C. In view of this, there is an innate protection in the steel for fire hazards. Fire resistant steels are weldable without pre-heating and are commercially available in the market as joists, channels and angles.

1.6.2 Fire engineering of steel structures

The study of steel structures under fire and its design provision are known as 'fire engineering'. The basic idea is that the structure should not collapse prematurely without giving adequate time for the occupants to escape to safety. As briefly outlined earlier, there are two ways of providing fire resistance to steel structures. In the first method of fire engineering, the structure is designed using ordinary temperature of the material and then the important and needed members may be insulated against fire. For the purpose of fire protection the concept of 'section factor' is used. In the case of fire behaviour of structures, an important factor which affects the rate of heating of a given section, is the section factor which is defined as the ratio of the perimeter of section exposed to fire (Hp) to that of the cross-sectional area of the member (A). As seen from Fig. 1.20, a section, which has a low (Hp/A) value, would normally be heated at a slower rate than the one with high (Hp/A) value, and therefore achieve a higher fire resistance. Members with low Hp/A value would require less insulation. For example sections at the heavy end (deeper sections) of the structural range have low Hp/A value and hence they have slow heating rates. The section factor can be used to describe either protected or unprotected steel. The section factor is used as a measure of whether a section can be used without fire protection and also to ascertain the amount of protection that may be required. Typical values of Hp of some fire-protected sections are presented in Fig. 1.21.

In the second method of fire engineering, the high temperature property of steel is taken into account in design using the Equations 1.5, 1.6and 1.7. If these are taken into account in the design for strength, at the rated elevated temperature, then no insulation will be required for the member. The structural steel work then may be an unprotected one. There are two methods of assessing whether or not a bare steel member requires fire protection. The first is the load ratio method which compares the 'design temperature' i.e. maximum temperature experienced by the member in the required fire resistance time, and the 'limiting temperatures', which is the temperature at which the member fails.

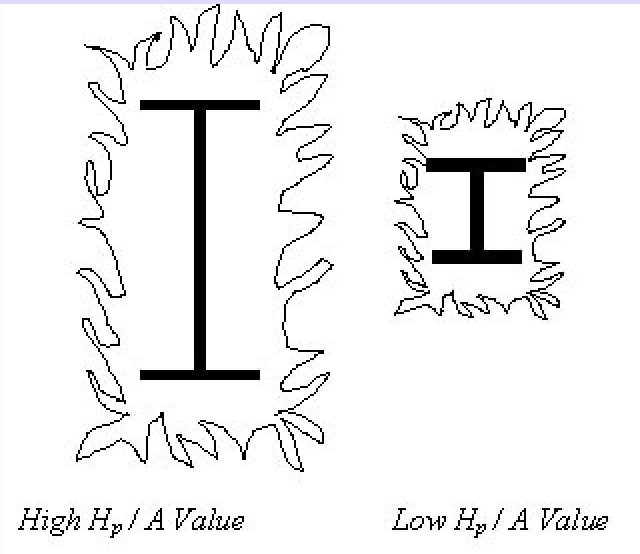

Fig 1.20 The section factor concept

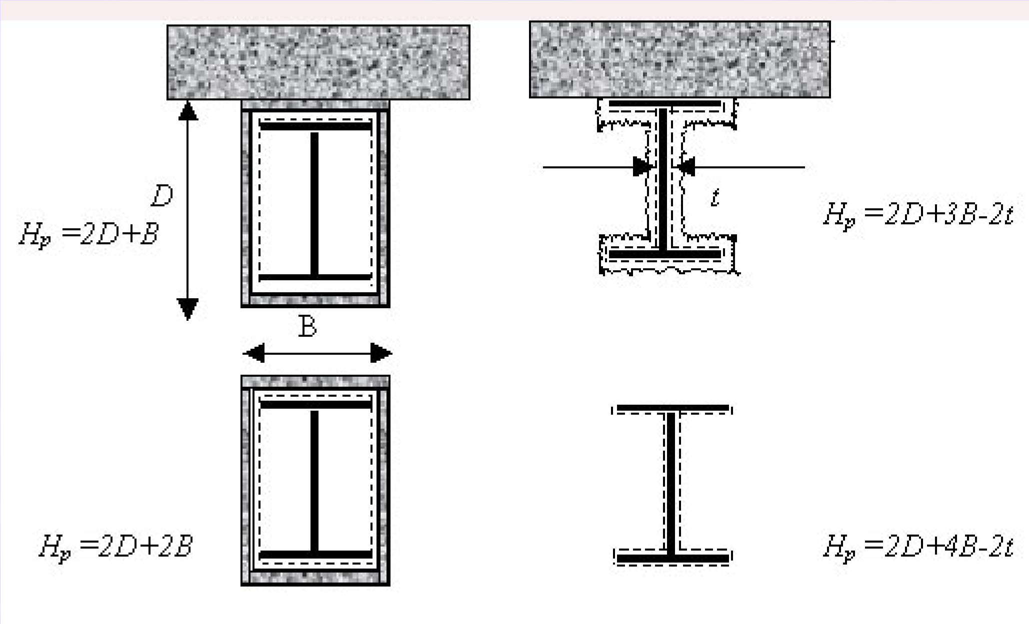

Fig 1.21 Some typical values of HP of fire protected steel sections

The limiting temperatures for various structural members are available in the relevant codes of practice. The load ratio may be defined as:

$$\text{Load ratio} = \frac{\text{Load applied at the fire limit state}}{\text{Load causing the member to fail under normal conditions}}$$

If the load ratio is less than 1, then no fire protection is required. In the second method, which is applicable to beams, the moment capacity at the required fire resistance time is compared with the applied moment. When the moment capacity under fire exceeds the applied moment, no fire protection is necessary.

Methods of fire protection

Fire protection methods are basically dependent on the fire load, fire rating and the type of structural members. The commonly used fire protection methods are briefly enumerated below.

Spray protection: The thickness of spray protection depends on the fire rating required and size of the job. This is a relatively low cost system and could be applied rapidly. However due to its undulating finish, it is usually preferred in surfaces, which are hidden from the view.

Board protection: This is effective but an expensive method. Board protection is generally used on columns or exposed beams. In general no preparation of steel is necessary prior to applying the protection. Intumescent coating: These coatings expand and form an insulating layer around the member when the fire breaks out. This type of fire protection is useful in visible steelwork with moderate fire protection requirements. This method does not increase the overall dimensions of the member. Certain thick and expensive intumescent coatings will give about 2-hour fire protection. But these type of coatings require blast cleaned surface and a priming coat.

Concrete encasement: This used to be the traditional fire proofing method but is not employed in structures built presently. The composite action of the steel and concrete can provide higher load resistance in addition to high fire resistance. However this method results in increases dead weight loading compared to a protected steel frame. Moreover, carbonation of concrete aids in encouraging corrosion of steel and the presence of concrete effectively hides the steel in distress until it is too late.