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FIRE BEHAVIOUR OF COMPOSITE STEEL TRUSS AND CONCRETE BEAM

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ABSTRACT

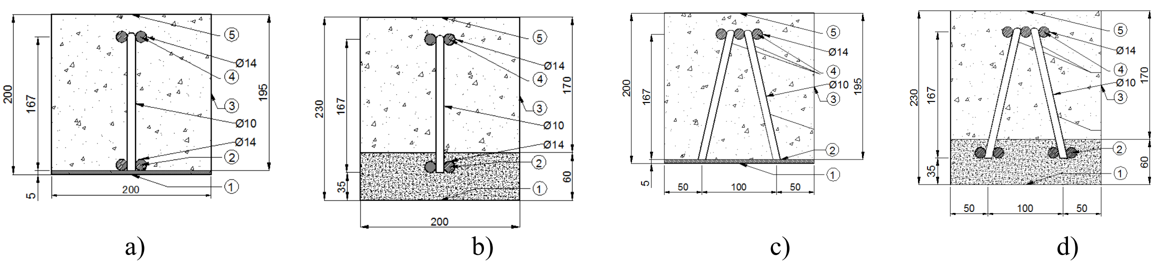
This work compares the thermal behaviour on four different Composite Steel Truss and Concrete Beam (CSTCB), when submitted to two different fire conditions (one side and four sides of fire exposure). This analysis aims to be a preliminary assessment of a series of experimental tests. CSTCB with concrete plate delay temperature evolution on the steel truss and reinforcement, increasing fire resistance.

Keywords: Fire, Numerical Analysis, Composite Beam, Steel Truss and Concrete.

INTRODUCTION

The prefabricated Composite Steel Truss and Concrete Beams (CSTCB) are composite elements designed to resist bending forces, consisting of a steel truss encased in concrete, casted in place, with different typologies and a steel base plate or pre-casted concrete plate, encased partially or totally in casted concrete. These beam elements present a wide variety of building solutions, being characterized by two constructive stages. The first stage considers the element made only by the self-supported steel truss, assuming the beam as simply supported. This structure is able to support its own weight and the weight of the slabs without any provisional supports. The design should follow the general rules for steel structures (CEN c, 2005). In the second stage, truss is encased by concrete and behaves similarly to a reinforced concrete (RC) beam (Quaranta G., 2011).

Longitudinal reinforcement at the bottom and at the upper chord depends on the chosen configuration. Usually two upper bars require one plane steel truss, while three or four upper rebars require two or three plane steel trusses, respectively (Quaranta G., 2011), see Fig. 1.



a) b) c) d)

Fig. 1 - Different typologies to be analysed: a)TI-SP; b) TI-CP; c) TII-SP; d) TII-CP.

These building elements have been widely used in Italy, generally for important structures.

Table 1 identifies each CSTCB to be analysed in the present work. Two gross cross section dimensions were considered (200x200 mm and 230x200 mm), by using a different number of steel trusses (Type I - TI and Type II - TII) and different material plate on the bottom (steel plate - SP and precast concrete plate - CP). The geometry and number of each rebar are also defined.

Table 1 - Description and designation of the elements.

Identification	Number of Trusses	Cross section dimensions b x h (mm)	number Rebars bottom+top	Rebars Diameter (mm)	Truss diameter (mm)
TISP-#	One	200x200	2+2	Ø14	Ø10
TICP-#	One	230x200	2+2	Ø14	Ø10
TIISP-#	Two	200x200	0+3	Ø14	Ø10
TIICP-#	Two	230x200	4+3	Ø14	Ø10

State of the art

The original calculation method used to fully understand the mechanical behaviour of CSTCB was proposed by Leone (Leone S., 1967; Tesser L., 2009). The evolution of the proposed method is well explained in this thesis. Three sets of experiments were developed. The first set considered four tests designed for Steel Truss (ST) in order to characterize the first stage and more four tests with complete casting of concrete (CSTCB) in order to characterize the second stage. The main objective was to investigate bending and shear failure modes. The second set used similar beams using different types of steel trusses. Two of them used ST stand-alone while six of them used CSTCB. The third set used a prestressed concrete base plate with steel truss without concrete cast to analyse cracking damage and propagation.

The best practice of Eurocodes (CEN b, 2002; CEN c, 2005 and CEN f, 2004) was also used by Quaranta *et al* (2011), to verify the structural safety of CSTCB at room temperature. Authors presented an interesting formula to investigate the stability and other limit states for simply supported beam for the transitory stage 1, by using the design loads from self-weight of the truss and dead loads from the floors. Regarding the Ultimate Limit State (ULS) of the steel truss, safety should be verified against element instability (lateral torsional buckling) or any local instability (buckling of each element diagonal or longitudinal bar) during building construction, according to EN1993-1-1. The resistance of the cross section should be also checked for the maximum bending moment and vertical shear. The Serviceability Limit State (SLS) should be verified in terms of stresses, deformations and cracking. For the second stage, all the remaining loads should be considered, such as the self-weight of concrete filling and also the live loads. Loads should be calculated according to EN1991-1-1 (Cen b, 2002), while the basis of design (partial safety factors based method) should consider EN1990 (CEN a, 2002). The structural design at room temperature was carried out by defining initially the gross dimensions of the cross sections (b and h), followed by the design of the steel truss and reinforcement, according to both limit states (SLS and ULS).

Trentadue *el al* (2011) developed a closed form solution for the elastic critical moment, avoiding any eigen-value three dimension numerical solutions. This formula should be validated by numerical methods.

Another important ULS to be analysed is related with the behaviour of the bottom steel plate. Plate punching shear resistance should be verified against transversal load of truss elements. Quaranta *et al* (2011) used classic von Mises resistance criterion to verify the safety of the bottom plate.

Tesser and Scotta (2013) recently presented twenty four tests on twelve CSTCB elements. The objective of this study was to analyse shear and flexural strength with different cross section dimensions and beam lengths, and compare the results with theoretical values, using European and American standards. Authors concluded that flexural experimental results are in good agreement with the theoretical results and some conservative shear results were demonstrated with respect to shear experimental results in the European standard (CEN e, 2004).

During the years of 2007-2009, the Italian Association ASSOPREM developed different lines of research to analyse CSTCB elements (Assoprem, 2011). At the University of Bologna, Savoia and Vicenzi studied the stability of steel truss by using the analytical formulation and numerical validation. At the University of Salento, Aiello and Cancelli developed a series of push-out tests to assess force transmission from steel to concrete. At the Universities of Brescia and Bergamo, Minelli and Riva tested CSTCB to shear load, performing experimental tests with stocky beams under three bending points. At the University of Calabria, Ombres compared the flexural behaviour for different typologies (bottom steel plate, bottom concrete plate and without bottom plate) and for different level of reinforcement and different types of concrete and steel grade, under four bending points. Six CSTCB were tested under flexural loading and compared with the flexural behaviour of two reinforced concrete beam, using the same longitudinal reinforcement. At the University of Brescia, Plizzari and Cominoli carried out several experimental tests to determine the behaviour of the bottom plate, in particular the progressive damage of concrete. Concrete mix was prepared with special additives and fibres to control crack propagation.

Objectives

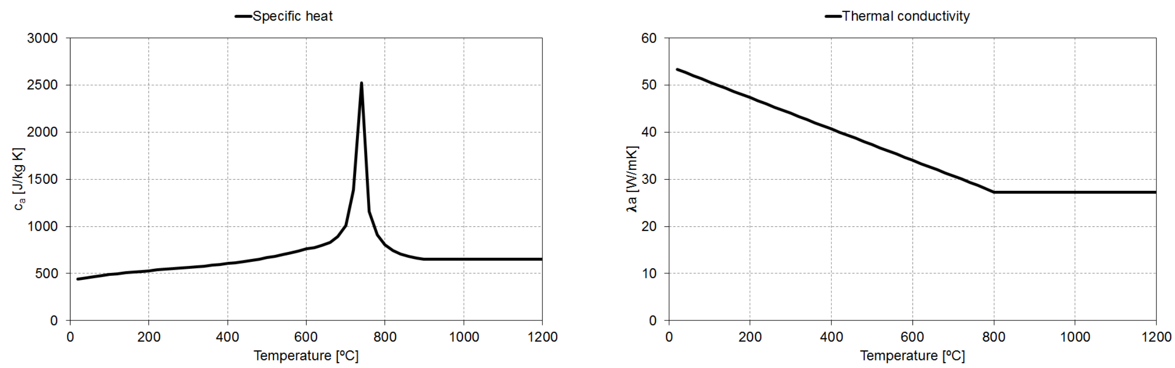
The main objective of this study is to determine the temperature evolution on CSTCB elements, when exposed to fire conditions. The models were analysed by using the finite element method (Ansys, 2013) to simulate the effect of fire, using the ISO 834 standard fire nominal curve (ISO, 1999). Four different models were built to analyse two fire scenarios (fire from one side (bottom surface) and from four sides.

MATERIAL PROPERTIES

The temperature effect in the thermal properties of both materials is represented in this section. These properties have been defined according to European standards. Eurocode 3 part 1-2 (CEN d, 2005) concerns about structural design of steel structures under fire conditions, while Eurocode 2 Part 1-2 (CEN f, 2004) defines structural design of concrete under fire conditions. The following properties were defined for each material: density (kg/m^3), specific heat (J/kg K), emissivity (-), and thermal conductivity (W/mK).

Steel

The value of the density was defined as constant, $\rho_a = 7850\ [kg/m^3]$. The value of the emissivity on the surface of the steel was considered equal to 0,7. The specific heat is defined in Fig. 2, characterized by the peak around 700ºC, related with an allotropic transformation. Fig. 2 also defines the variation of conductivity with temperature.



a) Specific heat of carbon steel. b) Thermal conductivity of carbon steel.

Fig. 2 - Thermal properties of steel.

Concrete

The concrete was considered with siliceous aggregates, assuming a moisture value of 3% of weight.

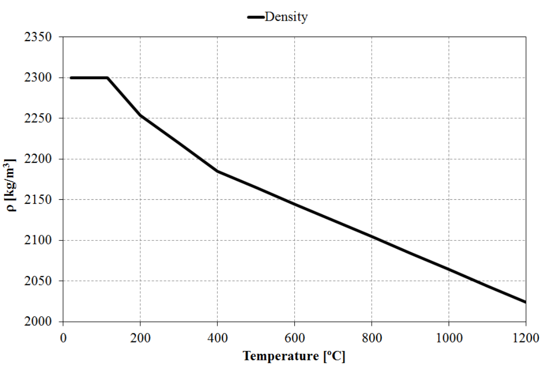
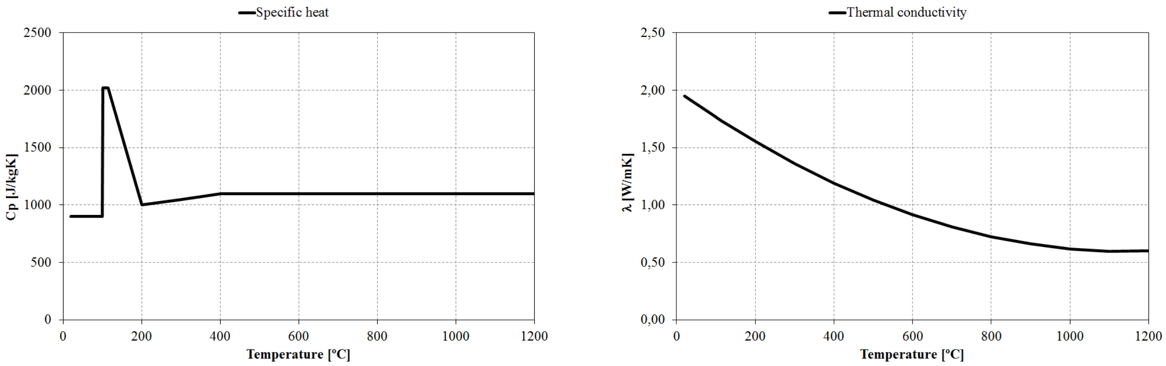


Fig. 3 - Thermal property of concrete (density).

Fig. 3 defines the effect of temperature in the density of the material. When temperature increases, concrete releases water. After 100ºC, the water starts to evaporate, being followed by other chemical reactions to release water. The emissivity for the surface of the concrete was defined constant and equal to 0,7.

Fig. 4 defines the effect of temperature on the specific heat and conductivity. The first property presents a peak value between 100ºC and 115ºC, eventually, a drop occurs between 115ºC and 200ºC; this peak reflects the first evaporation phase of water. The upper limit for the thermal conductivity was considered for the model proposed herein.



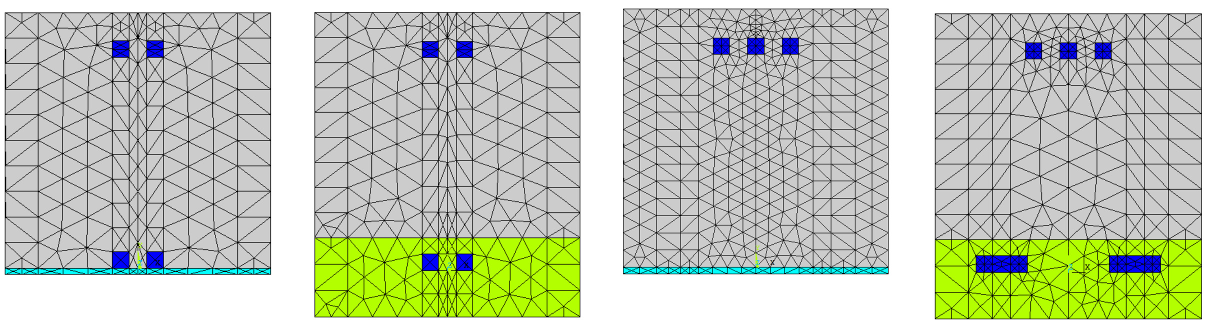
a) Specific heat for concrete. b) Thermal conductivity for concrete.

Fig. 4 - Thermal properties of concrete.

NUMERICAL MODEL

Three dimension analysis was required to analyse the time temperature history of each model. This analysis used three dimensional finite element Solid 70 (Ansys, 2013). This element is able to analyse any thermal conduction analysis in three dimensions. It uses 8 nodes, and one degree of freedom in each node (temperature).

Fig. 5 presents one section of each mesh used for each CSTCB beam model. The steel truss is represented in dark blue, the steel plate is represented in light blue, the concrete in grey and the pre-cast bottom plate in green.



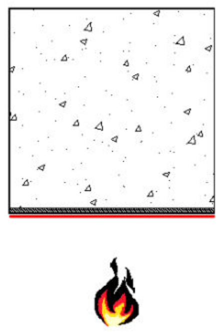
a) TISP. b) TICP. c) TIISP. d) TIICP.

Fig. 5 - Mesh models using tetrahedral finite elements.

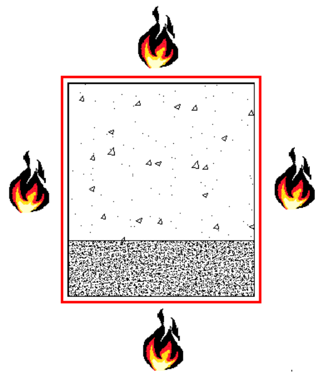
These models have a length of 1310 mm, for matching further real testing in the laboratory of the polytechnic Institute of Braganza. The simulations were performed under a full transient solving method, in a total time of 3600 seconds.

Fire simulation model

The models were exposed to fire conditions, simulating two different fire scenarios, using the standard nominal fire curve. According to each fire scenario, the external surfaces of the model were submitted to both radiation and convection conditions, using the condition for fire environment (emissivity equal to 1,0). Fire scenario 1 (one side) will replicate the behaviour of an embedded beam in the slab, exposed to fire from the bottom surface, while fire scenario 2 (four sides) will simulate a full engulfed beam in fire (Fig. 6).



a) Scenario 1.



b) Scenario 2.

Fig. 6 - Fire scenarios for every type of base plate and truss.

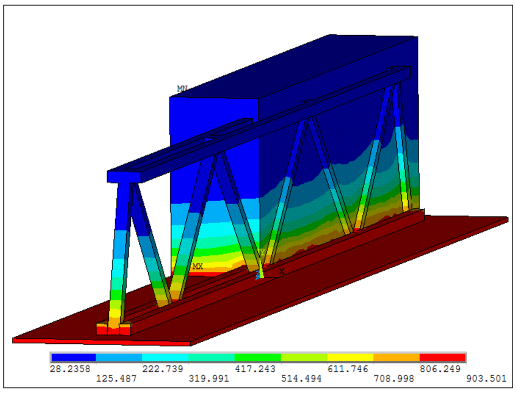
Results with fire scenario 1 (one side)

The results were taken from the middle section of the beam models, and include temperature time history in five points (Fig. 1). Results also include the isosurface temperature for 500ºC at two time steps, 1800 s and 3600 s.

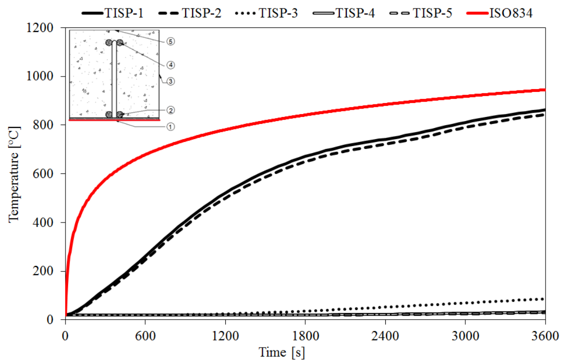
The first simulation result is the TISP (Type I with Steel Plate), using fire scenario 1. The results are represented in Fig. 7. The steel plate is transferring heat flux to the steel truss, overheating the bottom chord of rebars. At the end of simulation time (3600 s) the temperature of the top chord of rebars is still equal to the room temperature. Fig. 7c and Fig. 7d show the caped isosurface of 500ºC in two different time steps (1800 s and 3600 s). The concrete temperature is higher near the truss and during the heating phase, this 500ºC isosurface will raise up very slowly. The bottom chord of rebar is below the isosurface for 30 and 60 minutes.

The next simulation describes the effect of fire scenario 1, on TICP (Type I Concrete Plate). These results were recorded in Fig. 8. The temperature of the concrete plate is very high in comparison with temperature in the truss elements. The temperature of the top and bottom chords of rebars is much closer in comparison with the previous simulation. The isosurface of 500ºC in concrete is always underneath the bottom chord of rebars, as recorded in 30 and 60 minutes of the simulation, see Fig. 8c) and Fig. 8d).

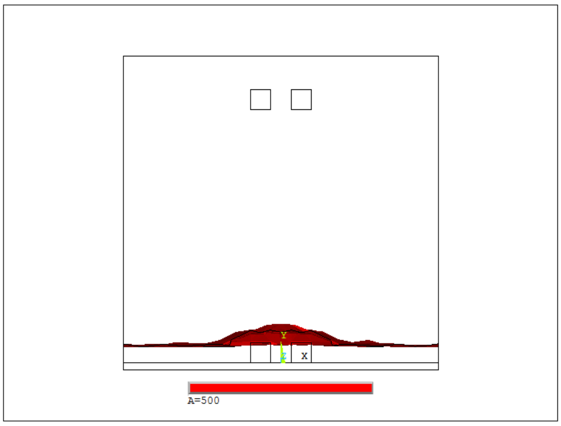
The results of fire scenario 1 on TIISP (Type II with Steel Plate) are represented in Fig. 9 (the bottom chord of rebar was omitted for this typology). Temperature in plate is very high during the heating phase but the top chord of rebar is almost near the room temperature (Fig. 9a and Fig.9b). Temperature in concrete will rise during the time of fire exposure, particularly near the steel trusses, due to heat flux (Fig. 9 c and Fig. 9 d).



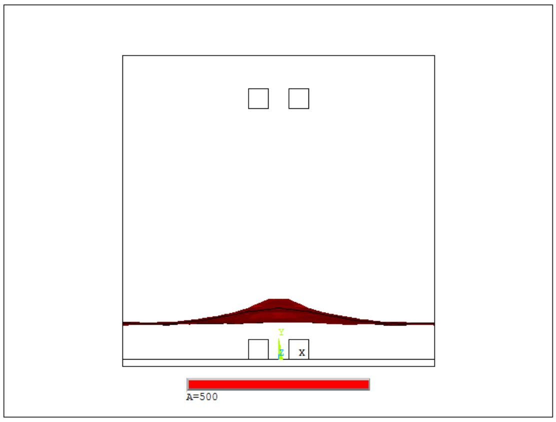
a) Temperature field (t=3600s).



b) Temperature/time history in specific points.



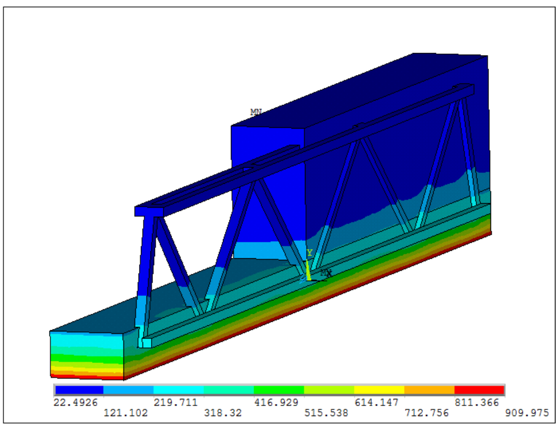
c) Isosurface of 500ºC (t=1800s).



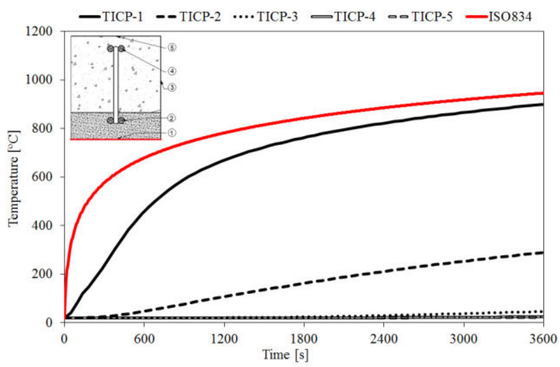
d) Isosurface of 500ºC (t=3600s).

Fig. 7 - Simulation of CSTCB Type I Steel Plate, submitted to fire scenario 1.

The effect of fire scenario 1 on the TIICP beam (Truss type II with Concrete Plate) is also represented in Fig. 10. This cross section includes four longitudinal rebars in the bottom chord. The heat flows from bottom to the top, though the steel truss, but the top chords of rebar remains at low temperature (room). The isosurface of 500 ºC is also represented in Fig. 10, showing that this surface will remain below the bottom chords of rebar, after 60 minutes of fire exposure.

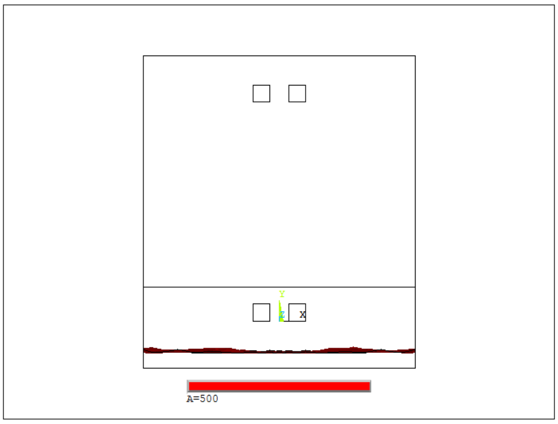


a)Temperature field (t=3600s)

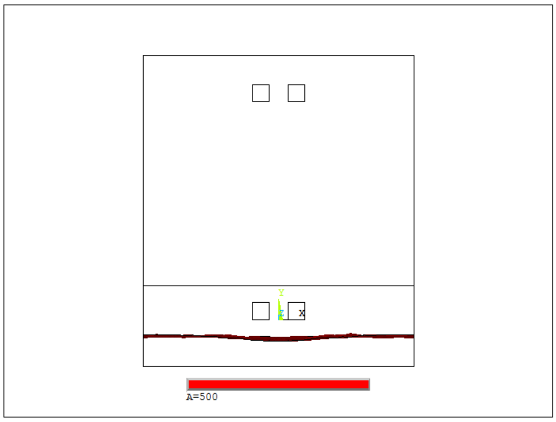


b)Temperature/time history in specific points

Fig. 8 - Simulation of CSTCB Type I Concrete Plate, submitted to fire scenario 1*(continue)*

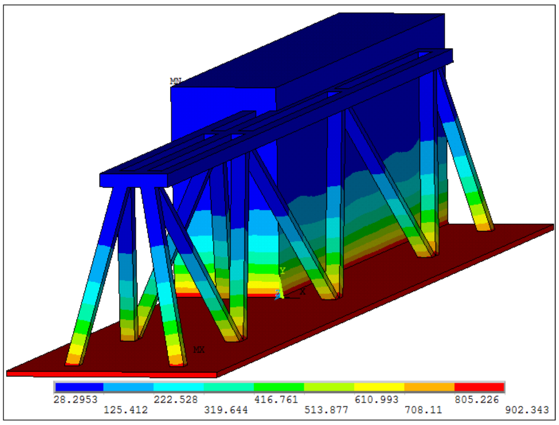


c) Isosurface of 500ºC (t=1800s).

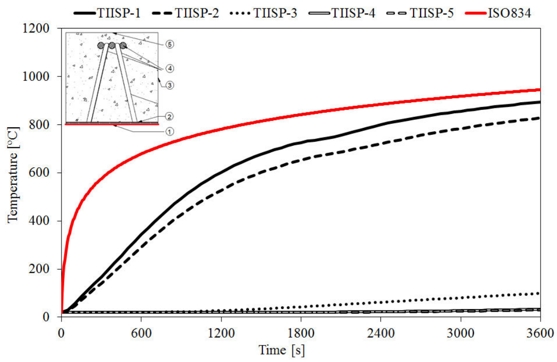


d) Isosurface of 500ºC (t=3600s).

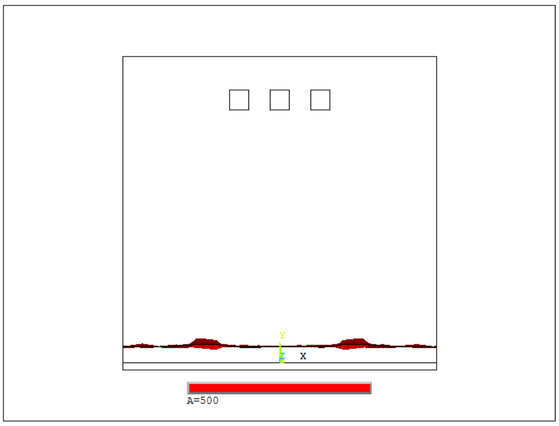
Fig. 9 *(continued)* - Simulation of CSTCB Type I Concrete Plate, submitted to fire scenario 1.



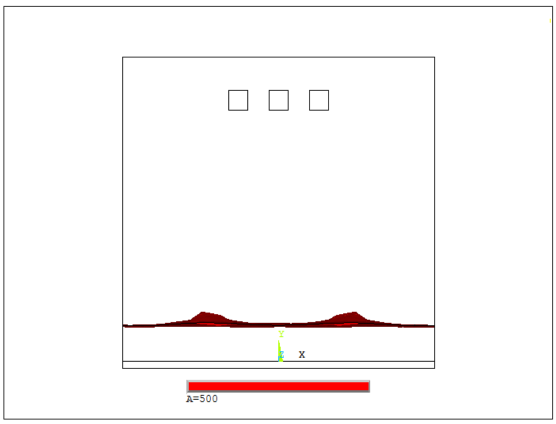
a) Temperature field (t=3600s).



b) Temperature/time history in specific points.

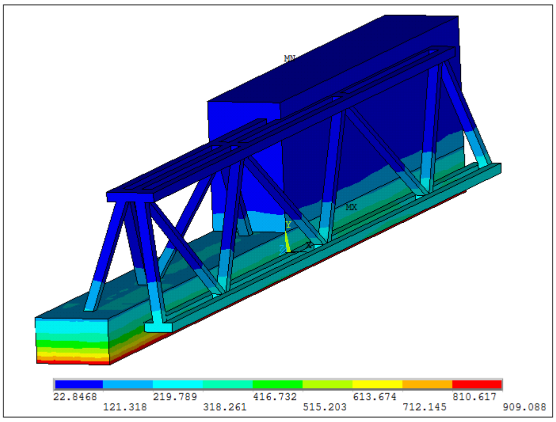


c) Isosurface of 500ºC (t=1800s).

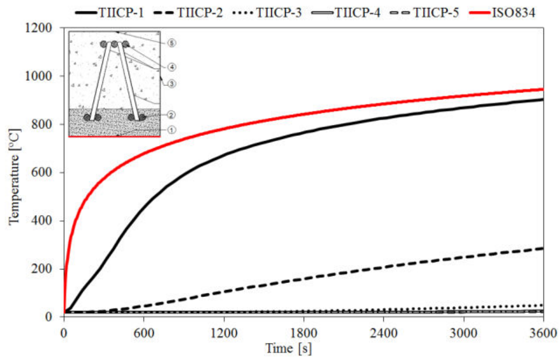


d) Isosurface of 500ºC (t=3600s).

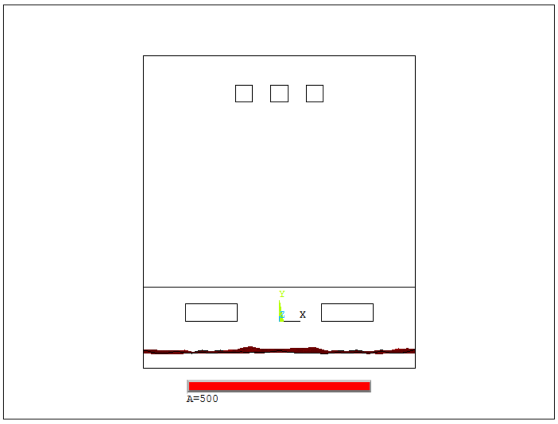
Fig. 10 - Simulation of CSTCB Type II Steel Plate, submitted to fire scenario 1.



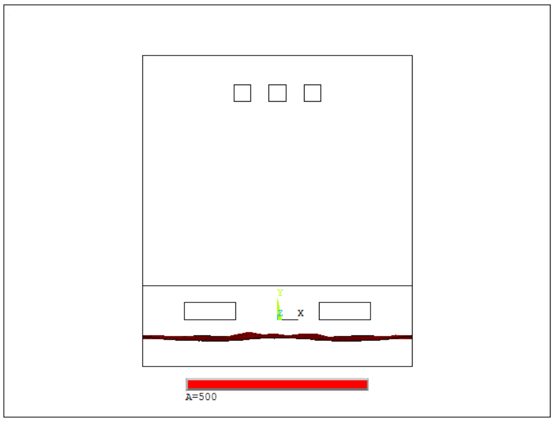
a) Temperature field (t=3600s).



b) Temperature/time history in specific points.



c) Isosurface of 500ºC (t=1800s).



d) Isosurface of 500ºC (t=3600s).

Fig. 11 - Simulation of CSTCB Type II Concrete Plate, submitted to fire scenario 1.

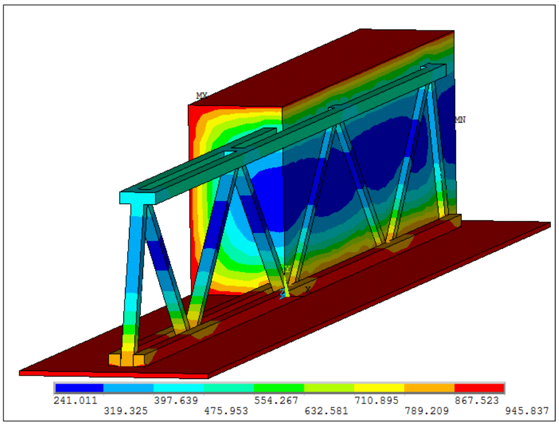
Results with fire scenario 2 (four sides)

This section presents the results of each cross section when exposed to fire scenario 2 (beams fully surrounded on fire).

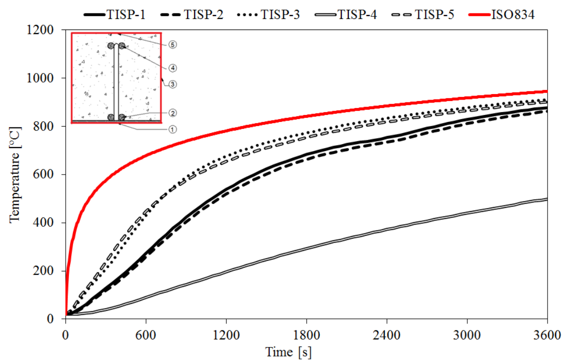
The first result accounts for the behaviour of TISP (Type I Steel Plate) exposed to fire in four sides. The results are presented in Fig. 11, showing the temperature field for 60 minutes and the temperature – time history for five specific points during fire exposure. Temperature of the top chord of rebar is smaller than the bottom chord, due to the existing contact with the steel plate.

The isosurface of 500ºC is also represented in concrete, showing that the bottom chord of rebar is out of the surface while the top chord is always inside the surface for 30 and 60 minutes. The bottom chord of rebars is rapidly overheated by heat flux of the steel plate.

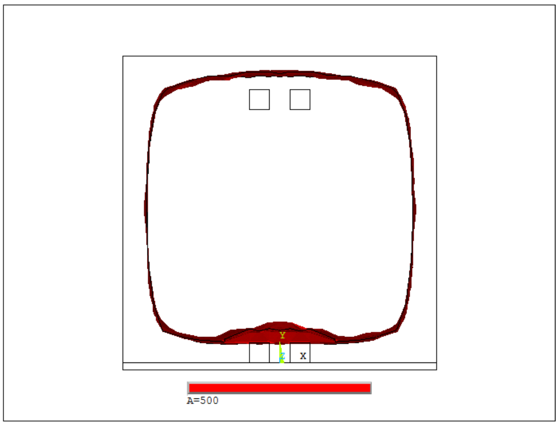
The effect of fire scenario 2 on TICP (Type I Concrete Plate) is ahead represented in Fig. 12. The temperature field shows a large temperature gradient from the outer surface to the interior of the cross section. The temperature on both chords of rebars is always below 500 ºC during 60 minutes of fire exposure.



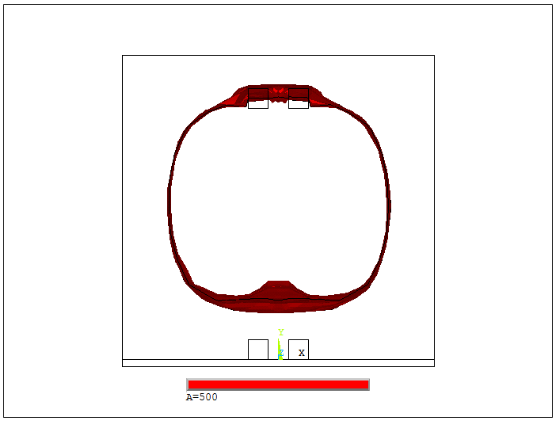
a) Temperature field (t=3600s).



b) Temperature/time history in specific points.



c) Isosurface of 500ºC (t=1800s).

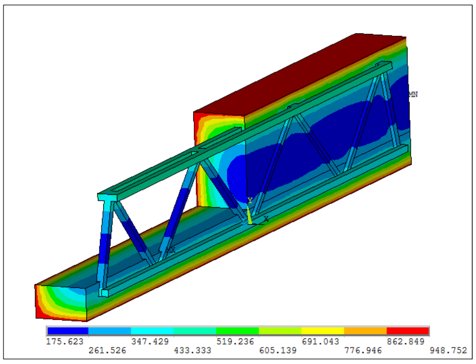


d) Isosurface of 500ºC (t=3600s).

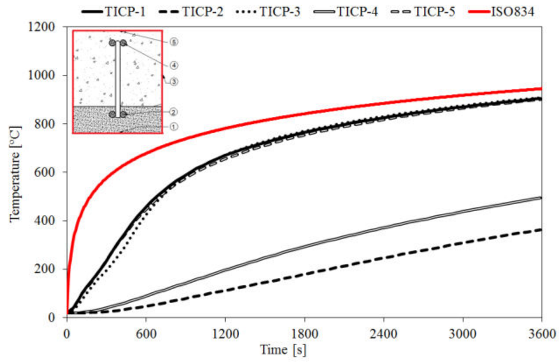
Fig. 12 - Simulation of CSTCB Type I Steel Plate, submitted to fire scenario 2.

Fig. 13 describes the results of the simulation with TIISP (Type II Steel Plate) under fire scenario 2. In Fig. 13 a) and Fig.13 b), the temperature field is represented after 60 minutes and temperature time history is also plotted for the same five points defined in Fig. 1. The temperature of point 4 rises according to the temperature of the fire compartment, but is always smaller in comparison with other points in analysis. After 30 minutes of fire exposure the top chord of rebar is inside the isosurface of 500ºC, while after 60 minutes is just on the border.

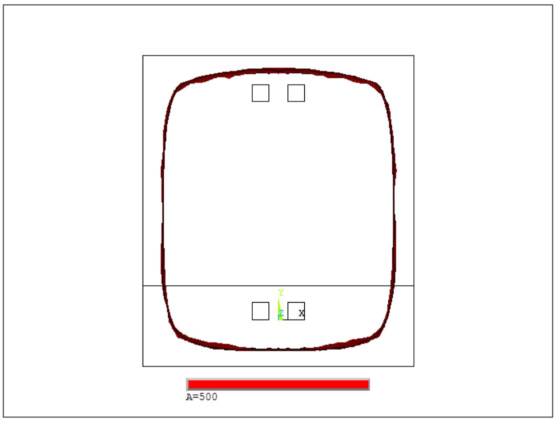
The effect of fire scenario 2 on TIICP (Type II Concrete Plate) is represented in Fig. 14. The temperature field shows a large temperature gradient from the outer surface to the interior of the cross section, as well as verified for the same scenario on TICP. The difference between the temperature of the top and bottom lines is smaller in this case. The isosurface of 500ºC is represented in Fig. 14 c and Fig. 14 d. This surface shows the location of the surface inside the concrete, for 30 and 60 minutes. The effect of the steel rebars on the shape of this line can be noticed. Both chords of rebar are below this temperature during 30 minutes of fire exposure. Furthermore, is showed that rebars started to become affected by this surface after 60 minutes of fire exposure.



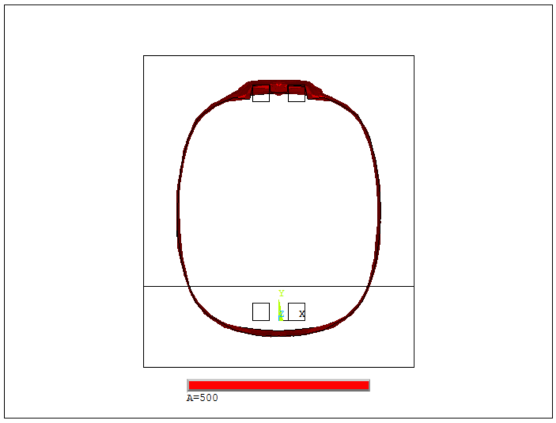
a) Temperature field (t=3600s).



b) Temperature/time history in specific points.

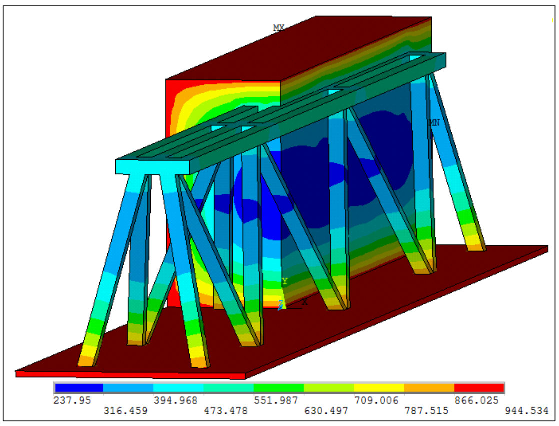


c) Isosurface of 500ºC (t=1800s).

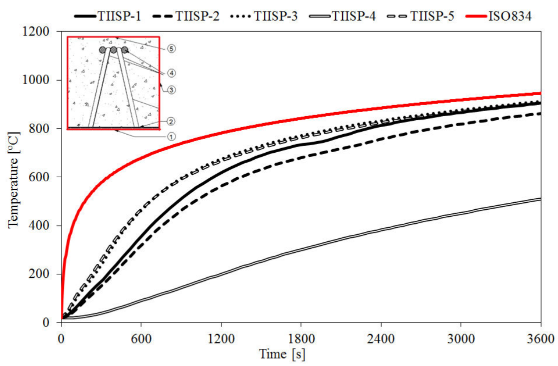


d) Isosurface of 500ºC (t=3600s).

Fig. 13 - Simulation of CSTCB Type I Concrete Plate, submitted to fire scenario 2.

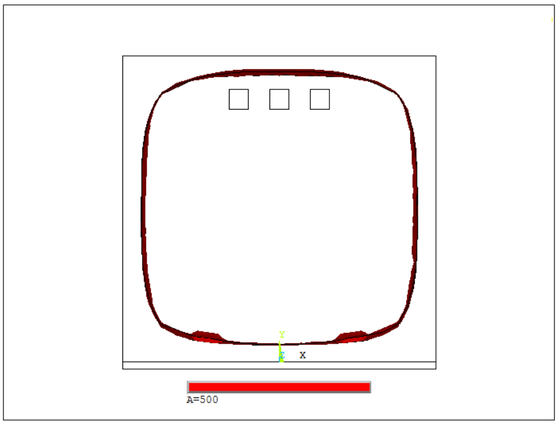


a) Temperature field (t=3600s)

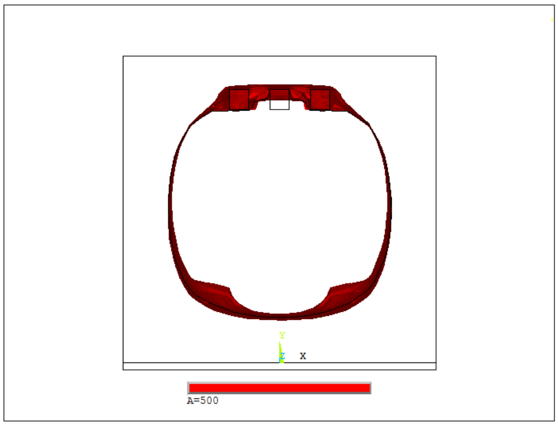


Temperature/time history in specific points

Fig. 14 - Simulation of CSTCB Type II Steel Plate, submitted to fire scenario 2 *(continue)*

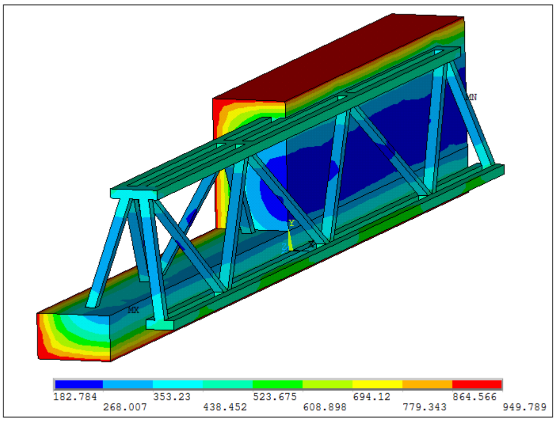


c) Isosurface of 500ºC (t=1800s).

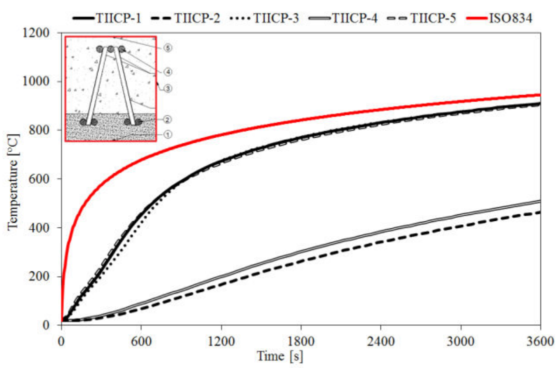


d) Isosurface of 500ºC (t=3600s).

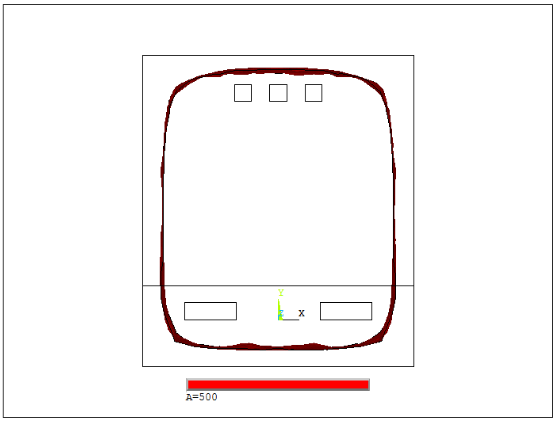
Fig. 15 *(continued)* - Simulation of CSTCB Type II Steel Plate, submitted to fire scenario 2.



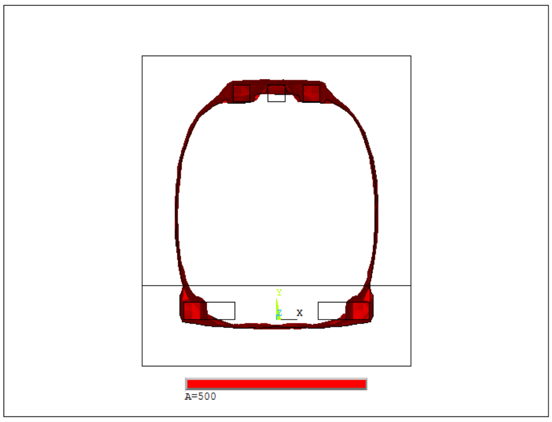
a) Temperature field (t=3600s).



b) Temperature/time history in specific points.



c) Isosurface of 500ºC (t=1800s).



d) Isosurface of 500ºC (t=3600s).

Fig. 16 - Simulation of CSTCB Type II Concrete Plate, submitted to fire scenario 2.

RESULTS AND DISCUSSION

The materials of the plate have great influence on the temperature evolution on the models. The next sections present the comparison between steel plate and precast concrete plate, used for type I and II, in two different fire scenarios.

Comparison of results with fire scenario 1

Fig. 15 shows the comparison results of temperature evolution, between TISP and TICP, for fire scenario 1, during 60 minutes. The model with concrete plate (TICP) presents higher temperature on the surface direct exposed to fire (point 1) and the bottom chord of rebar (point 2) presents lower temperature values for the same period of fire exposure. The temperature on the top surface of both models presents similar values during fire exposure. Point 1 in TICP model overheats faster than in TISP model. The major cause is related with the conductivity of both materials (steel and concrete). Concrete plate also delays the heat on the overall steel truss and rebar.

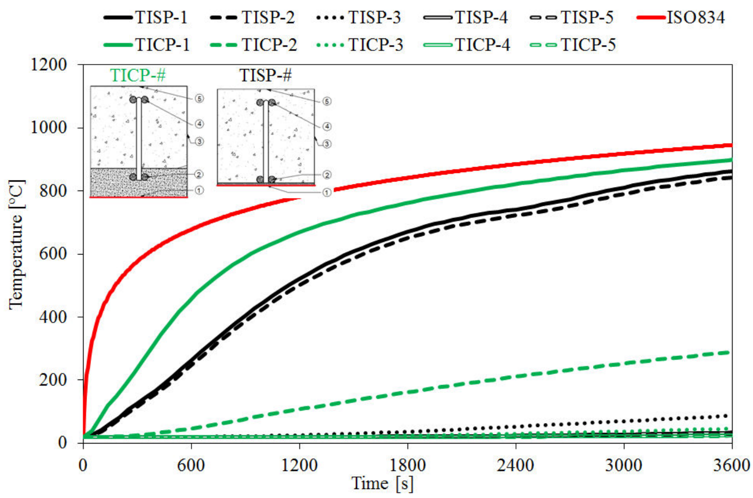


Fig. 17 - Temperature evolution in model's TISP and TICP, submitted to fire scenario 1.

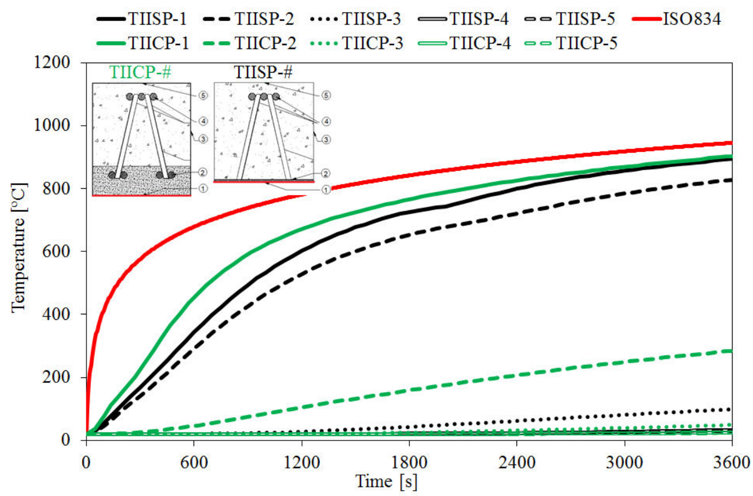


Fig. 18 - Temperature evolution in model's TIISP and TIICP, submitted to fire scenario 1.

Fig. 16 compares the effect of fire simulation in type II models, for fire scenario 1. These two models, TIISP and TIICP, have different material bottom plates, steel and precast concrete, respectively. Similar conclusions were found for this model Type II. There is a big difference between temperatures in point 2 for both models; in TIISP the temperature is higher. The other control point's remains almost equal during fire exposure.

Comparison of results with fire scenario 2

This section presents the comparison of results, for all cross section, under fire scenario 2.

Fig. 17 shows the temperature evolution for beam type I, with steel and precast concrete plate. Temperature in the bottom chord of rebar differs from each other (point 2). The precast concrete plate introduces an additional thermal resistance to the temperature in the truss. Temperature on the exposed surface (Points 3) and temperature on the top line of rebars (Point 4) are coincident for both models. It's also possible to conclude that the exposed concrete plate surface heats faster than steel plate.

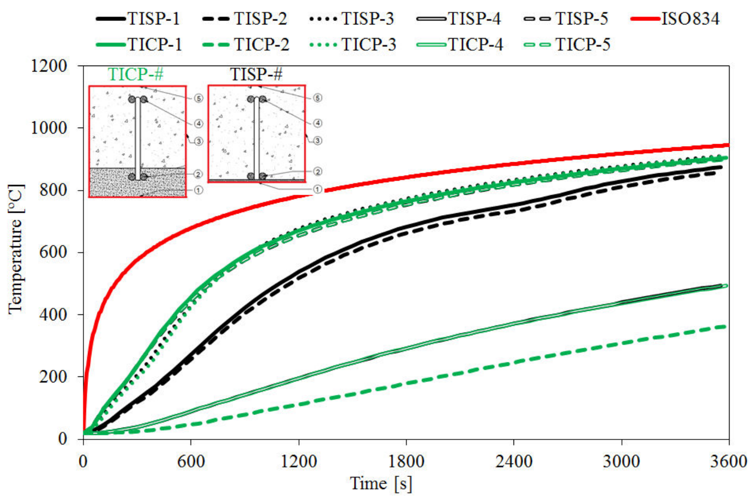


Fig. 19 - Temperature evolution in model's TISP and TICP, submitted to fire scenario 2.

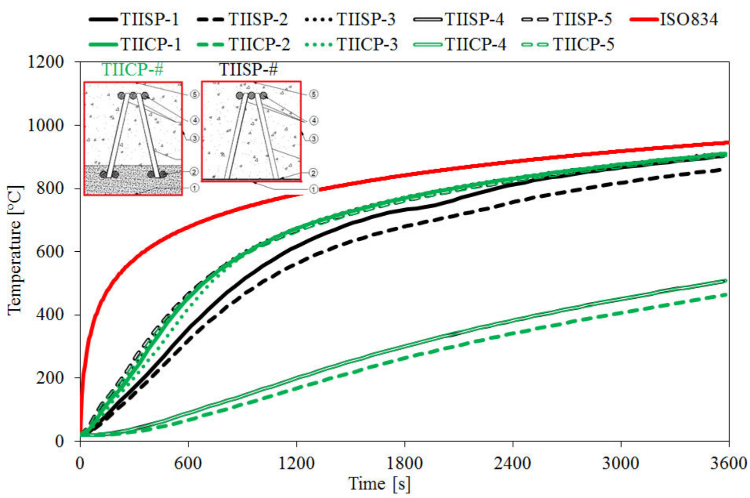


Fig. 20 - Temperature evolution in model's TIISP and TIICP, submitted to fire scenario 1.

Fig. 18 represents the thermal behaviour of the beam Type II with fire scenario 2. Mainly the same phenomena happened, when comparing temperature evolution on discrete points of both sections. The bottom chord of rebar (point 2) is colder in the model with precast concrete plate.

CONSLUSIONS

Eight numerical models of Composite Steel Truss and Concrete Beam (CSTCB) were simulated under fire conditions. Two different typologies were tested, using single truss and double truss (type I and Type II). Each typology was tested with two different prefabricated plates (steel plate and precast concrete plate). Moreover two different fire scenarios were defined (one side exposure and four side exposure).

The exposed surface of precast concrete heats faster than steel, because thermal resistance is also higher in the first case. Points embedded in concrete are protected to high temperatures. The delay of the temperature evolution on the bottom chord of rebar was noticed for the case of precast concrete plate.

The residual cross section of concrete was represented for 30 and 60 minutes of fire exposure, for every simulation. The precast concrete plate is able to include the bottom chord of rebars inside the residual cross section of concrete for 60 minutes, which means that its temperature should be below 500ºC and the reduction of the strength of the rebars is small or even null.

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