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BI-DIMENSIONAL THERMAL MODELLING OF A TIMBER-CONCRETE COMPOSITE CROSS SECTION IN FIRE

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Abstract. *The timber-concrete composite structure is a type of construction in which a timber beam is connected to an upper concrete slab using connectors. Timber-concrete composite structures have some advantages, highlighting good behavior in fire, having similar performance to common reinforced concrete floors. The fire behavior of timber-concrete composite members is governed by each of its components. The thermal action in wood causes its transformation in char. Thus, the rate of char formation (charring rate) indicates the residual cross-section of wood and it's essential in fire engineering studies. The fire engineering studies can be performed by numerical, experimental or both approaches. The numerical approach is a good method for fire engineering studies, been economical and capable of show many different situations. In this paper, a numerical model is proposed using the finite element program Abaqus, being studied the interference of refinement of the finite element mesh in the results. It was observed that the use of numerical models is a good alternative for the study of timber-concrete composite structures in fire, being possible to follow the evolution of char rate as well the temperature profile of the cross-section and that a greater mesh refinement yields better results.*

Keywords: *Composite beams, Timber, Concrete, Fire, Thermal analysis*

1 INTRODUCTION

The technological advances in civil construction provides the adoption of new structural arrangements with materials already used in an isolated form, as is the case of timber-concrete composite elements, formed by joining timber beams to reinforced concrete slabs through shear connectors. According to Yeoh *et al.* (2011) timber-concrete composite elements have some advantages when compared to timber structures and those of reinforced concrete. Considering timber structures, timber-concrete composite structures are more rigid and have better acoustic and thermal performance. When compared to reinforced concrete systems, timber-concrete composite structures have lower weight, are faster to build and have lower energy costs and reduced carbon dioxide emissions.

Currently, there is a concern about the performance of structural elements in fire situation to avoid the premature failure of the structure in this exceptional situation. Yeoh *et al.* (2011) states that the timber-concrete composite structures exhibit good resistance to high temperature, having performance comparable to conventional reinforced concrete structures.

According to Frangi *et al.* (2010), shear connectors and timber are the components of the system that have the greatest influence on the thermal-structural performance of timber-concrete composite structures. The wood when subjected to high temperatures goes through a combustion process, occurring the release of gases and formation of charcoal and, consequently, the reduction of resistant cross-section. O'Neill *et al.* (2011) quotes that the reduction in timber resistant cross section due to its carbonization is more critical than the reduction in its properties with elevation of the temperature in the behavior of timber-concrete composite structures in fire.

In general, analysis of the elevated temperature behavior of structures can be performed in experimental way, numerical way or both together. Experimental analysis can only represent specific situations and require considerable financial resources. On the other hand, numerical modelling consists of a more economical procedure, which allows different analysis to be carried out with variation of parameters of interest for the evaluation of different situations.

In this way, it is proposed in this work to establish a numerical modeling strategy using as a tool the ABAQUS computational program for thermal analysis of cross sections of composite beams of wood and concrete subjected to high temperatures. For this purpose, a T cross section is analyzed, with timber in the lower region and concrete in the upper part, connected through a steel bar positioned vertically. It is intended to evaluate the finite element mesh refinement interference in the numerical code results, the reduction of the resistant cross-section as well as the evolution of the temperature inside the cross-section with the time of exposure to the elevated temperature.

2 MATERIALS AND METHODS

The Finite Element Method (FEM) consists of an important technique for solving differential equations that govern engineering problems, such as heat transfer. Using the finite element program ABAQUS, a two-dimensional numerical model was developed to determine the temperature profile in a timber-concrete composite section subjected to a fire situation.

2.1 Characteristics of the studied element

The studied element is composed of a timber beam with a cross-section of 0.05x0.15 m² and a concrete slab with cross-section of 0.30x0.05 m². The materials are connected through steel pins with a diameter of 12.5 mm and a length of 0.10 m. (Figure 1)

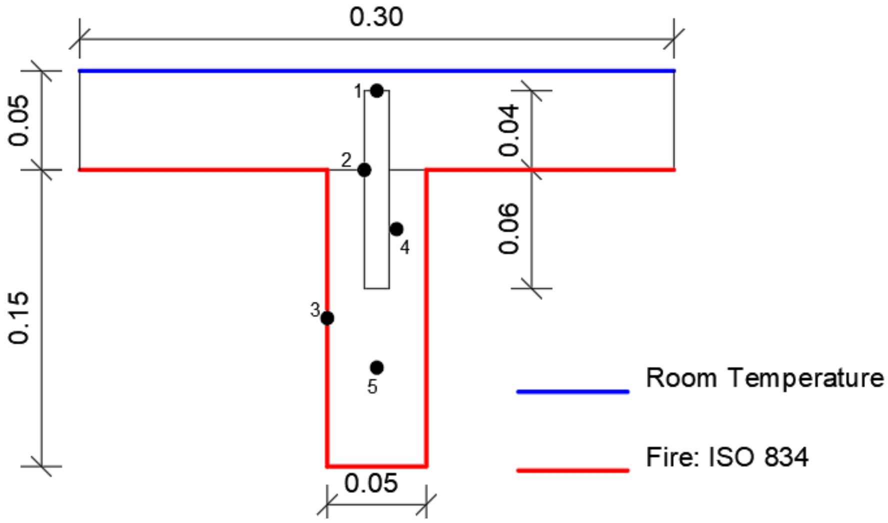


Figure 1. Cross-section of the timber-concrete composite element (dimensions in meter)

It is considered the standard fire curve ISO 834 (1999), Eq. (1), acting on the lateral and lower faces of the timber beam and on the lower surface of the concrete slab for 60 minutes. The heat exchange between the flames and the structural element occurs in two ways: by convection and by radiation. For convection, it's considered a coefficient of heat exchange by convection equal to 25 W/(m².K). For the radiation, the resulting emissivity is equal to 0.8 and the Stefan-Boltzmann constant is equal to 5.67×10^{-8} W/(m².K^4). In the upper region of the concrete slab is adopted a constant ambient temperature of 20ºC and a coefficient of heat exchange with convection of 9 W/(m².K), which also considers the exchange of heat by radiation, (EN 1991-1-2, 2002).

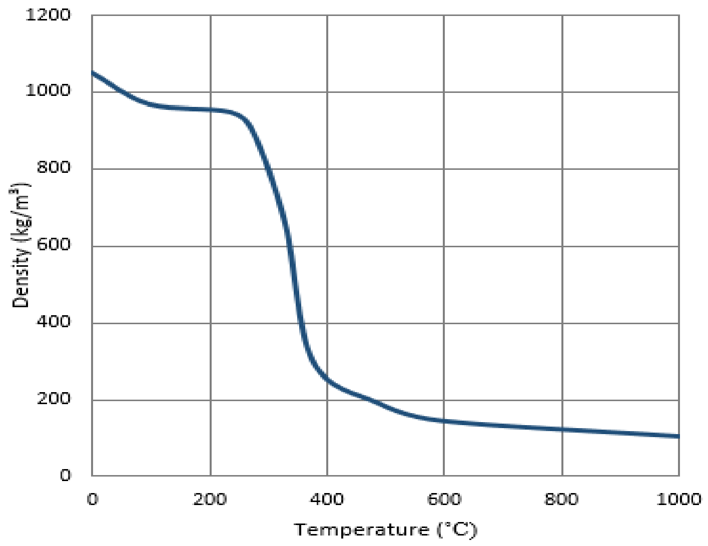
$$\theta_g = \theta_0 + 345.\log(8.t+1) \quad (1)$$

In Eq. (1), θ_g is the temperature of the gases (˚C) in the instant t (minutes) and θ_0 is the temperature of the gases in the beginning of fire (usually taken as 20˚C).

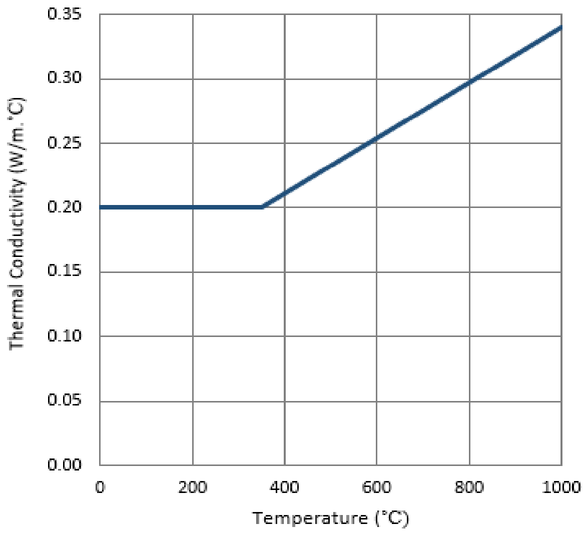
2.2 Thermal properties of the materials

Thermal properties of materials may vary with temperature change. In this paper, the variations established by Brazilian standards for concrete (ABNT NBR 15200, 2012) and for steel (ABNT NBR 14323, 2013) are adopted. For wood, due to the absence of data in the current Brazilian standard, ABNT NBR 7190 (1997), it has been used the thermal properties of wood modeled by Regobello (2007).

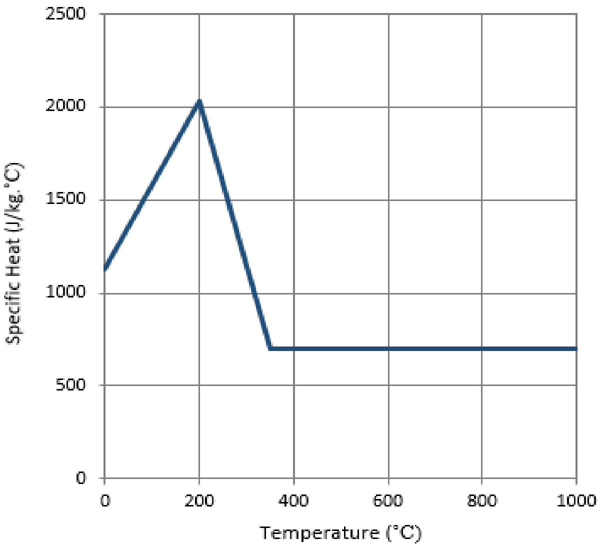
At room temperature, the wood density used is 1050 kg/m³ and the density reduction with the temperature rise is shown in Fig. (2.a). The variations of the thermal conductivity and the specific heat with the temperature are presented in Fig. (2.b) and (2.c), respectively.



(a)



(b)

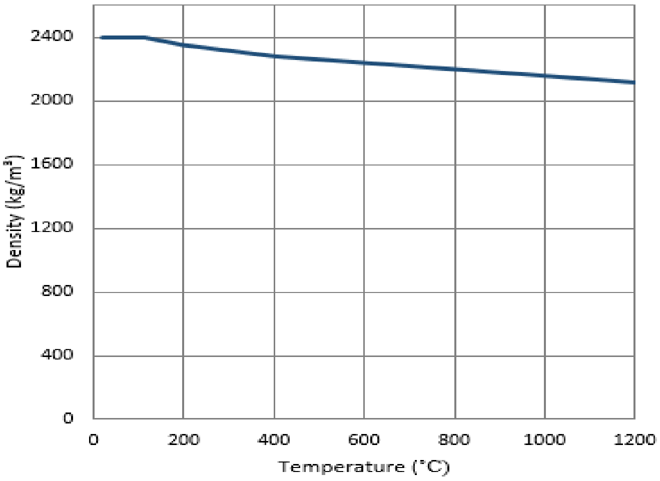


(c)

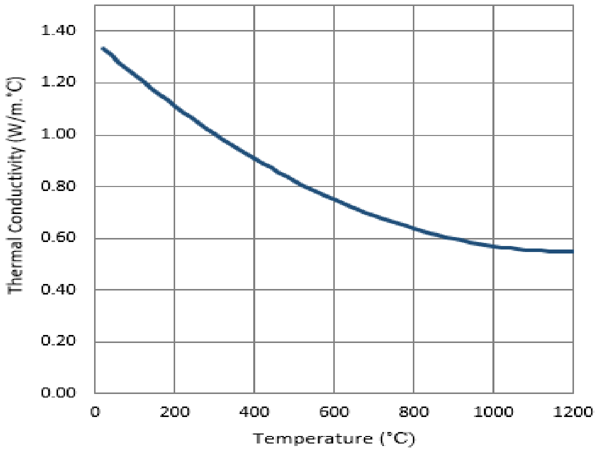
Figure 2. Thermal properties of Timber (a) Density (b) Thermal conductivity (c) Specific heat

For the concrete, the density at room temperature is 2400 kg/m³ and its reduction with the elevation of temperature is shown in Fig. (3.a). Figures (3.b) and (3.c) show, respectively, the variation of the thermal conductivity and the specific heat with the temperature.

The density of the steel is considered constant with the elevation of the temperature, 7850 kg/m³. The variations of thermal conductivity and specific heat are shown in Fig. (4.a) and (4.b), respectively.



(a)



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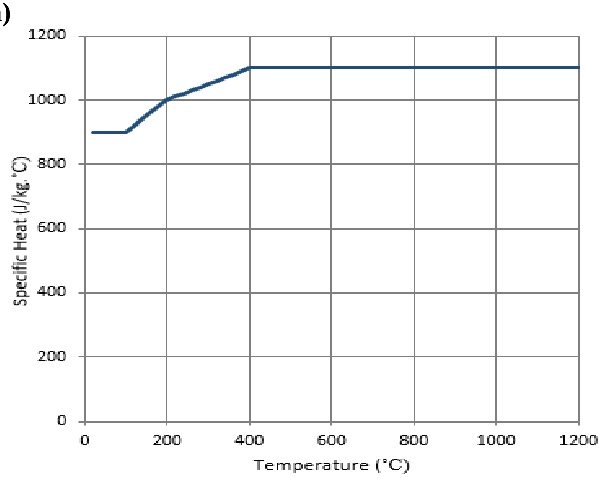
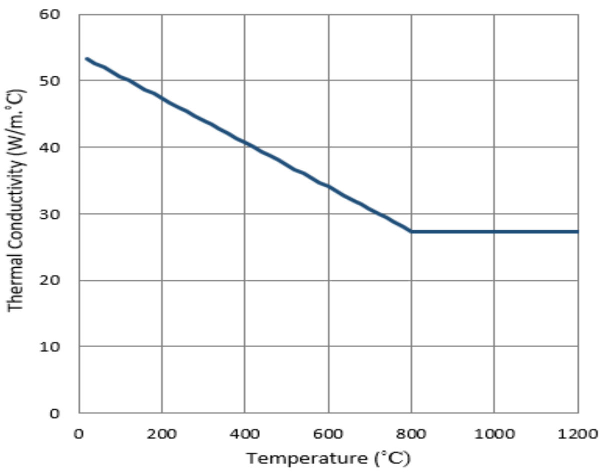
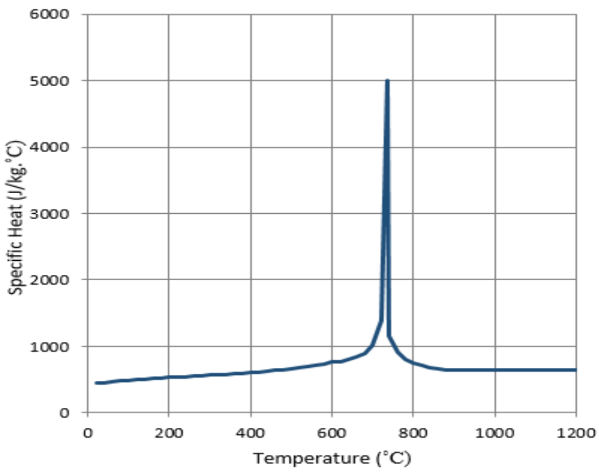


(c)

Figure 3. Thermal properties of Concrete (a) Density (b) Thermal conductivity (c) Specific heat



(a)



(b)

Figure 4. Thermal properties of Steel (a) Thermal conductivity (b) Specific heat

2.3 Finite element mesh

Four models were developed by varying the dimensions of the finite element mesh. The TM-1 model has the poorest mesh, gradually increasing the refinement up to the TM-4 model. Table 1 shows the dimensions adopted in the finite element mesh, as well as the number of elements in each component of the cross section.

Table 1. Characteristics of the models

Model	Element Size (mm^2)	Number of Elements		
		Timber	Concrete	Steel
TM – 1	10 x 10	69	151	10
TM – 2	7.5 x 7.5	124	242	26
TM – 3	5 x 5	276	584	60
TM – 4	2.5 x 2.5	1080	2340	200

3 RESULTS AND DISCUSSIONS

The results obtained in this paper through the ABAQUS finite element program are compared to experimental data as well as numerical data, obtained through the computational code ANSYS, present in the works of Molina and Calil Junior (2015) and Molina and Calil Junior (2016).

3.1 Influence of the finite element mesh

Table 2 shows the processing time of each model. It is possible to notice a low processing time of all the models as well as a small difference between them, being the TM-4 model the slowest, taking 93 seconds. It should be noted that the TM-4 model is the most refined and, thus, a slower processing time of the model is expected.

Table 2. Processing time

Model	Processing Time (sec)
TM – 1	69
TM – 2	73
TM – 3	75
TM - 4	93

Figures (5) to (9) show the temperature versus time curves for points 1 to 5 shown in Fig. (1), respectively. There is little difference between the temperatures obtained with different refinements of the finite element mesh. The exception of this fact occurs in point 4, as can be seen in Fig. (8). At this point the temperature evolves faster in the TM-3 model. The temperatures with the fire time are similar for the TM-1 and TM-2 models, presenting the lowest values. The TM-4 model showed an intermediate temperature evolution to the TM-3 and TM-1/TM-2 models.

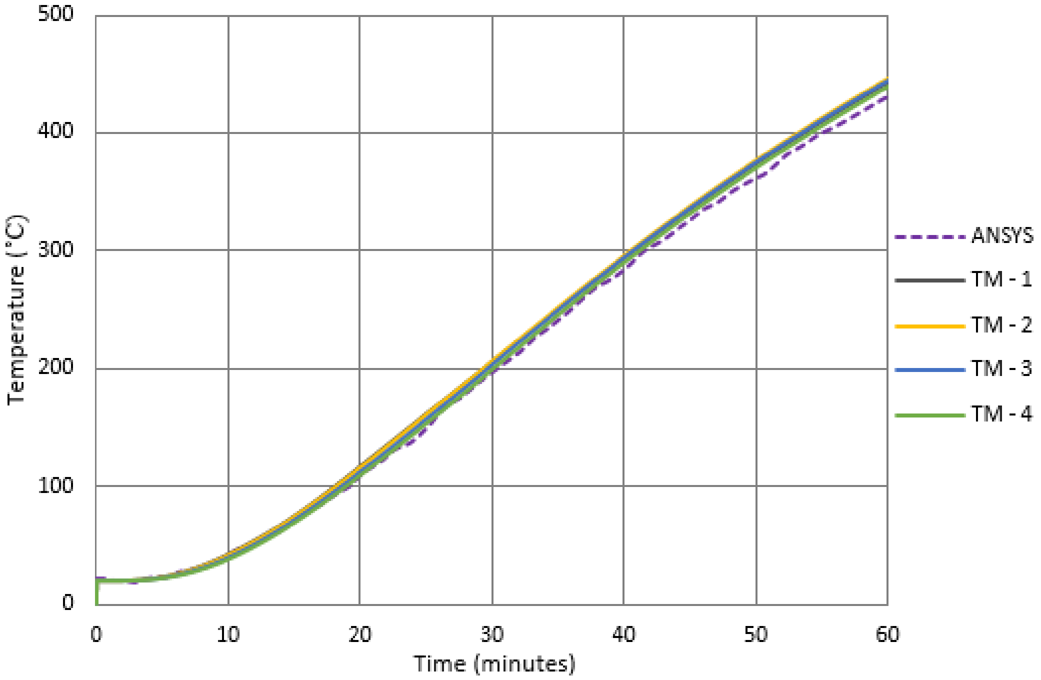


Figure 5. Temperature versus time of point 1

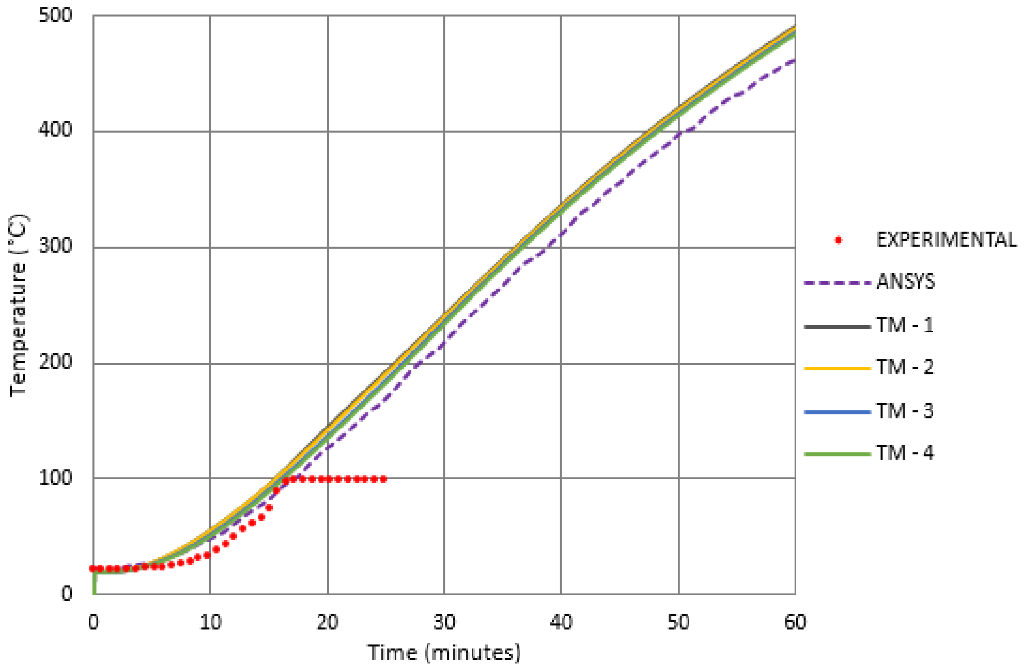


Figure 6. Temperature versus time of point 2

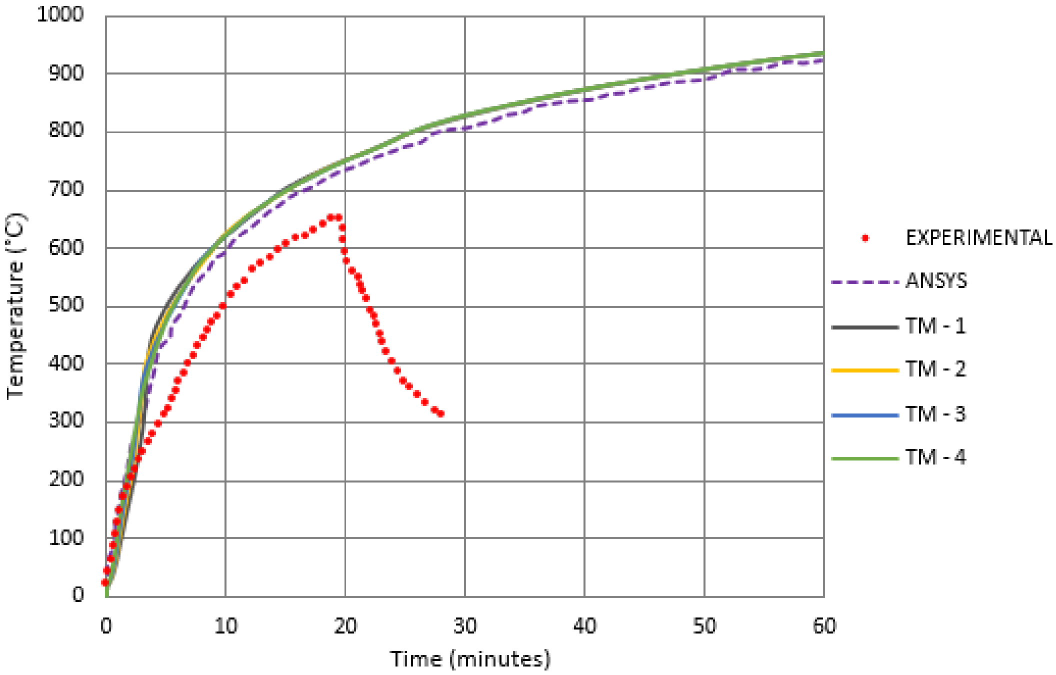


Figure 7. Temperature versus time of point 3

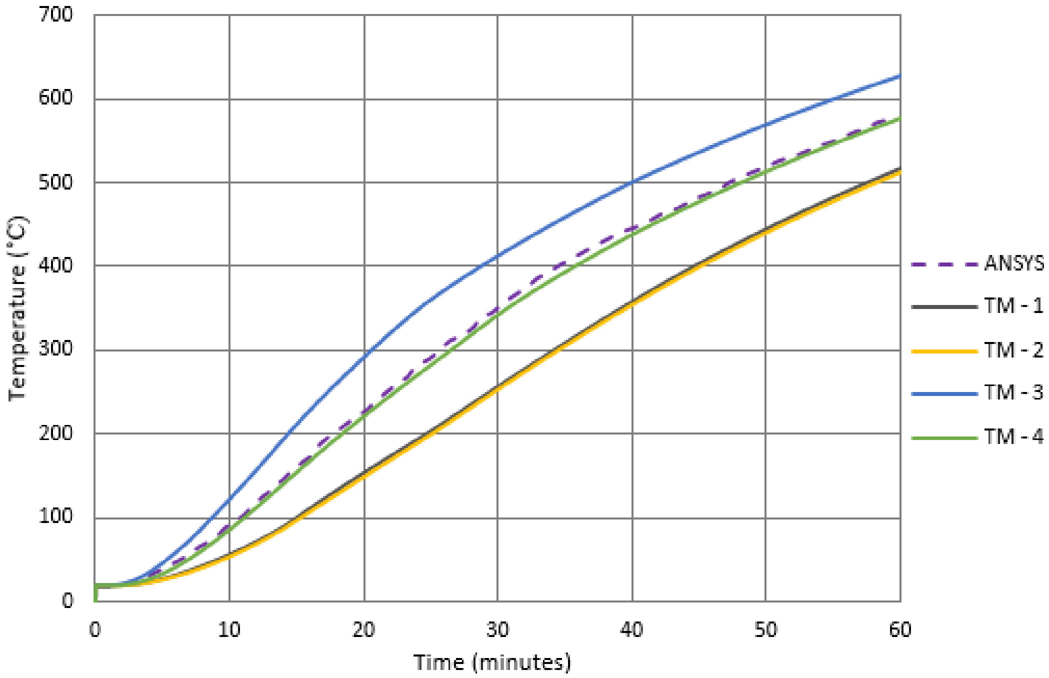


Figure 8. Temperature versus time of point 4

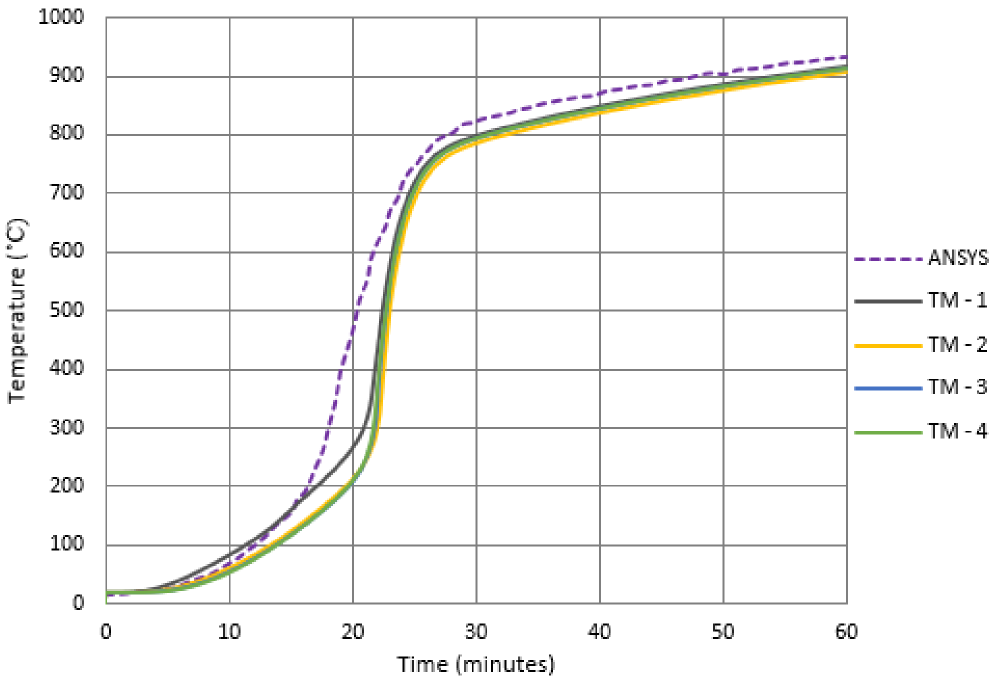


Figure 9. Temperature versus time of point 5

It is also possible to observe from Fig. (5) to (9) a good correlation between the results obtained in this research through ABAQUS with the experimental and numerical results obtained through the ANSYS program presented in Molina e Calil Junior (2015) and Molina e Calil Junior (2016). It should be highlighted that the experimental investigation in the furnace lasted approximately 20 minutes and the temperatures were measured until 27 minutes, while the fire time considered for the numerical simulation was 60 minutes, causing divergence between the numerical and experimental results between 20 and 27 minutes.

For point 4, the temperature obtained by the TM-4 model were closer to the temperatures presented by ANSYS. Because of this, and due to the little difference in the processing time of the four models, the TM-4 model is chosen for the analysis of the reduction of the cross section of the wood with the fire time as well as for the analysis of the temperature profile that follow in this work.

3.2 Reduction of the resistant cross-section with fire

The Eurocode 5 part 1.2 (2004) takes the isotherm of 300ºC as the char front the wood. Thus, temperatures equal to and above 300°C indicate charred timber. The charcoal formed from the timber's carbonization has negligible strength and stiffness and, in this way, its growth represents the reduction of the resistant cross section of the timber. From these considerations, the timber carbonization growth for the TM-4 model is analyzed.

Figure (10) shows the curve of the relationship between the charred cross section and the initial cross-section with the fire time obtained by the TM-4 model. For 10 minutes of exposure to the elevated temperature there was approximately 37% carbonization of the cross section. This percentage is raised to 69% in 20 minutes of exposure to elevated temperature. With 40 minutes of fire the total carbonization of the cross section is observed.

An approximately linear behavior can be observed up to 25 minutes of exposure to the elevated temperature, with a constant cross-sectional reduction rate. From 25 minutes to 40 minutes the carbonization velocity of the wood is reduced, evidenced by smoothing the curve of the relationship between the carbonized area and the initial cross-sectional area with time.

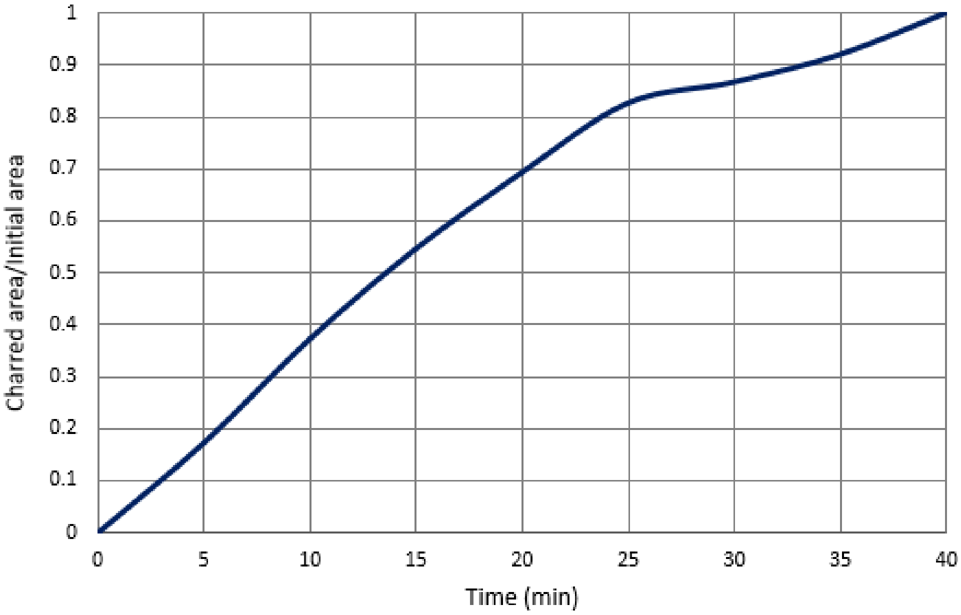


Figure 10. Curve of the ratio between the charred area and the initial area versus time

3.3 Temperature Profile

Figures (11) to (14) show the cross-sectional temperature profiles for the exposure times at elevated temperature of 10, 20, 30 and 60 minutes, respectively. From the 300ºC isotherm it is possible to observe the advance of the carbonization of the wood, and in 60 minutes of fire the timber is already completely charred. In these figures can be noted the rounding of the lower corners of the timber beam. This fact is related to the greater heat flow in this region of the cross section, which causes its greater burning and, consequently, the rounding of the lower region of the cross section of the wood.

It can be also noted the thermal gradient in the cross section. For timber, in 10 minutes of exposure to high temperature, the temperature on the faces is higher than 600ºC, while the inside temperature is below 100ºC. For 30 minutes of fire the temperature in the outside is higher than 700ºC while the interior region presents temperatures below 200ºC.

The shear connector also undergoes temperature rise with the time of exposure to fire situation. For 10 minutes, the temperatures on the metal pin are between 20 and 50ºC. The temperature is raised to the range of 100 and 200ºC in 20 minutes of exposure to elevated temperatures. For 30 and 60 minutes, it is observed the temperatures ranges of 200 to 300ºC and 300 to 600ºC, respectively. The temperature variation of the metal pin shows the thermal protection function of the wood. In the initial moments of the fire, the temperature in the shear connector is still relatively low, however, with the advance of the carbonization of the wood, its temperature rises more quickly.

It can also be seen from Fig. (11) to (14) the thermal gradient in the concrete slab. For 10 minutes of exposure, the temperature on the upper surface is between 20 and 50ºC while in the lower part is above 400ºC. For 20 minutes of exposure, the maximum temperature on the top and bottom surfaces are 83.95ºC and 671.95ºC, respectively. For 30 minutes of exposure, the minimum temperature is 154.5ºC, while the maximum temperature is 767.18ºC. At 60 minutes of exposure to fire, these values result, respectively, 335.3ºC and 906.84ºC. The thermal gradient along the height of the concrete slab is formed by bands with practically constant thickness along the width of the slab, these strips being thicker at the top (colder) than the lower region (warmer).

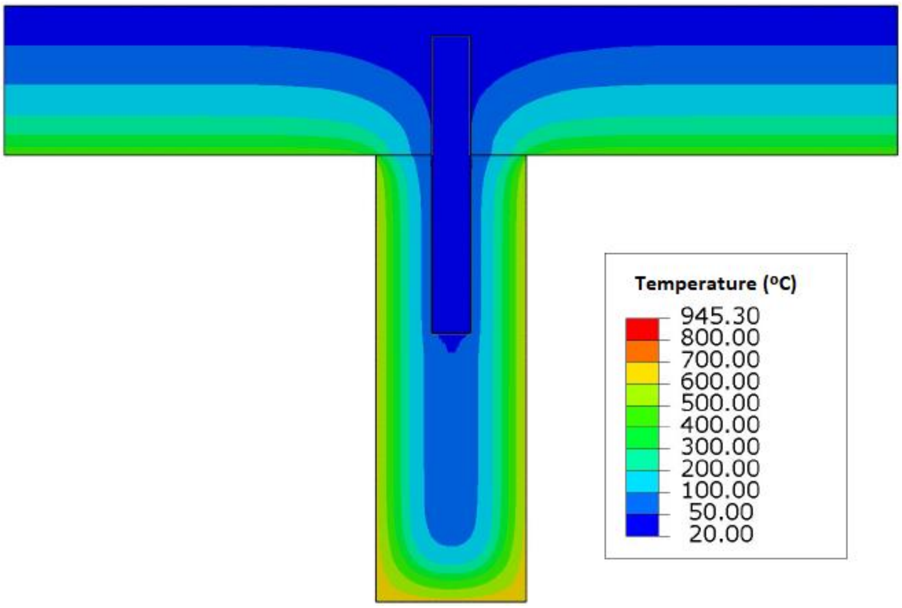


Figure 11. Temperature profile for 10 minutes

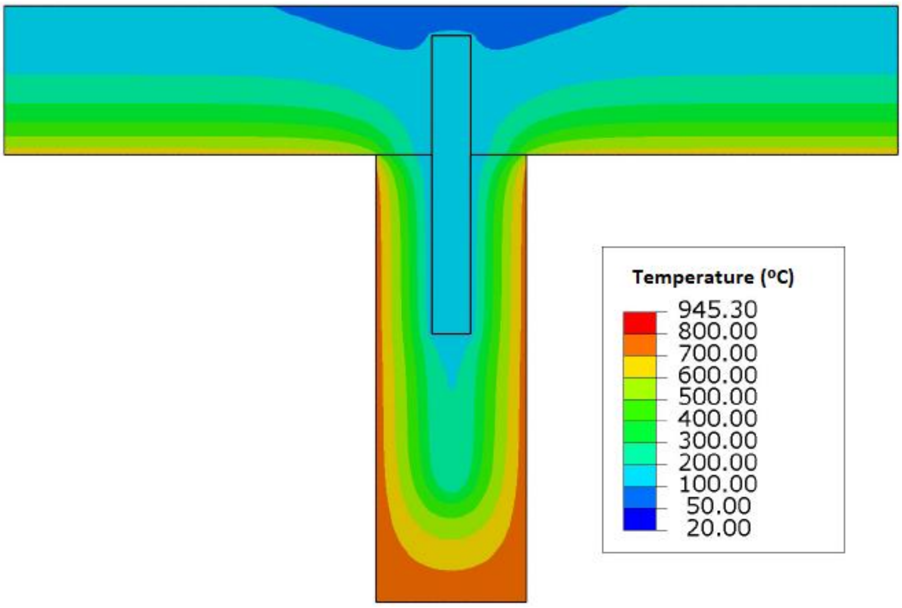


Figure 12. Temperature profiles for 20 minutes

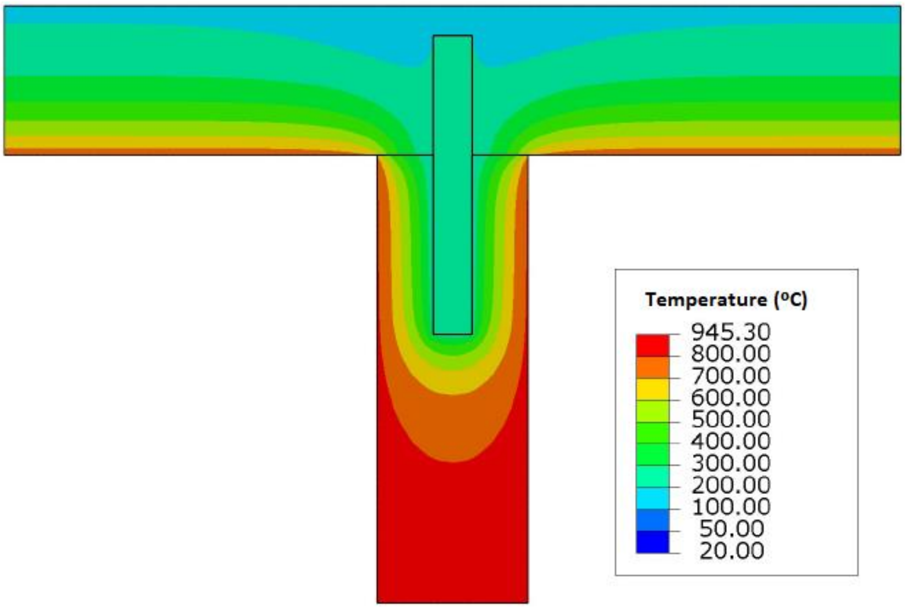


Figure 13. Temperature profile for 30 minutes

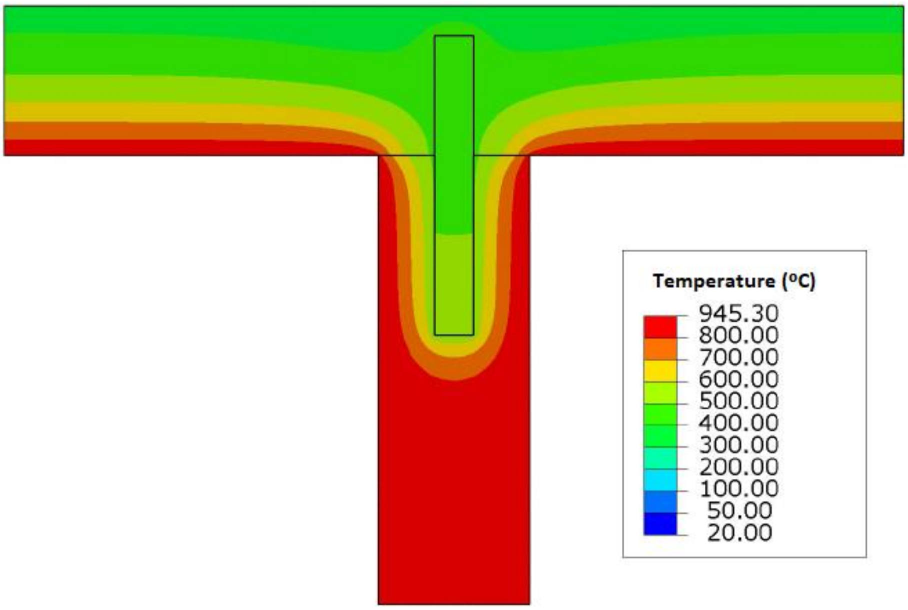


Figure 14. Temperature profile for 60 minutes

4 CONCLUSIONS

The use of numerical models, through the ABAQUS computational program, is shown as a good alternative for the bi-dimensional thermal analysis of timber-concrete composite structures in fire. It was found that the processing time for different finite element meshes differs very little. It may be noted that the better finite element refinement doesn't cause major changes in temperature versus time curves. Due to the little difference in processing time, it is advisable to use a more refined finite element mesh composed of approximately square elements with 2.5 mm of side.

From the numerical model, it is possible to verify the advance of the charred layer considering the isotherm of 300ºC as the carbonization front. It is noticed that the resistant cross section reduction due to the carbonization of the timber is faster in the beginning of fire, having a reduction in this hate after a certain time.

In addition, it should be highlighted the role that the timber plays as thermal protector of the shear connector. Before the timber carbonization, the temperature on the metal pin was relatively low, increasing rapidly when the carbonization front reaches the inner region of the element.

In relation to the concrete slab, a thermal gradient was observed along its height, presenting constant temperature ranges in their width, with bands less thick in the lower region of the slab and thicker in the upper region.

It should be emphasized that this study is related to the first part of an ongoing research in the Department of Structures of the Engineering School of São Carlos, on what it is intended to know the thermos-structural behavior of timber-concrete composite structures.

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