Experimental and Numerical study of the temperature influence from the fire on the load bearing capacity of the protected steel beam with a secondary unprotected steel component.

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Abstract

In this work the thermo-mechanical response of the protected steel I-beams with secondary unprotected steel components under the influence of fire are studied. The primary aim of the study is to investigate the fire resistance of the protected beams. The beams were insulated by hollow encasement of uniform thickness made of calcium-silicate material. The structural load was applied externally vertically on unexposed side; while the temperature-time curve according to ISO 834 was considered for thermal (fire) load on the 3 exposed sides of beams. The load ratio and the critical temperature for the beams were calculated analytically by Eurocode 3. To carry out numerical analysis, the Finite Element Method (FEM) approach was implemented. The numerical and experimental results have been validated for temperature-time values measured at different locations and the maximum vertical deflection at the point of load applied on the beam.

Keywords

Fire resistance; Load bearing capacity; Protected Steel beam; Finite Element simulation; Experiment; Unprotected substructure; Eurocode 3

1 Introduction

There are two main purposes of fire protection system. One is to protect the residents from hazardous effects of fire and second is to mitigate the spread of fire to prevent structural damage. Fire protection system could be either Active or Passive. They help in easily detecting of fire and providing passages for escape. Active system is achieved by installing devices such as Sprinklers and Fire Alarms, while Passive system by insulation material on walls, slabs, Beams and other structures. The insulation material around the beam must have proper thickness to withstand the impact of a fire. This will also ensure the protection of other building structures and lead to safety of residents. In Eurocode 3 [1] a method has been described for steel structures to evaluate the thickness of insulation material.

The resistance capacities of a beam depend on the material properties such as specific heat, thermal conductivity, thermal expansion and stress-strain curve which vary with temperature [2]. To study the influence of fire on structures, experiments are conducted in fire furnaces. The surrounding air across the beam in furnace follow the fire temperature curves such of ISO 834 standards. There have been studies which explain the response of beams subjected to mechanical load and standard fire. The study conducted by Zhang et al. [3] for unprotected steel beam subjected to ISO 834 and localized fire. For localized fire it was concluded that the temperature distribution was non-uniform along the beam axis and throughout its depth. The temperature at the region of beam near to fire source was much higher than far regions. In comparison to ISO 834 the failure temperature in localized fire was too low. Yin and Wang [4] has done parameter study to analyze the large deflection of beam with different axial and rotational restraint and found that large deflection behavior of beam affect the survival temperature. Salama et al. [5] conducted experimental and numerical study on fire resistance of steel column with partial fire protection. The failure of the column takes place at unprotected part and for the shorter length of column, the critical temperature is higher.

The experimental results give a real picture of the deformation of the structures but the experiments in furnaces could be time consuming, hazardous and economically costly. Numerical studies have proven to be a substantial mean to analyze the structural behavior. ANSYS Mechanical is a numerical tool based on Finite Element Method approach that was used in this project to study the thermo-mechanical behavior of protected beams. Firstly the thermal simulation is executed to calculate the thermal gradients which are then transferred to mechanical simulation to find out deformation. The temperature-time histories at the points of interest from the numerical results are validated against experimental results.

2 Numerical Analysis

The finite element solver ANSYS Mechanical version 15.0 [6] has been used to carry out nonlinear transient simulation of steel beam to study the action of thermal (fire) load and structural load. The thermal expansion, temperature dependent steel material properties and Multilinear isotropic hardening stress-strain relationship for elasto-plastic behavior were considered in the simulation. The Newton-Raphson approach was enabled for the solution convergence. To determine the temperature distribution and deflection of beam, thermo-mechanical analysis was carried into two steps. First the thermal analysis was done to determine temperature values for each time step. These results were then used for mechanical analysis to calculate displacement values. The mesh remains the same in both the analysis but the elements get changed.

To reduce the computational cost the beams were modeled half symmetric. The geometry and the FE discretized model of the protected beam with substructure (attached unprotected steel component) is shown in Fig. 1 and Fig. 2 respectively. The contact behavior between beam and hollow encasement was modeled using contact elements CONTA174 and TARGE170 for the source and target surface respectively. The surface to surface contact was bonded.

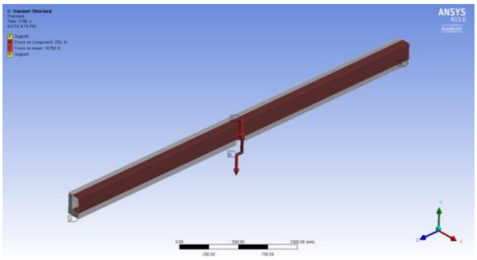


Fig.1: Half symmetry geometry of beam T1

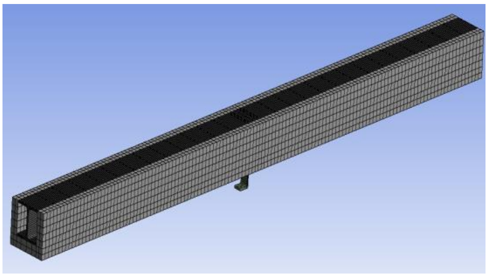


Fig. 2: Finite Element model of beam T1

2.1 Thermal Analysis

In thermal analysis the beam is subjected to the measured furnace temperature through 3 sides. The total heat transfer is the sum of heat transfer due to convection and radiation. The heat transfer coefficient for the exposed surfaces was taken as 25 W/m^2k and for unexposed surfaces as 9 W/m^2k. The emissivity value for steel and calcium silicate taken as 0.7 and 0.8 respectively. The thermal material properties of calcium silicate like density, thermal conductivity, specific heat as provided by manufacturer were 285 Kg/m^3, 0.18 W/mk and 1.05 KJ/KgK respectively. For steel the density was 7850 Kg/m3 and the thermal conductivity [1] and specific heat [1] were time dependent as shown in Fig. 3 and Fig. 4 respectively. In thermal analysis the model was meshed with SOLID90, 20-Node high order thermal element with single degree of freedom: temperature at each node. SURF152 elements were used for load and surface effect applications.

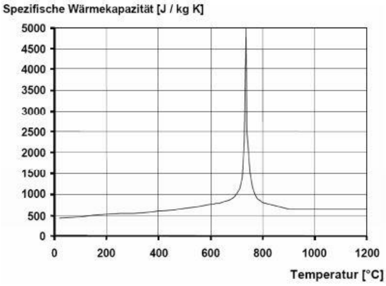


Fig. 3: Specific heat capacity of carbon steel [1]

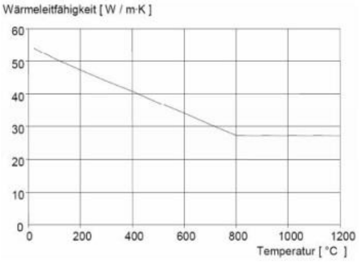


Fig.4: Thermal conductivity of carbon steel [1]

2.2 Mechanical analysis

In order to carry out mechanical analysis, beams T1, T2 and 23 were subjected to maximum vertical load of 33.5 KN, 36 KN and 63.7 KN respectively and the substructure to 5 KN. The beams were simply supported. The material properties were elastic-plastic and the stress strain relationship for S235 carbon steel [1] is shown in Fig. 5. The value of young modulus for steel and calcium silicate was 200 GPa and 135 GPa [7] respectively and poison ratio was taken as 0.3 for both. The coefficient of thermal expansion was temperature dependent. In structural analysis mesh had 3-D 20-node solid element SOLID186, having 3 degrees of freedom at each node:

translation in X, Y and Z direction. It supports plasticity, large displacement and large strain capabilities. SURF156 elements were present for surface line load applied effect.

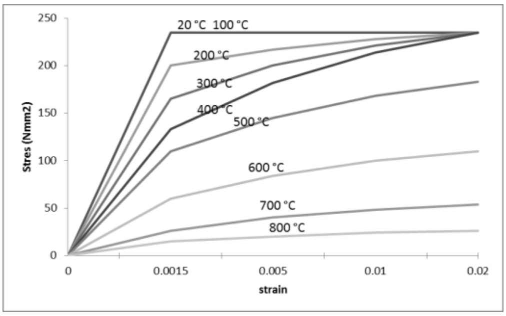


Fig. 5: Stress-Strain relationship for S235 for carbon steel at elevated temperature [1]

3 Experimental study

3.1 Description of the experiment

This experiment was carried to study the effects of fire exposed from the unprotected substructure on the fire protected steel beam. The scope focus lies particularly in the questions, how the heat will be generated in steel beams with an unprotected substructure, when the critical temperature will be reached and what influence does the substructure generates.

In total, three steel beams T1, T2 and T3 with different load capacity, load application points and different positions of the substructure were tested in the fire furnace. The location of the load application points and substructures are shown in the Table 1, where L is the length of beam.

Beam	Load application	Load factor	substructure
T1	1/2 x L	62%	1/2 x L
T2	1/3 x L	60%	1/3 x L
T3	1/4 x L	89%	1/4 x L

Table 1: Location of load application and substructure and load factor of each beam

The substructure was set to represent an attachment of sub-ceiling or other permanent installations on a ceiling structure. For this purpose a load of 47.3 kilos was attached on the substructure. The substructure was, against the claim of DIN 4102-4 [11], unprotected against fire. This was supposed to simulate a non-competent placement.

3.1.1 Description of the steel beams

The three test beams were HEA 160 Steel Beams with a total length of 3.85 meter. They were covered on three sides with 5 cm thick calcium-silicate plates. The upper side of all three beams, which was unexposed to fire, was uncovered. The calcium-silicate plates were connected to the beams via steel angle brackets on the upper flange. The plates were screwed into the steel angle brackets. The plates on the bottom of the steel beams did not have direct connection to the beam. They were connected via screws to the side plates. All the beams were coated along the total length of 3.40 meter, which was exposed to fire. The plate at the bottom of each beam has a 9 x

10.5 cm sized hole to allow a gap for substructure to steel beam attachment and to simulate a subsequent integration.

The substructure chosen was 5 cm broad and 16 cm high U-Profile (U-160). On all three beams these U-profile was welded with its upper flange directly to the lower flange of the beam. At the end of the lower flange of each U-Profile a load of 47.3 kilogram was fixed. This load was supposed to simulate loads out of a sub-ceiling or other installation. The substructure was located in the coating hole on each beam with a edge distance to each side about 2 cm. To measure how the beams were heated up, all beams were equipped with 11 thermo elements. All elements were located inside the covering: on the upper side of the lower flange, on the web and on the lower side of the upper flange. All thermo elements were fixed onto the beams with iron sheets, welded on the beam. The horizontal distance between thermo elements in each row was 50 cm. The exact locations of all elements are shown in Fig. 6.

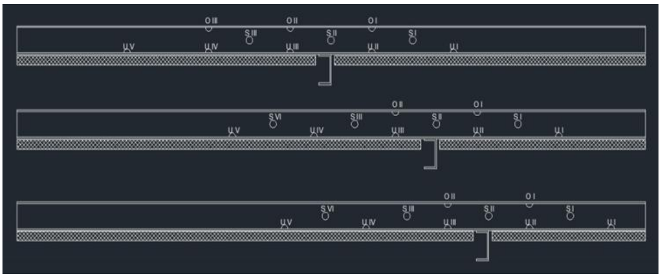


Fig. 6: Location of all thermo elements

3.1.2 Description of experiment

The experiment was conducted on all three beams in the test fire furnace of the TU Kasierslautern at once. Firstly, all the beams were coated and equipped with thermal elements. Also the substructure with its load of 47.3 kilogram was connected via welding to each beam. When the experimental setup was done, the beams were placed over the ceiling test frame on top of the fire furnace. All the openings were covered with concrete plates and high temperature wool. The composition of the load application for all three beams results out of the chosen geometry for the experiment can be seen in Fig. 7 and Fig. 8. To stress the beams one remote cylinder was located above the test frame. On all three beams each load application was provided with one way sensor to measure the particular bending. For monitoring the load of each beam, the beams T2 and T3 (see Table 1) were equipped with a load cell. The load on beam T1 was then calculated out of the total load given by the remote cylinder and the load application on one side and the load of beam T2 and T3. It was not possible due to geometric reasons to place a load cell on beam T1. At the beginning of the experiment the load had to be established. During the experiment the load needed to be constant. After this, the actual experiment begun by starting the 12 burner of the test oven. A time limit for the experiment was set by 180 minutes. Reasons to abort the experiment were failure of one beam or the blow out of flames or big amounts of heat.

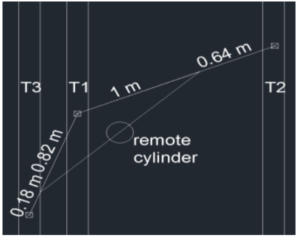


Fig. 7: Schematic diagram of the load application

Fig. 8: Load application set in experiment

3.2 Calculations

The beams were calculated in terms of statics and for thermal loads. In terms of static calculation all actual present loads were included. The substructure was considered only in the static calculation, not in the thermal. In this way the actual influence of the unprotected substructure and its load was studied.

3.2.1 Static calculation

The total load of each beam consists out of:

- Self weight of each beam	1.1700 KN/each
- The load out of the fire protection coating	0.2108 KN/each
- Moment loading out of the substructure (load and own weight)	0.0235 KNm
- Load out of the load application on each beam (total application)	5.0100 KN (total)
- Load out of the remote cylinder	128.00 KN

Each beam has its own load application. The load application induced a specific force in each beam which can be seen in Table 2 and the substructure induced a moment of 0.0235 KNm. Out of these two components, a total for the beam moment is formed. Compared to the maximum capacity of 51.7 KNm [8] a utilisation factor can be calculated. This factor is given in Table 1.

Beam	Load application [m]	Total Load [kN]	Total Moment [kNm]
T1	1.925	33.50	32.26
T2	1.28	36.00	30.82
T3	0.96	63.70	46.00

Table 2: Total load and total moment force of all test-items

3.2.2 Thermal calculation

For the thermal calculation it was assumed that all three beams are completely coated and the substructure does not exist. The results of the thermal calculation were compared to the test results and the results of the simulation.

Data of the calcium-silicate plates as provided by supplier [9]
Thermal conductivity $\lambda = 0.18$ [W/mK]
Density ρ_p = 285 [kg/m³]
Specific heat C_p = 1050 [J/kgK]
Insulation thickness = 2 x 2.5 [cm] = 5 [cm]

Calculation of the critical temperature by Eurocode 3 [1]

$$\theta_{a,cr} = 39.19\left[\frac{1}{0.9674\,\mu_0^{3.833}} - 1\right] + 482$$

Table 2 shows the critical temperature for the 3 sides protected beam (without substructure):

	T1	T2	T3
Load factor μ	0.62	0.60	0.89
Critical temperature $\theta_{a,crit}$ [°C]	548.5	554.3	463

Table 3: Critical temperatures of the beams according to load factor

3.3 Performance of the experiment

All beams where fit in the ceiling test frame as planned, obdurate against blow out of flames and heat and equipped with the required measuring instruments and elements. Afterward the load application was set and arranged. The load out of the remote cylinder was set and thereafter the burner of the test oven was started. The fire in the furnace was started according to ISO 834 standard fire curve. The experiment had to be abounded after 75 minutes after the failure of an internal isolation wall which lead to a blow out of massive amounts of heat.

3.4 Observation

During the whole time of the experiments the actual measured temperature in the test oven was below the temperatures claimed by ISO 834 standard fire curve.
After 21 minutes few plates fell down into the test oven. These plates were Isolation bricks, as seen after the experiment.
After 30 minutes all cables for measuring tools equipped to beam T1 scorch under heat, blown out of the oven. At this point it was assumed, that the cables scorched because of an unusual heat rise in beam T1.
After 59 minutes the cable for the way sensor on beam T2 scorched under a heat blow out.
After 73 minutes it came to a massive heat blow out. The front side of the steel ceiling test frame was blackened due to fire exposure.
After 75 minutes the experiment was aborted due to the high risk for the oil-powered remote cylinder to catch fire.

4 Results comparison

4.1 Experiment results

None of the three test models collapsed, until the experiment was aborted, after 75 minutes under the mechanical or thermal load. They also didn’t reach the critical temperature. Because of the collapsed inner isolation wall, which was detected afterwards, it was not possible to run the experiment any longer. The collapsed inner isolation wall was also the reason for the discrepancy between the temperatures claimed by ISO 834 standard fire curve and the actual measured temperatures in the fire furnace.

The measured data from beam T1 was available only until 30 minutes. All data for beam T1 after this time was unusable.

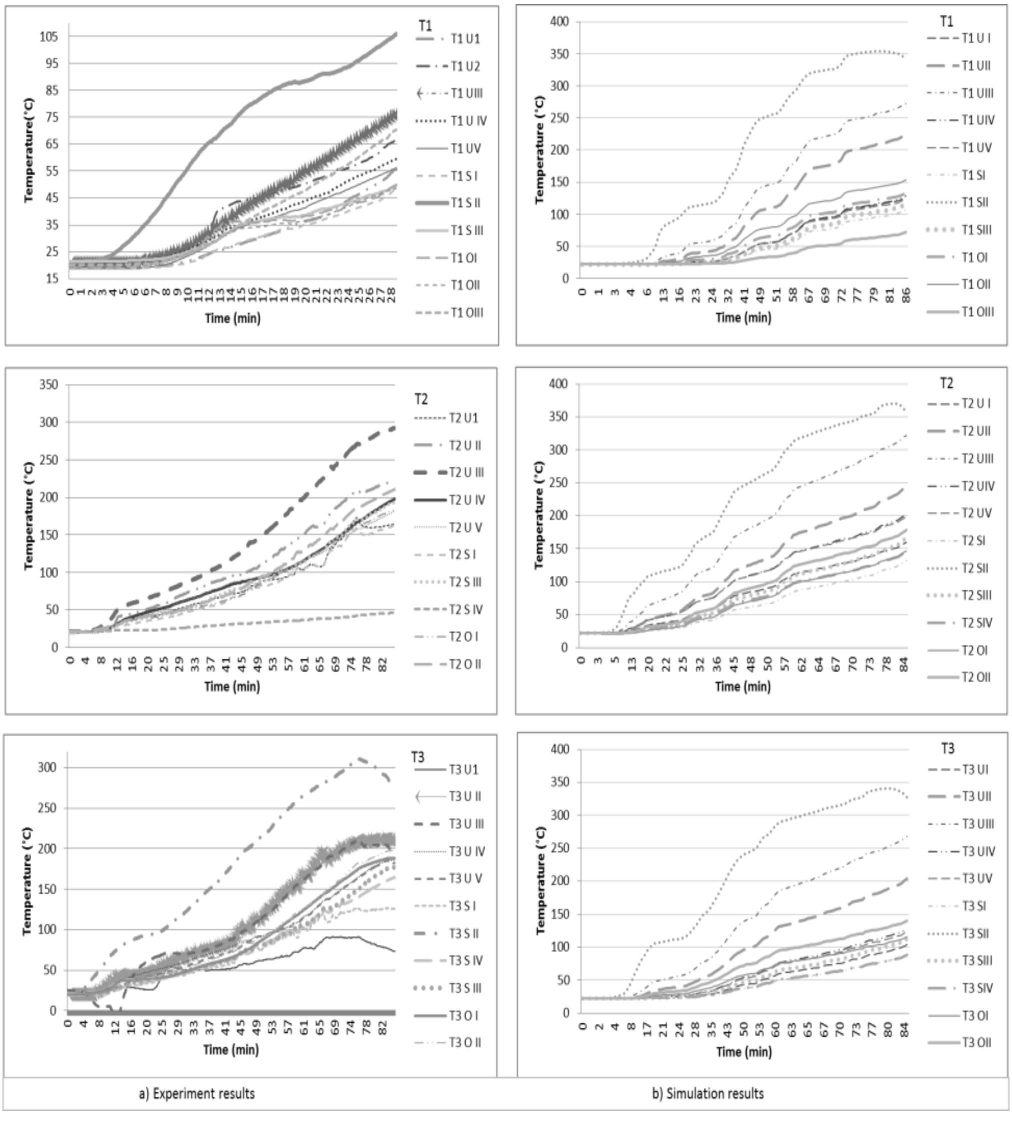
During the whole test the important data of the measuring point S II of beam T2 was not functioning, so its data couldn’t be evaluated and compared to the other beams.

With the usable data shown in the figure 9 (a) it can be seen how the temperature was raised on the measuring points. The measuring points of the thermal elements are shown in figure 6.

As seen in the fig. 9 (a) all three beams exhibit same behaviour. Independent of the location of the substructure, a massive raise of temperature is seen around it while the measuring points in farther distance didn’t heat as much. The rise of temperature also seems to behave related but can’t be estimated clearly due to the unusable measured data and the broken inner wall.

4.2 Simulation results

Fig. 9 (b) shows the temperature-time plot for the same locations as taken in experiments. Through the hole in the insulation, the fire was exposed directly to the steel. The SII location just 76 mm above the hole was subjected to higher temperature in comparison to other locations. As expected the temperature for SII is always higher for all beams. In very short time a sharp increase in temperature is observed. The UII and UIII locations on lower flange of beam and were on the left and right side of the hole at the distance of 250 mm have slight variation and their curve are below that of SII. The locations UI, UIV and UV are at far distance from hole and have little effect. The temperature at these locations calculated mostly due to the heat conduction through insulation from the bottom side. Similarly, in comparison to SIII, the temperature at locations SI and SIV is lower. The locations OI and OII on the upper flange were the least exposed locations.



a) Experiment results

b) Simulation results

Fig. 9: Temperature-Time history for T1, T2 and T3 beams

Fig. 10 shows the temperature distribution for the steel beam T1. The insulation is hidden in figure. As it can be seen that at the bottom flange in the middle where the substructure and hole is present, the temperature is maximum. The maximum temperature at the bottom flange is 536 °C in 75 minutes. The temperature was propagated and also reached the top flange where the temperature was 220 °C.

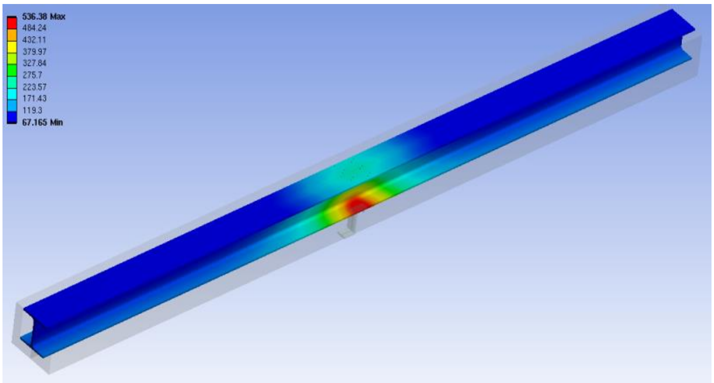


Fig. 10: Temperature distribution in beam with substructure at 75 minutes

5 Conclusions and Discussion

In both experimental and numerical analysis, the same temperature-time trend was seen. It was observed that the temperature around the substructure rose much faster than in the other parts of the beams. This applies to all three beams independent of the location of load application and substructure and also for the different loads. Particularly, the temperature in measuring point S II rose very fast in all beams and behaviour was very similar for all beams.

The maximum deflection value at the point of load applied for beams T1 for run time of 30 minutes and T2 and T3 for run time of 75 minutes from simulation are 15 mm, 13 mm and 15 mm respectively and from experiment results are 13 mm, 16 mm and 19 mm respectively. The variations between the data from the experiment and the simulation can be explained by the circumstances of the experiment described in subsection 3.4 (Observations) and section 4 (Results). The maximum temperature found from the simulation and experiment was in the range of 300 - 350 °C for location SII at 75 minutes for all beams. Neither of the beams could reach the critical temperature, as shown in Table 2, calculated by Eurocode. From simulation, the maximum temperature at the lower flange of the beam with the substructure was 536 °C in 75 minutes. Another simulation was performed for the beam without substructure and the temperature observed at the lower flange was only 211 °C in 75 minutes. This clearly shows that if the beams in our study were exposed to fire for longer time, then there could be possibility of the failure of beam, as they could have reached the critical temperature in shorter time. Also it can be concluded that the unprotected substructure can be dangerous for the load bearing steel beams in fire.

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