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Effect of Elevated Temperature on Steel Structural Buildings

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Abstract: The structural steel elements of buildings are normally not subjected to full design strength, under normal operation. Structural steel is a non-combustible material and its properties can be affected by elevated temperatures. The terrorist attack on multi-storey steel structure World Trade Centre in New York is worst event in the history, which resulted in tragic loss of lives. Therefore, high rise steel buildings must be able to resist high temperatures so that there is a minimum damage to the structure. The main purpose of this paper is to investigate the temperature effects on multi-storey steel building subjected to elevated temperature. In this paper, a study is made to investigate the effect of elevated temperature on structural elements of steel buildings. The main properties of steel that were found to change with an increase in temperature from 20 degree centigrade to 1400 ^{0}C are modulus of elasticity of steel, and yield strength of the structural steel. High grade steel, Fe410 was found to better resist the temperature changes as compared to Fe250. These results are expected to help the designers and planners in making appropriate provisions for providing a higher temperature resistance to the steel structures.

Keywords: ANSYS, Deformation, High temperature, STAAD pro V8i, Steel members, Thermal analysis.

I. Introduction

With the rising standard of living in urban areas and population explosion, cities are growing vertically and there is pressure throughout the world to construct multi-storey buildings to provide accommodation for residential, offices and commercial uses. However, multi-storey buildings are subjected to higher level of forces, particularly with respect to wind loads and earthquake forces.

The design and serviceability aspects are as follows:

- Selection of appropriate structural system
- General requirements including:
  - height limitation of different structural systems,
  - height to plan aspect ratios,
  - Storey stiffness and strength, and
  - Resistance to wind and earthquake forces.

The steel buildings, widely used in India, are commercial spaces, institution buildings, university building, residential towers, and exhibition halls, Delhi Metro Rail Corporation station buildings superstructure, transmission line towers. Steel offers the following advantages as a structural material:

- Steel has high strength per unit weight. Therefore, steel members are lighter in weight for large spans and provide more space for utilization.
- Steel has high ductility and hence steel structures resist seismic forces due to ductile behavior.
- The structural steel members are prefabricated as per design and analysis. Therefore, it requires less construction time for assembling structural members at construction site, saving in time and also ensuring better quality control.
- Steel structural members can be strengthened at later stage by simply welding/bolting additional structural members.

Structural steel has the following properties:

- Steel Density = 7850 kg/m^3
- Elastic Modulus, E= 2.0X10^5 N/mm^2
- Poisson's ratio = 0.3
- Thermal expansion = 12x 10^{-6}/^{0}C

Under regular operation, such structures are not subjected to the full design strength. Unfortunately, fires are a common occurrence in many areas and can badly damage steel structures. There could be various causes of such fires. The most prominent example of failure of the steel structures is the terror strike on the World Trade Center in New York, US. Generally, steel structures in the cities are exposed to ambient temperatures of up to 50 ^{0}C. Above this temperature, the structural elements start to show thermal effects. The mechanical properties of steel such as, modulus of elasticity, yield strength, Poisson's ratio, and stiffness of steel structural elements changes rapidly at 800 ^{0}C to 1200 ^{0}C and reduction factors reduces initially from 1 to 0 at 1300 ^{0}C temperatures [1-5]. The important properties of steel at elevated temperature are yield strength and modulus of elasticity. All these properties vary with temperature, as is the case for most structural materials. It is observed that the loss of strength of steel starts at 300 ^{0}C and it follows a steady variation till a temperature of about 800 ^{0}C. The residual strength, which although small, reduces in a gradual manner and finally steel starts melting at a temperature of about 1500 ^{0}C.

The building elements subjected to elevated temperatures depict large deflections, deformation in members, shear force, and member stress. Therefore, it is necessary to evaluate the performance of steel elements at high temperature so that building remains in serviceability condition. Past studies have evaluated the high temperature properties of steel members (such as, steel columns) at elevated temperature up to 800 ^{0}C [6-8]. Other studies have focused on the failure mechanism of steel members at high temperatures of 400 ^{0}C and 600 ^{0}C, and rapid deformation above 500 ^{0}C temperature in steel elements [9-10].

The main objective of this paper is to investigate the temperature effects on multi-storey steel buildings subjected to elevated temperatures. The study was conducted for a hypothetical steel structural building located in the Delhi-NCR area, India and lies in the seismic zone IV. Acommercial multi-storey steel framed structure building consisting of beams, column, slabs and walls and other structural members was considered for study of high temperature effects. Two different types of steel grades (Fe410 and Fe250) were studied using ANSYS software for potential effects at temperatures up to 1400 ^{0}C. The results of this study are expected to help the planners and designers decide on the appropriate structural adaptations for making the steel structures more resistant at higher temperatures.

II. Materials and Methods

A. Temperature Influence on Yield Stress

As per IS 800 - 2007, the temperature change influence on the yield stress of mild and high strength steel can be given as:

$$f_y(T)/f_y(20) = 905 - T / 905 \le 1.0$$

where, $f_y(T)$ = yielding stress of steel at a temperature T ^{0}C, $f_y(20)$ = yielding stress of steel at room temperature of 20 ^{0}C, and T = Steel surface temperature in ^{0}C.

The temperature influence on yield stress of steel is shown in Fig. 1.

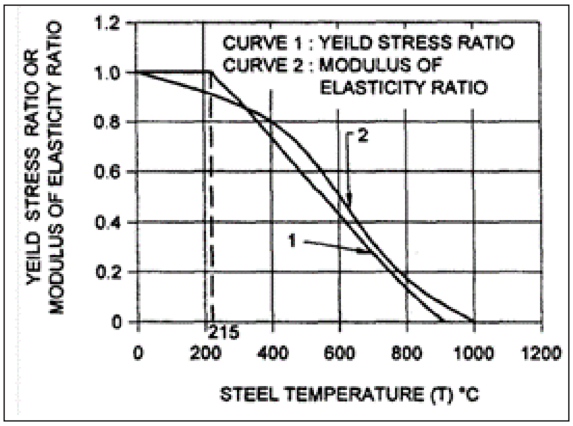

Fig. 1: Variation of Mechanical Properties of Steel with Temperature

Yield stress reduction is not to be considered when the temperature falls below 215 ^{0}C.

B. Temperature Influence on Elastic Modulus

For mild and high strength alloy steel the temperature influence on elastic modulus can be calculated as follows:

$$\frac{E(T)}{E(20)} = 1.0 + \left[\frac{T}{200\left[\ln\left(\frac{T}{1100}\right)\right]}\right]$$

(applicable for 0 ^{0}C < T ≤ 600 ^{0}C)

$$= \frac{690\left(1 - \frac{T}{1.000}\right)}{t - 53.5}$$

(applicable for 600 ^{0}C < T ≤ 1000 ^{0}C)

Where, E(T) = modulus of elasticity of steel at T ^{0}C, and E(20) = modulus of elasticity of steel at 20 ^{0}C (room temperature).

This relationship is shown by curve 2 in Fig. 1.

For special steel with higher temperature resistance, such as TMCP steels, the manufacturers' recommendation shall be used to obtain the variation of yield strength and modulus of elasticity of steel with temperature.

C. Description of Commercial Steel Structural Building

To study the effects of elevated temperatures on steel structures, a commercial office steel building consisting of multiple width bays and multiple length bays was studied. The commercial steel Structural building is symmetrical in geometry. The building consists of grids along length and 5 grids along width. All grids along length and width are of same size (6 metre wide and 6 metre span). The total height of building is 35 metres and it consists of 10 storeys. The span of steel beams is 6 metres. The building shape is regular and it lies in seismic zone 4. The location of this hypothetical steel building is in South Delhi, in northern India. High temperature effects are investigated by simulation method. The design loads on beams are taken as 4.0 kN/m, and the live loads are taken as 4.5 kN/m. The floor plan area at the base is assumed to be 24x24 m and it remains same throughout the entire height of building. This building is subjected to elevated temperatures and the effects of temperature variations from 20 to 1300 ^{0}C were studied. The structural framing elevation of proposed steel building is shown in Fig. 2. The structural framing plan of the 10-storey steel building is shown in Fig. 3. The 3D structural framing isometric view of the proposed 10 storey building is shown in Fig. 4. Two different types of steel: Fe410 and Fe250 were studied for temperature effects.

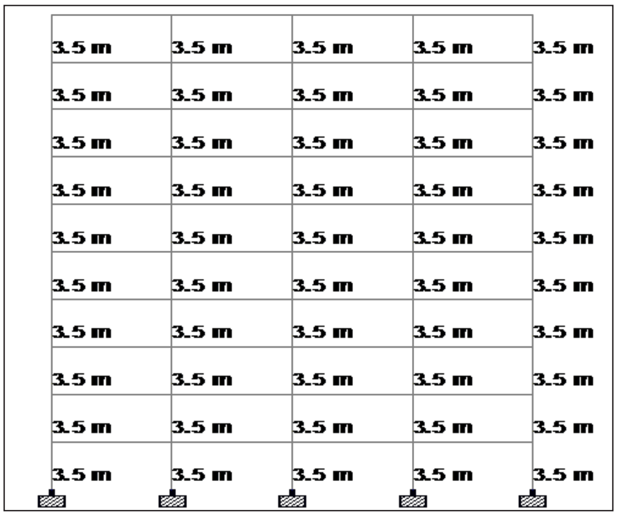

Fig. 2: Structural Framing Elevation of the Proposed 10 Storey Steel Building

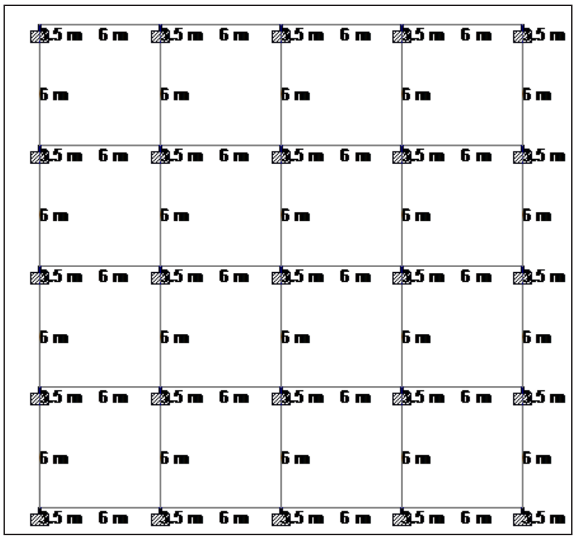

Fig. 3: Structural Framing Plan of the Proposed 10 Storey Steel Building

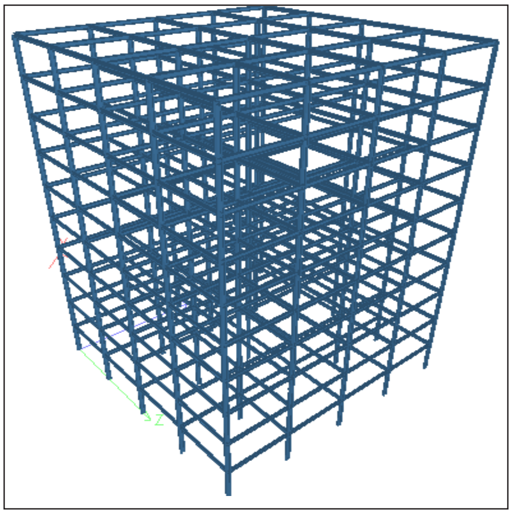

Fig. 4: 3D Isometric View of Steel Structural Framing of 10 Storey Building

D. Simulation of Elevated Temperature on Steel Building

ANSYS (version 16) software was used for simulating the effects of temperature variations of the proposed steel building and its members. This software performs thermal analysis of steel structural elements in systematic simulations in small time. It also evaluates the various steel properties, deformation, stresses and strains for a given structure. This is powerful software in the functionality and for optimizing structural components [11-14].

This software uses various inputs such as, material properties, design, engineering models, temperatures, etc. to carry out both static structural analysis, and transient thermal analysis. This model can also carry out buckling analysis, optimization, vibrational analysis, etc. It can generate bending moment and shear forces analysis at high temperature, deformation for steel structures and investigate stress and strain parameters. It is also useful for evaluating the modulus of elasticity and yield strength of various steel structures at high and very high temperatures [15-20].

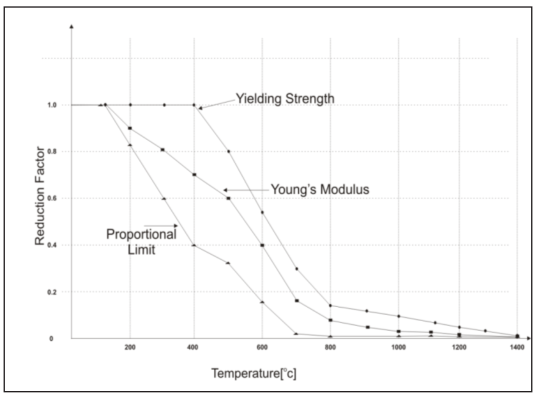

Fig. 5: Reduction Factors for Yield Stress, Young's Modulus and Proportional Limit

III. Results and Discussion

The results of the simulation studies on the effect of elevated temperatures on the steel building are shown in Fig. 5. The temperature values are shown on the x-axis (horizontal direction) in degree centigrade, and the modulus of elasticity ratio, strength reduction ratio and proportional limit ratio values from zero to 1 shown along the y-axis (vertical direction).

The reduction factor for modulus of elasticity ratio for steel is negligible when temperature reached to 200 ^{0}C and strength reduction ratio factor remains constant upto 400 ^{0}C. The reduction factor for the modulus of elasticity, above 250 ^{0}C temperature, changes rapidly till the temperature reached 800 ^{0}C. The strength reduction factor beyond 400 ^{0}C reduces rapidly till the temperature reached to 900 ^{0}C. The temperature range between 750 ^{0}C to 1400 ^{0}C resulted in lesser variation in the result factors for all the parameters (Young's modulus, yielding strength and proportional limit). The ANSYS (version 16) analysis results shows reduction in all steel properties, a remarkable reduction in stiffness of members, reduction in young's modulus of elasticity, reduction in yield strength and large deformation in steel members and finally reduced to zero value at 1400 ^{0}C temperature.

The steel grade Fe410 is a high strength steel and it was found to better resist temperature variations and the building was better in terms of serviceability conditions. The steel initially starts losing its material property after 400 ^{0}C temperature. The present study work shows that steel reduces yield strength after 400 ^{0}C temperature and after 600 ^{0}C temperature a rapid reduction in yield strength. Stiffness and modulus of elasticity. The yield strength, stiffness, young's modulus of elasticity of Fe410 grade steel investigated by ANSYS version 16 software at 1400 ^{0}C temperature is observed as zero. The Young's modulus of steel Fe410 reduces in value after 230 ^{0}C temperature and after 530 ^{0}C a rapid decline in the Young's modulus reduction factor was observed and it ultimately reduced to zero at 1200 ^{0}C.

Fe410 steel showed higher yield strength as compared to Fe250 grade steel, esp. at high temperatures. The yield strength of Fe410 at elevated temperature shows better results as compared to the Fe250 grade steel, therefore high strength steel resist more fire loads. Similarly, the effect of high temperature on high strength steel Fe410 grade is less as compared to Fe250 grade steel and better Young's modulus for a higher grade of steel.

A number of past studies have investigated the effect of fire events on industrial steel buildings, multi-storey buildings; including traveling fire. Thermal behavior of such structures has been studied for temperatures of up to 800 ^{0}C and similar results (as compared to the current work) were obtained [18-20].

IV. Conclusions

The important conclusions based on the current work (steel structures subjected to high temperature) are as follows:

- In the finite element ANSYS simulation method, the mechanism of heat transfer in building structure due to high temperature loads becomes easy and accurate and useful for investigating the temperature effects in terms of reduction in yield strength, reduction in modulus of elasticity values, etc.
- The value of modulus of elasticity reduction factor changes negligibly up to 300 ^{0}C for Fe410 grade steel. The modulus of elasticity ratio changes rapidly from 1 to 0.3 when temperature increased to 800 ^{0}C and reduces to zero at 1300 ^{0}C.
- The damage of steel members at high temperature in high strength steel is less as compared to lower grade steel (such as Fe250). Therefore, high strength grade steel is recommended for use in the industrial and commercial buildings.
- As per serviceability criteria for steel buildings deformation, stresses in members, Young's modulus of elasticity, yields strength, stiffness, deflection must lies (span/300) in permissible limits and beyond 400 ^{0}C temperature and above 600 ^{0}C, building elements reaches its plastic deformation. By increasing the size of steel members, the capability of building at high temperature is slightly increased.

It is recommended to apply fire protection coatings to structures prone to fires.

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