AN EXPERIMENTAL STUDY ON DEFLECTION BEHAVIOUR OF SIMPLY SUPPORTED STEEL BEAM SUBJECTED TO HIGH TEMPERATURE

V Bala Ganesh[1], S Vidhya[2], P K Prabhukumar[3]

[1]M.E. Student, Department of Civil Engineering, New Prince Shri Bhavani College of Engineering and Technology, Chennai, Tamilnadu, India
[2] Assistant Professor, Department of Civil Engineering, New Prince Shri Bhavani College of Engineering and Technology, Chennai, Tamilnadu India
[3] Assistant Professor, Structural Engineering division, Anna University, Chennai, Tamilnadu India

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Abstract - *The effect of high temperatures on the structural steel members is a significant parameter to be considered in the design. The anticipated temperature based on fire loads have been proposed by different codal provisions. However limited experimental studies have been carried out on the residual characteristics of steel members subjected to high temperatures based on the literature survey. The effect of this temperature literally alter its behavior as well as changes its physical, mechanical and microstructural characteristics, thus the residual strength and stiffness becomes an important factor in designing the structure for its stability. Though many models and theories are proposed all these have not converged for an consensus values. Hence an attempt is made here to test specimens made to scale and subjected to varying high temperatures of 250ºC, 500ºC and750ºC for a period of two hours and then these were cooled down to room temperatures before they were subjected to testing. One set of specimens were cooled suddenly by quenched in water thus the high temperature is being reduced to room temperature. The effect of this sudden cooling will be compared with that of specimens that were subjected to high temperatures and cooled normally. The differences in the mechanical characteristics and stiffness properties are being proposed to be experimented and the observation are to be recorded. From these it would be interpreted the effect of sudden cooling vs the other types were compared and analysed and will be reported as the results of this study outcomes. The same shall be validated with the available data in the literatures. All these were summarized and concluded and will be presented in the thesis report.*

Key Words: Steel beam, Temperature, Quenching, Thermal, Deflection, Young's modulus.

1. INTRODUCTION

Structural steel has been widely used throughout the world. It is one of a designer's best options in view of its advantages over other materials. Steel is available in a range of discrete size, and its ductile behavior allows plastic deformation upon yielding, therefore avoiding brittle failures. In reinforced concrete structures, steel enhances the concrete strength by carrying the tensile forces. It is also commonly used to reinforce timber constructions. In spite of its advantages, steel on its own is vulnerable in fire. Elevated temperatures in the steel cause reduction in its strength and stiffness which eventually leads to failure due to excessive deformations. This is crucial in steel in compared with concrete or timber members as steel conducts heat very well and often comes in thin or slender elements.

Steel is one of the construction materials which has been in use for a long time. It is a versatile and economical building material whose use is on the increase. The continuing improvement in the quality of fabrication, erection techniques and manufacturing processes in conjunction with the advancements in analytical techniques, made possible by computers, have permitted the use of steel in just about any rational structural system for buildings of any size.

Steel frames for building were first introduced in buildings approximately one hundred years ago, and since then, have made it possible to build different kinds of buildings from those previously in common use. No doubt the kind of buildings that emerged were in response to market requirements of the day. Early buildings with steel frames were generally heavy in dead weight, contained much masonry, were lightly serviced and were generally not of a large span. In some instances, the steel structure was used as a substitute for masonry and timber, and was simply a skeleton around which the building fabric was wrapped.

In the early use of steel as a substitute for a building framework, compatibility between the steel frame and the building as a whole was obviously relatively easy to achieve. The requirement was for short spans, heavy cladding and partitioning which substantially stiffened the framework and, in many situations, provided the entire lateral load carrying resistance of the building. Fire protection requirements were not onerous or non-existent. This may be as a direct consequence of the widespread practice of using encasement to protect the steel structure. As a result, the steel frames used in the early buildings were very simple, mainly pin jointed in design, with simple non-welded connections, which proved quick and simple to erect.

Modem steel framed buildings, by comparison, are of much lighter construction, are often required to have longer spans giving more flexible use, have lightweight partitions incapable of carrying lateral load, are heavily serviced and are liable to alterations in layout and use. With modem construction practice, there are more extensive requirements for fire protection. However, the relatively cheap material costs, fast erection sequences and lighter foundations, achieved by using steel in modem buildings, compare very favourably with those of other building materials. One of the main costs in the use of steel, for the main framework of a building, is the additional protection required to provide adequate safety in the event of a fire. The problem arises because steel softens at high temperatures with significant degradation of strength and stiffness. Current structural fire protective measures concentrate on limiting the rate of temperature rise of the steel framework by a combination of measures which usually include some form of protection to some or all of the exposed surfaces of the members.

1.1 Scope of the investigation

The main objective of this report is to conduct a comprehensive literature review on the behaviour of steel structures in fire conditions. The observation of steel structures that suffered from fire events has shown that many collapses take place after the fire is extinguished and the steel structural elements start to cool down. This led to the development of important principles that were found to govern the overall behaviour of the structure. These principles are very useful in interpreting the results from much larger and sophisticated computational models and in helping to develop a coherent picture of the deflection behaviour.

Single simply supported unprotected steel beam subjected to nominal gravity loads has been considered for the investigation. The beams are assumed to be exposed to temperature.

1.2 Relation of steel properties to composition and manufacturing process

Iron and carbon are the two major constituents of steel. In nature, iron is most abundant in the form of iron oxide ore. To recover iron, iron ore is cooked in a furnace with the addition of coke, a carbonaceous material. The reduction reaction will lead to the formation of iron with a relatively high content of carbon. The carbon-rich iron is then put into another furnace where high purity oxygen is blown through. With the oxidation of carbon, the carbon content continually decreases. Once the required carbon content is reached, the flow of oxygen is stopped. If required, other alloying materials are added at this stage. The steel is then poured into a mould to form a solid piece called an ingot. The ingot is transported to the milling plant where it is reheated and turned into the required shape (e.g. steel section, bar) by passing the softened steel through rollers. After the required shape is formed, steel can be cooled down at different rates. The most common process is called normalising, which means that the steel is cooled slowly in the air. At high temperature, iron exists in the -form (austenite), which allows all the carbon atoms to be dissolved. As temperature decreases, iron transforms into the -form (ferrite) with a crystal structure that is different to austenite. In ferrite, the solubility of carbon atoms is very low. As a result, a precipitate of iron carbide (Fe_3C), or cementite, is formed. For low carbon content, the resulting microstructure consists of grains of iron and granules called pearlite which consists of alternate layers of iron and Fe3C (Fig -1). Compared to iron, Fe_3C has higher yield strength.

The amount of Fe3C in the steel increases with the carbon content. Therefore, with a higher carbon content, the steel strength increases. However, the ductility will decrease. When steel is deformed beyond the yield point, cracks tend to form at the interface between iron and Fe_3C. With higher carbon content, and hence more interfaces, it is easier for the cracks to link together, resulting in final rupture.

For construction applications, a very commonly used steel, called Grade 36 in the US, has a carbon content around 0.25-0.29%. The yield strength is 250MPa (36 ksi) and the ductility is about 35%. Steel strength of 250 MPa is sufficient for many structural applications and the high ductility ensures sufficient pre-failure warning.

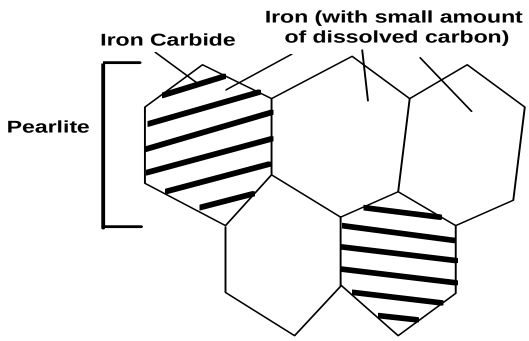

Fig -1: Microstructure of Normalised Steel

If one wants to increase the yield strength without significantly reducing the ductility, alloying elements can be added. Low alloy steels contain small amounts of alloy elements such as chromium, nickel, vanadium, etc. These materials form a solid solution by replacing iron atoms in their crystal lattice (Fig.1.2). Due to the difference in atomic size between iron and the alloying elements, the crystal lattice becomes distorted. Since it is more difficult for dislocations to go through a distorted lattice, the yield strength is improved. As no additional brittle phase is introduced, the ductility is not significantly affected. An example of commonly used low-alloy steel is the US Grade 50 steel, with a yield strength of 345 MPa (50 ksi) and a ductility similar to Grade 36.

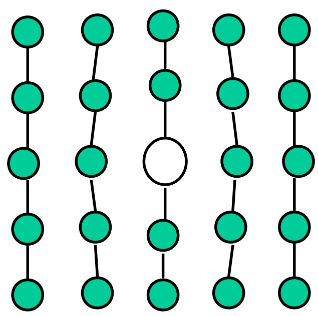

Fig -2: Distortion of Crystal Lattice due to Mismatch in Atomic Size

If a higher strength (550 - 760 MPa) is required, a special heat treatment of the steel is employed. Instead of cooling it slowly, the steel is quenched, or cooled rapidly with water or oil. The resulting microstructure will be very different from normalised steel. The formation of Fe3C precipitate requires the diffusion of carbon atom out of the iron lattice. If cooling occurs so fast that a critical cooling rate is exceeded, there is insufficient time for the diffusion to take place. As a result, the carbon atoms have to stay inside the iron lattice. Since there is insufficient space within the crystal structure of ferrite (the low temperature phase) to hold all the carbon atoms, the crystal lattice becomes severely distorted.

This highly distorted structure is called martensite. It has very high strength but is also extremely brittle. To produce steel that is useful for structural application, the martensite is reheated to about 600ºC, and left at this temperature for a period of time. This process is called tempering. At the tempering temperature, the carbon atoms possess much higher energy than at room temperature and can slowly diffuse out of the iron lattice. The resulting Fe3C precipitate, however, is in the form of uniformly distributed small particles (Fig -3), rather than thin layers as in normalised steel.

In the absence of the iron layer that acts as a soft phase, tempered steel has a higher strength than normalised steel of the same carbon content. Therefore, through the "quenching and tempering" process, a better compromise between strength and ductility can be obtained.

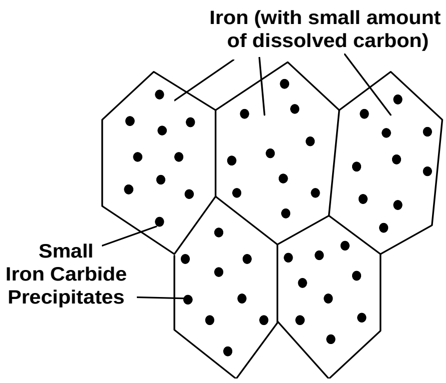

Fig -3: Microstructure of Quenched and Tempered Steel

For small members, the cooling rate is uniform and martensite can be formed all over the member on rapid cooling. For larger members, due to the slower interior cooling rate, martensite will only form on the surface layer, and uniform hardening of the whole member is not possible. The addition of alloying elements can reduce the critical cooling rate, so even the slow interior cooling rate is sufficient for martensite to form. US A514 Steel is an alloy steel made by "quenching and tempering". The yield strength is 690 MPa while the rupture strain is about 20%.

As discussed above, alloying elements can strengthen steel through solution hardening. It can also reduce the critical cooling rate and hence improve the "hardenability" of steel. The presence of certain alloying elements improves the resistance of steel against rusting. For steel structures exposed to severe weather (e.g. marine environment with salt spray), weathering steel is usually specified. Weathering steel consists of a combination of alloying elements, including chromium, copper, nickel, silicon, manganese, etc. In the presence of such elements, a dense layer of rust will be formed and it will adhere well to the steel. As a result, the rust forms a natural protective layer and no painting is required. Tests in a severe industrial environment indicate that the corrosion penetration in weathering steel is only 25% of that in regular carbon steel.

When a very high resistance to corrosion is required, stainless steel can be used. Stainless steel usually contains chromium and nickel. For example, the common 18/8 stainless steel has 18% of chromium and 8% of nickel. Chromium reacts with oxygen in the air to form a dense and strong chromium oxide (Cr2O3) layer to protect the underlying steel. Despite its high durability, stainless steel is rarely used in construction due to high cost. One example application is in the waterside promenade in front of the Sydney Opera House.

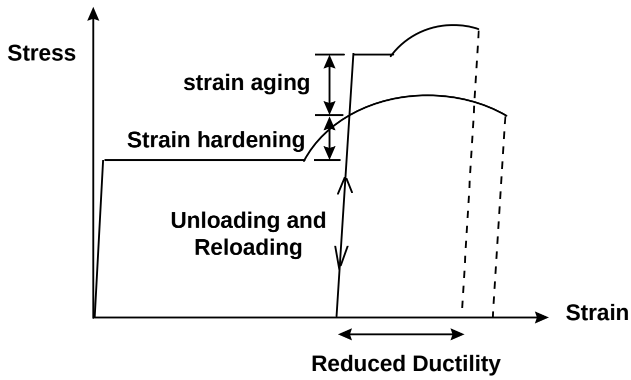

Fig -4: Effect of Cold Working on Steel Behaviour

Steel of very high yield strength is required for prestressing applications. Due to creep and shrinkage of concrete, the loss in initial prestress is expected to be within 240 to 410 MPa. If steel of 690 MPa yield strength is employed, most of the initial stress will disappear in the long term. Steel for prestressing has yield strength ranging from slightly above 1000 MPa to over 1600 MPa. To produce such a high strength, cold working is carried out. In cold working, steel is stretched to a high strain level so it work hardens. On immediate reloading, the new yield stress becomes the stress at which unloading takes place. After a period of time, the yield strength can further increase (Fig.1.4). This phenomenon is called strain aging and is due to the diffusion of small atoms (such as carbon and nitrogen) to the dislocations, and the consequent increase in resistance to dislocation movement. After cold working, the steel is usually reheated to a temperature below 500º C for stress relief. This will provide a better compromise between strength and ductility. In typical prestressing steel, despite its high strength, the ductility is beyond 4%.

When steel structures are subject to cold temperature, the engineer needs to ensure brittle failure will not occur. The fracture toughness of metals decreases with temperature. There exists a transition temperature below which the toughness is significantly reduced and hence the risk of brittle fracture is high. Steel with a transition temperature below the minimum operating temperature of the structure should therefore be used. The transition temperature for various steels can be found from handbooks. Also, the engineer can specify the required transition temperature when ordering steel from the supplier. The supplier will then provide the appropriate steel. To attain a low transition temperature, below -45º C, the steel is often quenched and tempered, to remove the Fe_3C layers in the grains.

1.2 Failure of steel under multiaxial stress

When stress is applied along a single direction, steel yields when the applied stress equals its yield strength. In this section, we will consider the yield criterion when stresses are present in various directions. Yielding is due to dislocation movements that are resulted from shear stresses. A physically correct yield criterion must therefore be related to the shear stress acting on the material. The Tresca criterion relates yielding to the maximum shear stress carried by the material, while the von Mises criterion relates yielding to the distortional strain energy. These criteria are discussed separately below.

1.3 Behaviour of steel structures in fire

Steel structures, when exposed to fire, will lose their strength and stiffness. This may cause excessive or permanent deformation that, in some situations, will lead to structural collapse. This situation certainly will violate the serviceability and ultimate strength criteria. Thus, it is common practice to provide protection to steel framework so that the integrity of the structure can be preserved for a sufficient period to enable safe evacuation of the occupants and to limit property damage.

The failure of a structural element under fire would mean that the element is no longer capable of sustaining the applied load on it. However, the failure of some elements in a fire would not necessarily cause the total collapse of the building. Therefore, the behaviour of an isolated structural element in a fire can be significantly different from the behaviour of the same element within a complete structure.

Fire has always been a very destructive natural phenomenon. There have been countless occasions throughout the history of make kind in which people lost valuable goods, estates of even their lives because of fire accidents. There are a lot of different methods for protecting structural steel to maintain its strength and stability in fire, but little is known about the true behavior of the steel members under various support conditions and heating patterns. The recommended fire resistance to be applied to the steel structures is usually determined based on furnace tests on single elements such as a beam or a column.

When assessing the performance resistance of steel elements subjected to fire, an important factor to take into account is the effect of temperature on the material. In the case of steel, the yield strength, the element ductility and its elastic proprieties, e.g., in Young's modulus, Poisson's Modulus and the proportional limit of stress, are strongly influenced by temperature increase.

1.4 Causes of thermal action

Thermal action is the action on structure described by means of the heat flux, by radiation and convection, caused by temperature differences between hot gases and structure parts. Exposed of materials to thermal action causes degradation of physical and chemical properties, reduction of strength and modulus of elasticity.

Heating induces thermal expansion strains in most structural materials. If a uniform temperature rise, is applied to a simply supported beam without axial resistant, the result will simply be an expansion or increase in length.

1.5 Fire resistance of structural steel

Steel is arguably the most important structural material in modern construction. Steel is used in construction as structural steel or as reinforcing steel for reinforced concrete. Reinforcing steel can be in the form reinforcing bars or high tensile strength steel tendons in pre stressed concrete. Structural steel is considered considerably more vulnerable to fire than reinforcing steels which are encased in concrete which has good insulating properties and so protects reinforcing steels from significant losses in strength.

Steels are very good conductors and tend to be used in thin sections. They are, therefore, liable to heat up very quickly in fires if not insulated. Due to these reasons most main structural steel members are required to be insulated in current design codes. The rate of heating depends upon the parameters of thermal conductivity, specific heat and density. The density of steel is approximately 7850 kg/m^3.

1.6 Effect of cooling

Observation of steel structures that suffered fire events has shown that many collapses take place after the fire is extinguished and the steel structural elements start to cool down. On several occasions, the steel joints fail from their tensile components by the thermal shortening that occurs during cooling. Most design for fire codes for the fire resistance of a steel beams are based on the test performed on simply supported beams.

The residual effects in members around the fire zone of a frame after cooling has taken place result from interaction between the thermal effects on these members and restraints from the adjacent structure. During the heating phase, a beam tends to expand due to the thermal expansion and to bend due to the loads applied on a softening material, these actions being partially resisted by the adjacent cooler structure. Additionally, extensive yielding of the beam is usually observed because of the reduction of the yield stress with increasing temperature.

If failure does not occur during the heating phase, subsequent cooling causes the beam to re stiffen and contract. Previous development of yield strains means that elastic unloading leads to residual deformations and a redistribution of internal forces that may induce tensile forces at the supports (joints). These tensile forces may finally lead to failure of the joints from their tensile components (such as bolts or end plate) and consequently to the failure in the structure.

2. METHODOLOGY

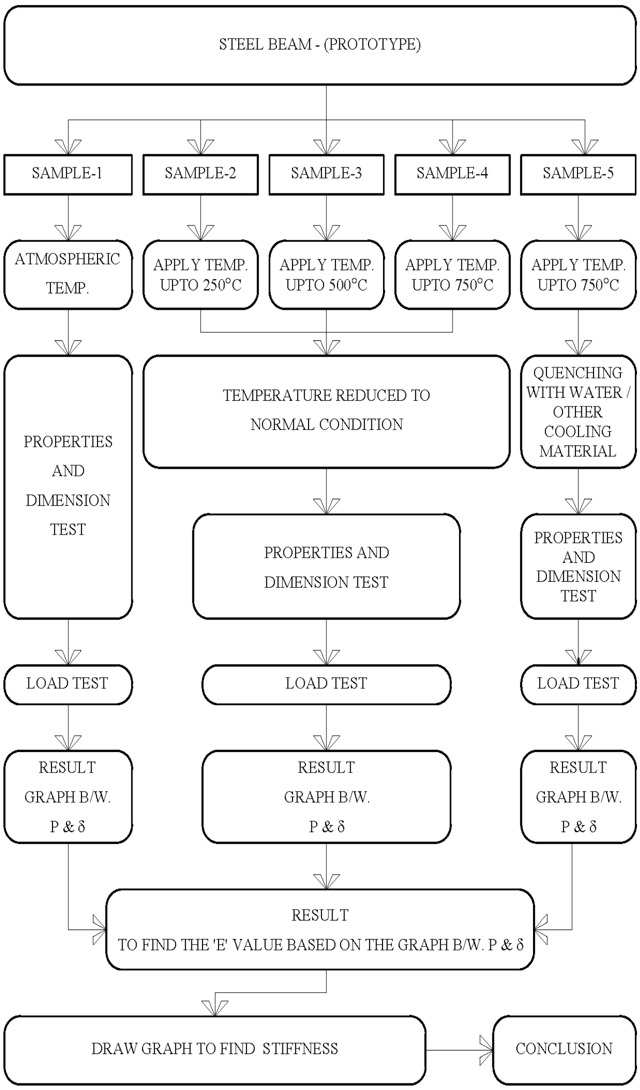

Fig -5: Methodology flow diagram

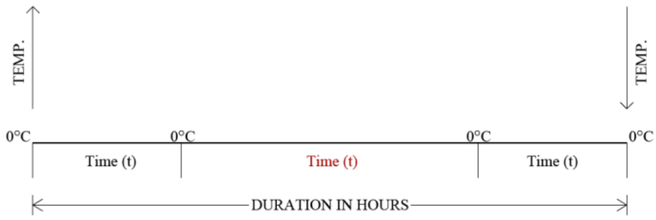

Fig -6: Steel standard beam with normal temperature

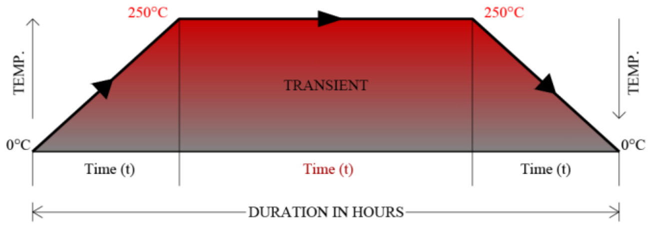

Fig -7: Steel beam under temperature upto 250°C

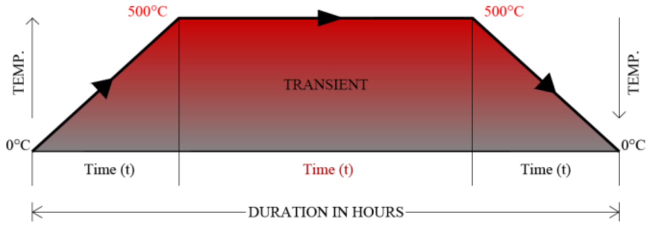

Fig -8: Steel beam under temperature upto 500°C

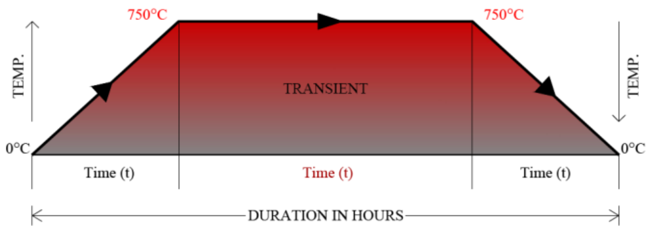

Fig -9: Steel beam under temperature upto 750°C

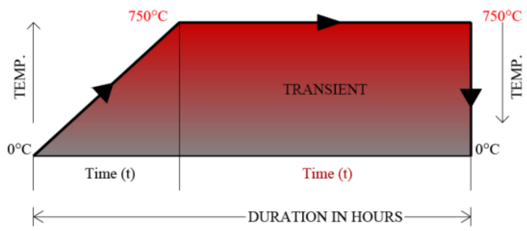

Fig -10: Steel beam under temperature upto 750°C & quenching

3. CONCLUSIONS

The testing's will be done as per the methodology. The tests have been conducted on steel beam of size as per the Indian standard codes. The same shall be validated with the available data in the literatures. All these were summarized and concluded and will be presented in the thesis report

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