NUMERICAL SIMULATIONS OF STEEL BEAMS TO INVESTIGATE THE BEHAVIOUR UNDER DEFINED FIRE EXPOSURE

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ABSTRACT

Beams are insulated for the protection against fire. The temperature distribution in the protected beam depends on the thermal influence of fire on material properties as well as on the geometry. In this work a parameter study is performed considering different geometrical design parameters like thickness of fire insulation, casing types and the types of fire protection. The propagation of temperature and the deformation behaviour were calculated by performing transient thermo-mechanical non-linear simulation using FEM solver ANSYS. The beams were subjected to standard time-temperature fire curve (ISO 834-1) to define thermal effect and a concentrated force for load ratio 0.62. The temperature distribution at different locations and mid-span deflection of the beams are compared.

KEYWORDS

Fire protection thickness, counter and hollow casing, full and partial protection, FEA, DIN EN 1993-1-2

NOMENCLATURE

ρ	density
k	thermal conductivity
c	specific heat
h	convection coefficient
ε	emissivity
σ	stefan-Boltzmann constant
q_c	convection heat flux
q_r	radiation heat flux
n_x, n_y, n_z	direction cosines of normal to boundary surface
q_x, q_y, q_z	heat flow
T_e	environment temperature
T_s	surface temperature
Q	internal heat generation
T	temperature
t	time
x, y, z	positions

INTRODUCTION

Many studies have been conducted with protected and partial protected beams to determine the temperature influence on them. To minimize the heat flow into the beams, they are provided fire protection of specific thickness to meet the fire resistance. The temperature distribution is greatly affected by material properties. The load bearing capacity of steel beam depends on yield strength which decreases with rise in temperature. According to DIN EN 1993-1-2 [5], the fire resistance of beam can either be checked in temperature domain or in moment domain. In temperature domain the temperature measured at the critical member like lower flange of beam must be less than or equal to critical temperature. In moment domain the design moment of the beam must be less than or equal to cross sectional moment resistance. According to Eurocode-3 [5] the beam should also be checked for the serviceability but in National Annex DIN EN 1993-1-1/NA [8] the vertical deflection limits are not given with which the calculated maximum deflection of beam can be compared.

In addition to material properties the geometry of the beam plays important role. Ding J. et al. [1] reported that ordinary steel has only 55% fire resistance capacities of fire protected beam under same conditions. Ahn J.K. et al. [2] conducted parameter study considering structural and thermal parameters and found fire protection has great influence on the resistance capacities of beam. Even a thin coating affects fire resistance significantly. Wang W.Y. et al. [3] concluded that the column fails at its part which is partially fire protected.

The work carried in present study is motivated from the previous study done by Patil. M. et al. [4] in which the protected beams were subjected to furnace temperature and to mechanical loading with load ratio 0.7, 0.6, and 0.5 separately. To check the failure of beams, the temperature at the bottom flange of beam measured from experiment and calculated from simulation were compared to the critical temperature calculated according to Eurocode-3 [5]. It was found that none of the beam failed in fire resistance period of 75 minutes. The study needed more investigation to determine the beam behaviour for different geometrical parameters to see how temperature distribution is affected.

Using ANSYS Mechanical (Workbench) [7] the transient thermo-mechanical simulations have been performed for different parameters. Thermal and Mechanical material non-linearities were set for accuracy. The thermal boundary conditions for the convection and radiation effects were taken into account. The results comparisons are made for each parameter and simultaneously discussed.

THEORETICAL BACKGROUND

There are three modes of heat transfer Conduction, Convection and Radiation. The heat transfer phenomenon into the solid as shown in figure 1 lies in the fact that heat is transferred from the surrounding atmosphere/gas to the surface of solid through convection and radiation and within the solid heat transfer takes place by conduction.

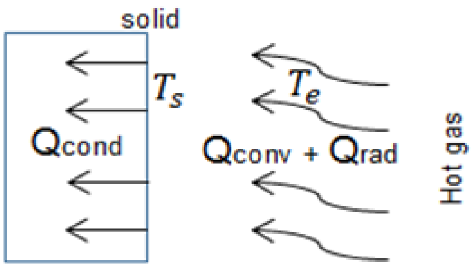

Figure 1 Heat transfer phenomena in solid

Equation 1 [6] shows 3-dimensional Fourier transient partial differential heat conduction equation.

$$\frac{\partial}{\partial x}\left(k\,\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\,\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\,\frac{\partial T}{\partial z}\right)+Q=\ \rho c\,\frac{\partial T}{\partial t} \qquad (1)$$

$$q_x = k\,\frac{\partial T}{\partial x}\,,\ q_y =\ k\frac{\partial T}{\partial y},\ \ q_z = \frac{\partial T}{\partial z}$$

The boundary condition is the summation of convection boundary condition and radiation boundary condition given in equation 2. Initial condition is given by equation 3.

$$q_x n_x + q_y n_y + q_z n_z = q_c + q_r \qquad (2)$$

$$q_c =\ h(T_e - T_s)\,,q_r =\ \varepsilon.\sigma(T_e^4 - T_s^4)$$

$$T(x,y,z,0) = T_0(x,y,z) \qquad (3)$$

PROCEDURE OF THERMO-MECHANICAL ANALYSIS

FEM tool ANSYS Mechanical (Workbench) [7] has been used in this study for thermo-mechanical simulations. The first step in the analysis is to define material properties. There are both thermal and mechanical properties which greatly influence temperature distribution in the steel. The material properties of steel were taken from Eurocode-3 [5]. The thermal properties of steel material such as specific heat, thermal conductivity and coefficient of thermal expansion are temperature dependent. For mechanical material property the non-linearity for the steel grade S235 was given by stress-strain relationship at elevated temperature to give the steel elasto-plastic behaviour. The thermal conductivity and specific heat of calcium-silicate protection were set to constant values of 0.18 W/mK and 1.05 KJ/KgK [4] .The density, young modulus of elasticity and poisons ratio for steel were 7850 Kg/m^3, 200 GPa and 0.3 respectively and for calcium silicate protection were 285 Kg/m^3, 135 GPa and 0.3 respectively.

The next step is the geometry and meshing. The steel I-beams types HEA160 S235 were modelled 3.85 m in length with calcium-silicate casing around them. The beams were modelled into half symmetry in order to save computational time. Figure 2 shows meshed cross-section of the counter casing and hollow casing on 3 sides of steel I-beam. For thermal analysis ANSYS uses SOLID 90 and SURF 152 element types. SOLID 90 is 3-D 20 node high order element with single degree of freedom temperature at each node. SURF 152 is surface element use to define surface load effects i.e. Convection and Radiation. For mechanical analysis ANSYS uses SOLID 186 and SURF 156 element types. SOLID 186 is 3-D 20 node element having has 3 degrees of freedom at each node: translation in X, Y and Z direction. SURF 156 is surface element use to define surface load effect i.e. force.

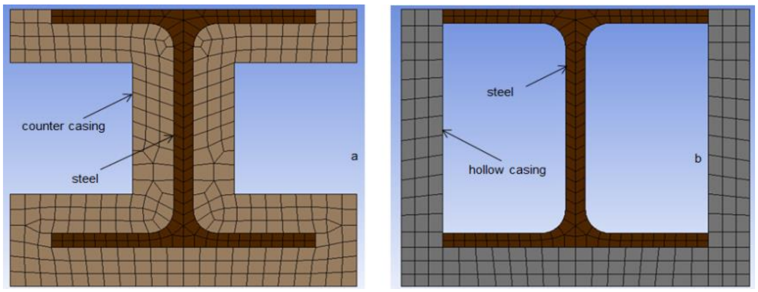

Figure 2 Mesh showing cross-section of steel I-beam with casing around it
a) Counter casing b) Hollow casing

3d non-linear transient simulations were performed. The loading and boundary conditions needed to be set separately for both analyses. The beams were subjected to fire on 3 sides as per standard fire ISO 834-1. The beams were simply supported and a concentrated force of 33.50 KN for load ratio of 0.62 (16.75 KN is defined for half symmetry) applied at the mid span. To take into account the convection effects the heat transfer coefficients for exposed and unexposed faces were taken as 25 W/m^2k and 40 W/m^2k and for radiation effects emissivity value for steel and calcium-silicate insulation were 0.7 and 0.8 respectively. The heat transfer coefficient and emissivity for the exposed faces were temperature dependent per ISO 834-1.

The Newton-Rhapson iterative solver has been used for convergence check. One way coupling approach has been used for the simulation, means once the thermal solution is done the body temperature values are transferred to mechanical mode as shown in figure 3 and then the mechanical analysis is performed to determine deflection. The mesh remains the same in both types of analysis but the element type’s change.

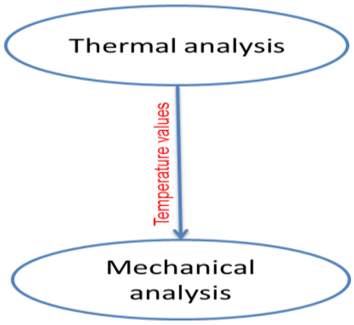

Figure 3 procedure of thermo-mechanical analysis

Total 9 beams: 3 for different insulation thickness, 3 for different casing types and 3 for type of protections were studied and they are designated by names as shown in table 1. In this comparison the bottom flange, web and top flange is denoted by BF, W and TF.

Table 1 parameters studied

Parameter		Casing and/or thickness	Designation
thickness	25	hollow	t25
	50	hollow	t50
	75	hollow	t75
casing	hollow	25	HC
	counter	25	CC
	No casing	25	NC
protection	full	hollow, 25	CP
	Partial	hollow, 25	PP

RESULTS AND DISCUSSION

In this section the simulation results for different parameters are discussed. The temperature distribution in the steel beam and mid span deflection is compared. As the beams exposed to uniform temperature and have protection along the full length, so the temperature measured at any random location at the bottom flange (BF), Web (W) and top flange (TF) are considered for comparison except for the beam with partial protection for which the average of temperature values measured at various locations on BF, W and TF are taken.

Thickness of fire protection

Three beams with insulation thickness of 25 mm, 50 mm and 75 mm are compared and for the simplification of comparison the beams were designated as t25, t50 and t75 respectively as shown in Table 1. The casing type was hollow for all beams. Figure 4 shows the temperature distribution comparison at the BF, W and TF and mid span deflection-time curve. It is obvious to say that the temperature at BF will be always higher than W and TF. For t25 the maximum temperature at BF is around 300°C which drop by half to 150 °C for t50 and further half to 75 for t75. Similarly the W and TF have similar type temperature distribution pattern. A direct relation can be seen and further prediction of temperature distribution in the beam can be made for different insulation thicknesses.

For t25 the high temperature difference between the initial and finial values for every time step produces high thermal stress, results in big reaction force which resist the acting load and therefore t25 reached maximum deflection of only 13 mm in 48 min. Beam t50 was less exposed to temperature in comparison to t25 and has small effect of force reaction and has maximum deflection of 19 mm in 40 min. The temperature influence was least on t75 beam and the beam deflection was gradual with time since beginning. The maximum deflection is large 21 mm in 75 min. It can be said that beam which has high temperature influence would have bigger reaction force acting on it and deflect less.

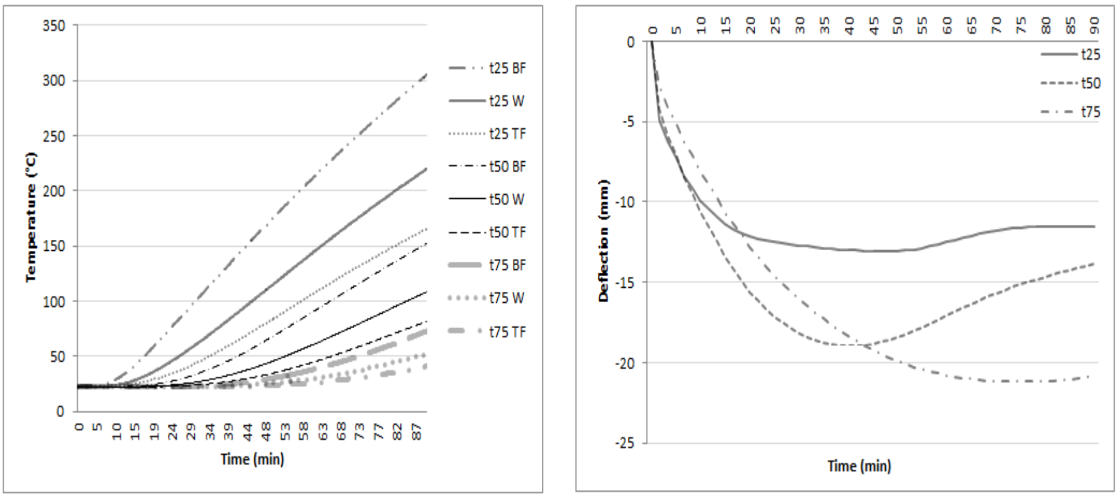

Figure 4 Temperature-Time & Deflection-Time curves for different insulation thicknesses

Fire protection types

Two beams designated as CP for full protection and PP for partial protection are compared. Both have hollow casing of 25 mm. PP has a square hole (opening) of 10 cm x10 cm in casing at the bottom side of the flange and average temperature was calculated from the temperatures measured at different locations of BF, W and TF as shown in figure 5.

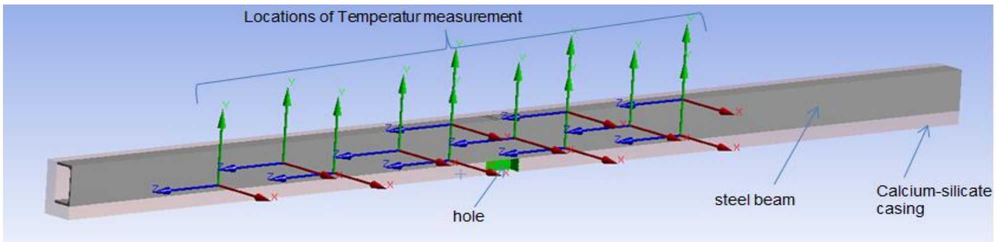

Figure 5 locations of coordinates in beam where temperature is measured

Figure 6 shows the temperature comparison measured at bottom flange, web and top flange and deflection-time curve. In the middle section of PP the temperature was higher which increased the average temperature on BF, W and TF. It can be seen for PP, the temperature transfer rate is faster than that of CP. Similar type of pattern is seen for W. Temperature at the TF grew slowly and maximum temperature difference of 50°C is seen between CP and PP. It was expected that due to higher temperature exposure in the middle of PP, large thermal strain would develop and the deflection will be faster and bigger. The maximum deflection of PP is 21 mm in 42 min. On the other hand for CP the temperature distribution was uniform and there has been reaction acting since beginning results in small maximum deflection of 13 mm in 48 min.

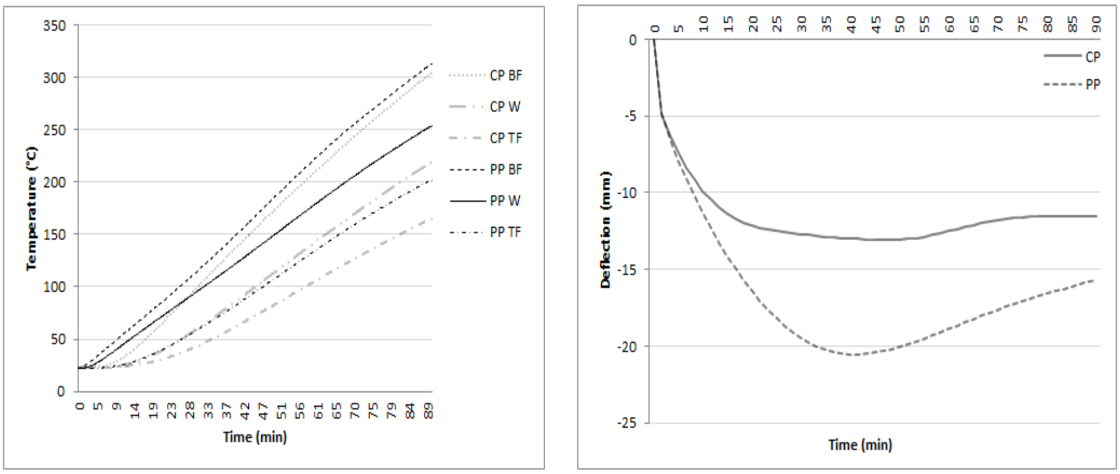

Figure 6 Temperature-Time & Deflection-Time curves for full and partial protection

Casing types

Three beams with counter casing, hollow casing and no casing named as CC, HC and NC as shown in Table 1 are analysed. Figure 8 shows the teperature-time curve and deflection-time curve. For NC the temperature at BF is identical to standard fire curve ISO 834-1 and on the W is slightly lower than it. There is maximum temperature difference of about 150°C between TF and BF. In CC as the coating is adjacent to beam the heat transfer from the outersurface of coating to the beam takes very fast and the maximum temperature reached is 510°C while in HC the heat transfer from BF to TF through W takes mostly from the coating side adjacent to BF therefore the maximum temperature reached at TF is less to 305°C. Figure 7 shows the heat flux vector in both casings.

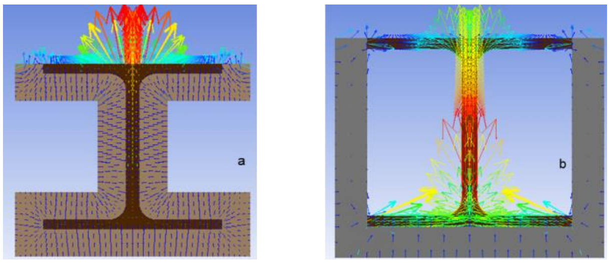

Figure 7 Heat flux vector a) counter casing, b) hollow casing

The strength of steel decreases decreases with rise in temperature. Therefore due to high temperature at NC, it couldnot bear the force and undergoes plastic deformation very quickly in time period of 10 minute. The HC reached maximum deflection of 16 mm in 15 min. As the temperature influence on CC is more than HC, so there was reaction force acting since beginning. This is the reason that HC has high value of maximum deflection than CC.

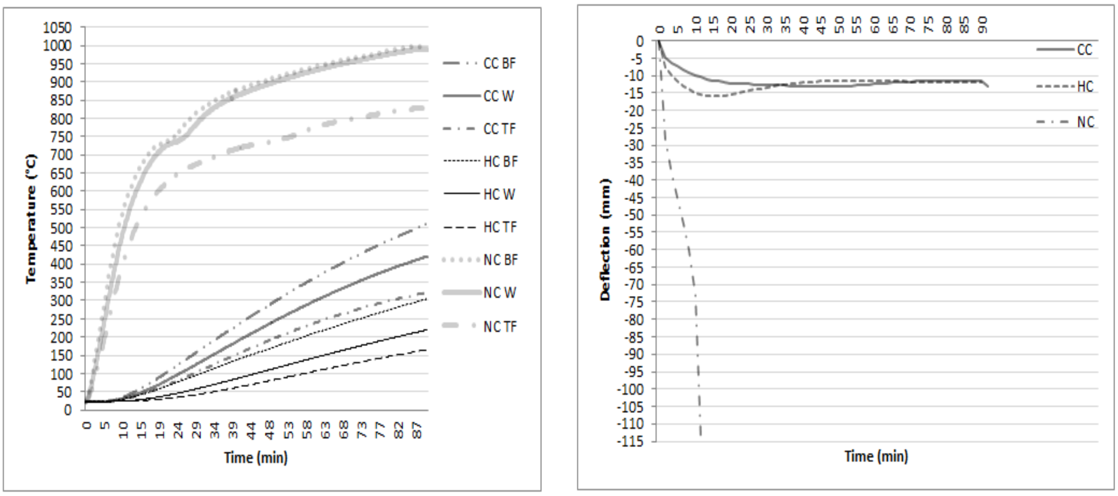

Figure 8 Temperature-Time & Deflection-Time curves for different casing types

The crititical tempearture calculated by Patil. M et. al [4] for load factor of 0.62 is 548.5°C. From the results obtained in present study, it is found that the maximum tempearture is always smaller than the critical temperature. Therefore after failure check of beams for 90 minutes in temperature domain it can be said that the beams have safe design. Exception is the beam with no casing in which the critical tempearure is reached in just 10 minutes, hence it is unsafe.

CONCLUSIONS

Different simulations of steel beam subjected to 3-side standrad fire ISO 834-1 and load for a load ratio of 0.62 with different thickness of fire proetction, casing type and type of protection were performed to determined the temperature distribution pattern and deformation behaviour. From the results obtained, the following conclusions can be made.

1) Geometrical parameters greately influence the temperature distribution in beam and with rise in temperature the steel expands. For high thermal strain the thermal stressses acting across the cross section produce high force reaction.

2) The thickness of insulation has big impact on fire resistance capacity of beam. The thinner the protection is the more temperature influence will the steel beams have and the faster but smaller the deformation is.

3) The partial protection leads to non-uniform temperature distribution in the beam due to which its deflection is twice that of the completely protected beam.

4) Beam with no casing couldnot sustain in fire for more than 10 minutes. Though the beam with counter casing has higher temperature than beam with hollow casing, they resemble almost same deflection behaviour after certain time.

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