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Thermal Stress Analysis of Beam Subjected To Fire

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ABSTRACT
The effect of thermal stresses and deformations on the performance of structure due to increase in temperature is generally not treated in design codes and standards. This project describes the behaviour of structure when subjected to high temperature. The change in temperature makes material to expand and if this expansion is restrained, stresses are induced which affect expected performance of structure. The force generated by restrains is very large and its ignorance can lead to unsafe design. When structure is subjected to high temperature, it results in reduction in stiffness and strength which significantly affects the structural performance. In this paper analysis of beam subjected to fire loading is done. Response of steel beam subjected to ISO 834 fire with different types of restraining support condition is studied.
Keywords: fire load, heat transfer, ISO 834, thermal analysis, thermal properties.

I. INTRODUCTION

Fire has great capacity to harm human life if it is not properly treated. It can lead to loss of human property and life.
Nowadays, in modern construction steel structure is more often used, hence its response in case of fire is necessary to study to be treated properly in design.

Structural response of steel structure in case of fire depends on material degradation, loss of stiffness and strength, thermal gradient, restrains for expansion. The effects of thermally induced forces and deformations on the performance and safety of steel structures subjected to fire are not well understood and are not properly treated in building codes and standards.

Hence, resistance behavior of a beam subjected to standard fire load iso834 curve is studied and response of beam for different types of restrains is studied which is helpful in understanding the behavior of frame structure.

II. REVIEW OF PRIOR WORK

Borst and Peeters [1],Yousong and Shizhong [2],developed closed form solution to obtain temperature distribution in structure.Enrique Mirambell and Antonio Aguado [3],presented study on temperature distribution affected by geometry of structure.C.A.Wade [4],gave summary on finite element modelling of building components subjected to fire.A.S. Usmani, J.M. Rotter, S. Lamont, A.M. Sanad, M. Gillie [5],provides fundamental principles about behaviour of structure subjected to fire loading.Work of K. W. Poh[6],presents a new mathematical relationship for representing the stress-strain behaviour of structural steel at elevated temperatures. JyriOutinen and Pentti Makelainen [7] studied the transient state test results of different grades of structural steel are presented and compared with Eurocode EN1993-1-2[8].Also test carried out to find out the remaining strength of the material after fire. Kodur and Sultan [9] developed relationship for thermal properties of high strength concrete which closely fit experimental observations. V. Narang[10]studied temperature distribution in beam and comapred the results for section protected with vermiculite and gypsum board coatings. C.Crosti [11]focuses on analysis of steel structure under fire loading and the evaluation of the structural collapse under fire load of a real building. Chung Thi Thu Ho [12] study on the influence of restraints to thermal expansion on the performance and safety of columns in steel buildings. Lisa Choe; A. H. Varma, Anil Agarwal and Andrea Surovek[13]studied moment curvature and buckling behavior of steel beam column under fire loading. V.Kodur, Esam Aziz, M.Dwaikat[14]studied the influencing factor for better performance in case of fire. Also reviews high-temperature constitutive relationships for steel available in American and European standards, and highlights the variation between these relationships through comparison with published experimental results. Lars-OlofBjorkstad [15] worked on modelling of the roof truss in finite element program and varied different parameters like boundary conditions, cross section areas. Jenny Seputro[16] investigated single span beam subjected to fire with varying parameters like restraining conditions, different fires, number of fire exposed sides.

III. METHODOLOGY

Finite element analysis has been shown to be a valuable tool in performing thermal analysis and evaluation of thermal quantities such as temperature, heat flux and so on. However, the main role of the engineer is to ensure the ability of a component to perform without failure. Thermal stresses arising from high thermal gradients can be directly combined with mechanical stresses and structure can be design for total stress.

1. Heat transfer

Heat transfer is energy transport in medium due to temperature difference by conduction, convection or radiation. Heat transfer is governed by principle of conservation of energy. Conduction takes place in all forms of matter solids, liquids and gases. Convection more likely occurs with a variation in density between the two fluids. Radiation is any process in which energy emitted by one body travels through a medium or through space absorbed by another body.

2. Behaviour of structure

Fundamental principles are explained below to get idea about estimation of stresses and displacement which can be used in design calculation.

Heating of material induces expansion strain (ε_T)in structure. When there is uniform rise in temperature ΔT in beam of length l and α is coefficient of thermal expansion of material then thermal strain produced is obtain as $\varepsilon = \alpha\Delta T$. And total increase in length is $\alpha\Delta T l$.

2.1. Thermal expansion of simply supported beam

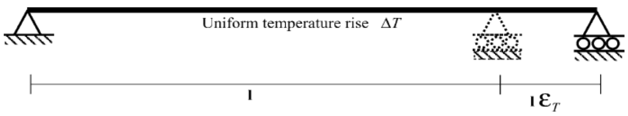

Fig.1 Free lateral expansion due to roller supports [5]

In case of simply supported beam having one roller support, allows expansion of beam along its length freely. Hence no stresses are induced due to thermal gradient.

2.2. Thermal expansion of axially restrained beam

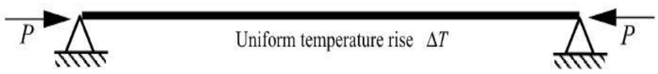

Fig.2 Reaction produced due to restrains to free expansion [5]

Thermal expansion is resisted by producing equal and opposite force P producing uniform axial stress $\sigma = P/A = E\alpha\Delta T$

If axial stress continues to increase, it will soon reach to yield stress. And if material is elastic-plastic then beam will continue to yield without increase in yield stress.

If beam is slender then it will buckle before reaching yield stress

2.3. Thermal bowing

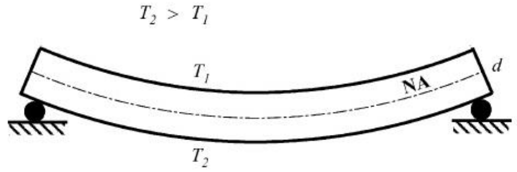

Fig.3 Thermal bowing due to temperature gradient along depth [5]

In case if real frame structure subjected to fire in one compartment, beam undergo vertical thermal gradient i.e. either of extreme fire subjected to high temperature than other which causes expansion of fire exposed surface more. This causes bending of member. The phenomenon is known as thermal bowing.

Combined thermal expansion and bowing takes place and compression and bending stresses are observed in most of the structures.

3. ISO834 fire

ISO 834 is a standard fire used as input in computer analysis. It is the international standard of time-temperature curve, which is defined by

$T=345 \log_{10}(8t+1) + T_o$

Where, t is time in minutes and T_o is the ambient temperature in degree Celsius.

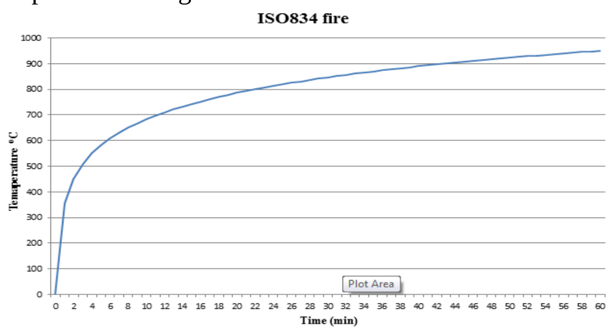

Fig.4. ISO fire834 time-temperature curve

4. Material Properties

Material degradation should be considered for analysis of structure subjected to fire. Guidelines are provided in Eurocode 1993-1-2 [8] are summarized below.

4.1. Mechanical properties

Unit mass: The unit mass of steel is independent of temperature. Its value is taken as 7850kg/m3

Ultimate and yield strength: The generalized stress-strain relationship is described in the Eurocode. It is used to obtain the strength and deformation properties of steel to determine the resistance to tension, compression, moment or shear.

Coefficient of thermal elongation: Thermal elongation is assumed as function of temperature as given in eurocode3, shown in fig.7

4.2. Thermal properties

Conductivity and specific heat: variation of thermal conductivity and specific heat can be obtained from formulas given in Eurocode 3.

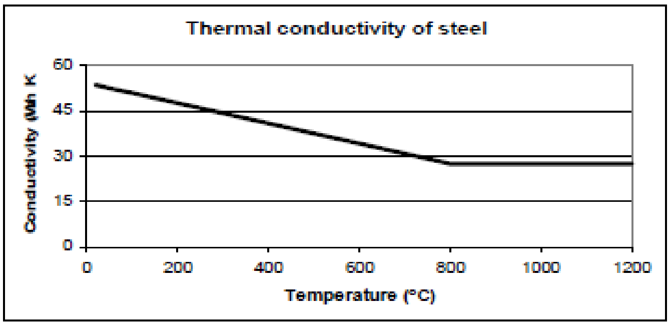

Fig.5 Thermal conductivity of steel as a function of temperature [8]

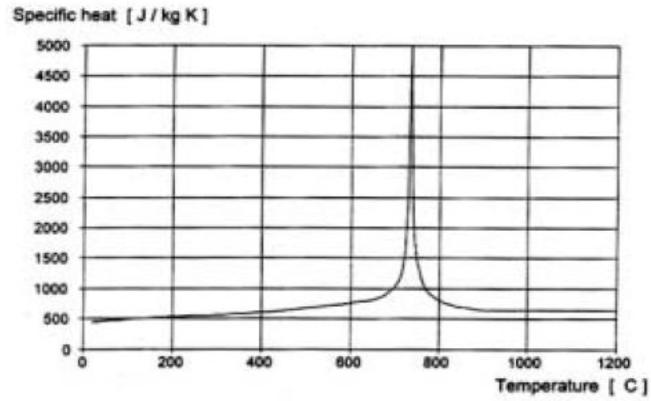

Fig.6 Specific heat of steel as a function of temperature [8]

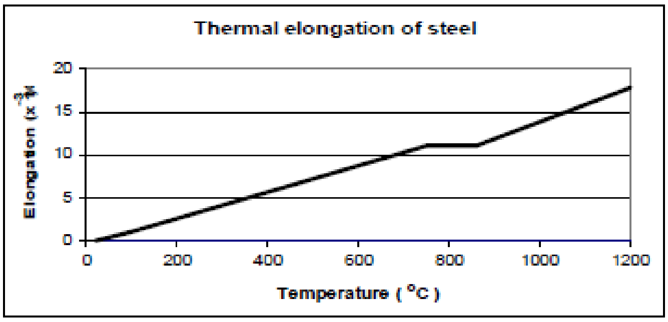

Fig.7 Thermal elongation of steel as a function of temperature [8]

Table.1. Reduction factors for stress-strain relationship of steel at elevated temperature [8]

Steel temperature T_s	Reduction factors at temperature T relative to the value at 20^0C		
	Reduction factor for effective yield strength	Reduction factor for proportionate limit	Reduction factor for the slope of the linear elastic range
20^0C	1.000	1.000	1.000
100^0C	1.000	1.000	1.000
200^0C	1.000	0.807	0.900
300^0C	1.000	0.613	0.800
400^0C	1.000	0.420	0.700
500^0C	0.780	0.360	0.600
600^0C	0.470	0.180	0.310
700^0C	0.230	0.075	0.130
800^0C	0.110	0.050	0.090
900^0C	0.060	0.0375	0.0675
1000^0C	0.040	0.0250	0.0450

Assumptions are for the computer analysis standard fire curve ISO 834 is used as input, which is considered as realistic fire action and the boundary conditions at supports and forces and moments at boundaries of part of the structure may be assumed to remain unchanged throughout the fire exposure.

5. Model Validation

C.Crosti [11] has done research on steel structure subjected to fire loading. Where, the use of thermo plastic material in FEA software Adina and Strand is done to obtain results. Numerical analysis on isolated beam is chosen as model to be validated, evaluating successfully another finite element software ABAQUS approach the fire resistance of steel structure. The analysis in software takes into account material as well as geometric non linearity.

Fig.6 shows displacement of mid span point in Y direction for a three meter long simply supported beam with rectangular section of 0.3X0.3 m subjected to constant vertical force F=1410 KN at the mid span and ISO 834 fire action.

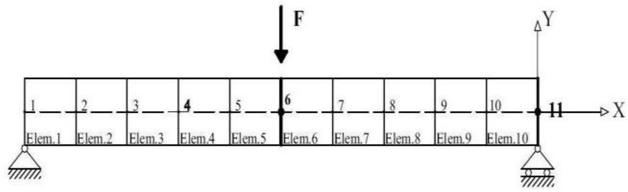

Fig 8.Mesh of beam[11]

Table.2.Result of mid span deflection from two finite element analysis software

Temperature in ^{0}C	Deflection of mid span in meter	
	ABAQUS 6.12-3	ADINA (C.Crosti[11])
100	0.0205	0.017
200	0.0227	0.018
300	0.0256	0.02
400	0.0293	0.023
500	0.0342	0.03
600	0.066	0.05
700	0.258	0.2

6. Example Analysis

The analyses are based on investigation work of J.Seputro [16] on a single span steel beam supported at both ends. A span of 8m of universal I-beam, 610UB101 with the dimensions and properties lay out in Table 4.1.Uniformly distributed static load of 25KN/m is acting on beam. Flange bottom face of beam is subjected to fire load.

At ambient conditions, the yield strength and the elastic modulus of the steel are 430 MPa and 210 GPa respectively, with a Poisson's ratio, μ of 0.3.

The beam is analysed for four types of support conditions. And deflection behaviour is observed in each case.

Table3. The steel beam properties[16]

Type	610UB101
Weight	101 kg/m
Depth	602 mm
Flange width	228 mm
Flange thickness	14.8 mm
Web thickness	10.6 mm
Root radius	14.0 mm
Depth between flanges	572 mm
Gross cross sectional area,	13000 mm2
Second moment of area	761 x 106 mm4
Plastic section modulus	2900 x 103 mm3

Different characteristics are observed for different supports. Response of beam varies with support restrains provided. Maximum deflection of mid span point is observed for fire loading. And temperature vs. deflection plot is presented

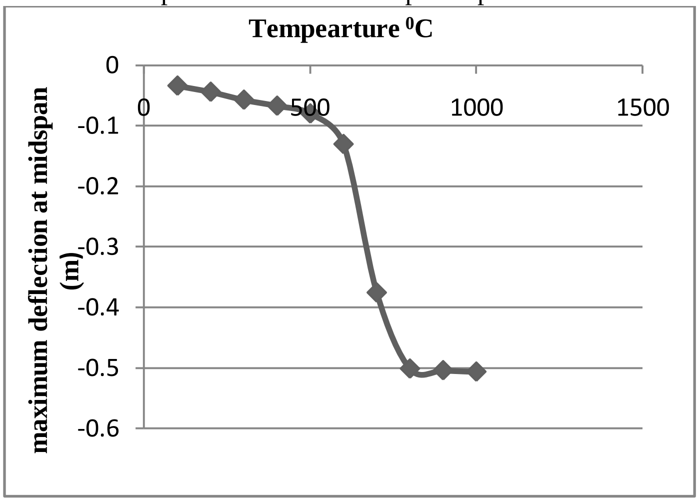

Fig.9.Mid span deflections of beam with both pin supports.

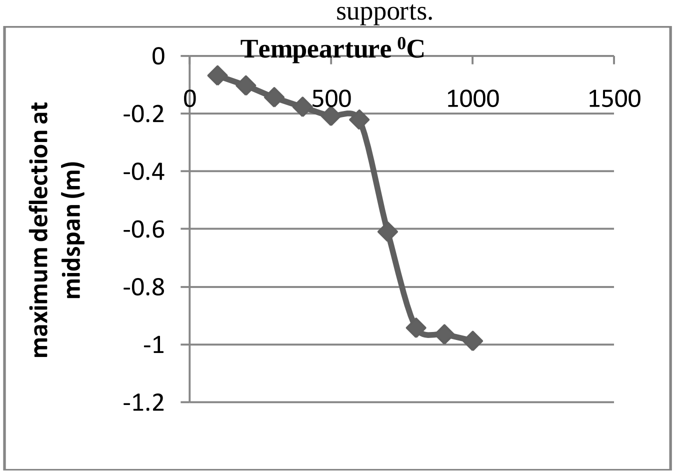

Fig.10.Maximum mid span deflections of beam with pin roller supports

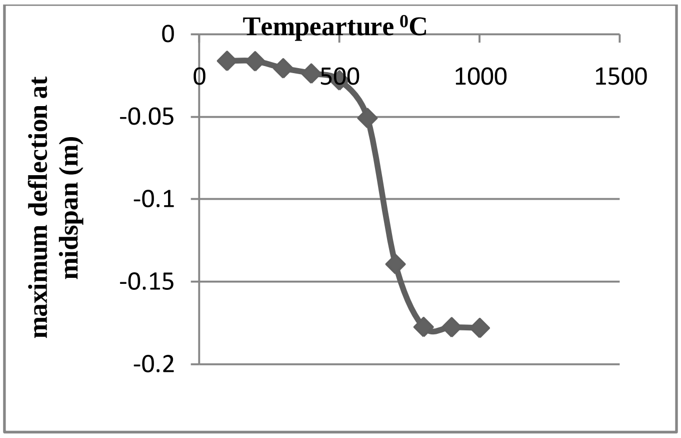

Fig.11.Mid span deflections of beam with both fix supports

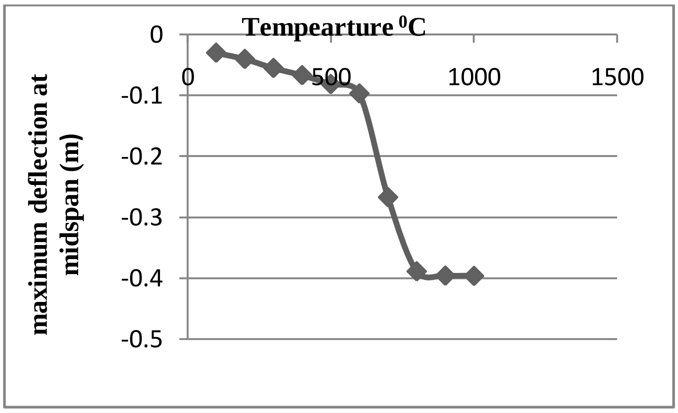

Fig.12.Maximum mid span deflections of beam with one fix and one roller supports

Deflection criterion is important when assessing failure of the structure. Rapidly increasing deflection indicates imminent collapse or very large deflections but no collapse, in which case the deflected members can be repaired or replaced after the fire. To assess fire rating of structure, deflection criteria is important to study as it gives safe time to escape out when structure is subjected to fire. This study has provided basic idea of thermal analysis, heat transfer and behaviour of structure subjected to thermal gradient.

IV. Conclusion

Following conclusions are drawn from the analysis work done.

- With finite element program, the study of heat transfer in any structure subjected to thermal loads becomes easy and less effort consuming.
- With previous research work, degradation behaviour of material is standardised and is modelled for analysis of structure subjected to fire. Standard fire curves like ISO834 can be modelled for analysis as it is temperature vs. time curve. Hence response of structure can be noted related to time and provisions can be made in fire safety design.

- Finite element program ABAQUS 6.12-3 deals successfully with fire loading and modelling of degradation of material properties and stiffness. With finer mesh and correct element type for analysis accuracy can be achieved.
- Due to static load present on structure and material is degraded to elevated temperature; deflection is excessive at fire case than that at ambient temperature in steel beam. At around 600^0C temperature, deflection of beam is ten times than deflection at ambient temperature condition. And at around 900^0C and above temperature, deflection is hundred times of that at ambient temperature.
- When temperature reaches more than 600^0C, deflection of beam increases excessively as material properties changes to large extend at this temperature.
- Stress also increases with increase in temperature. And reaches yield limit at around 600^0C to 700^0C. Therefore, understanding of response of beam structure subjected to fire helps to design the structure safe and serviceable
- Deflection of beam with pin and roller support is more and deflection of beam with both supports fix is lesser than beam with other supports. Beam with one fix and one roller support deflects less than beam with both pin supports.

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