XLIII
CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Thermal analysis of timber cross-sections via CS-ASA/FA

Jackson S. Rocha Segundo[1], Rafael C. Barros[2], Ricardo A. M. Silveira[1], Dalilah Pires[3], Ígor J. M. Lemes[4]

[1]*Dept. of Civil Engineering, Federal University of Ouro Preto*
Morro do Cruzeiro, 35400-000, Ouro Preto/MG, Brazil
jackson.segundo@aluno.ufop.edu.br, ricardo@ufop.edu.br
[2]*Sereng Engineering & Consulting*
34006-056, Nova Lima, Minas Gerais, Brazil
rafaelcesario@hotmail.com
[3]*Dept. de Tecnologia em Engenharia Civil, Computação, Automação, Telemática e Humanidades (DTECH), Universidade Federal de São João Del-Rei*
Campus Alto do Paraopeba Rod.: MG 443, KM 7, 36420-000 Ouro Branco/MG, Brazil
dalilah@ufsj.edu.br
[4]*Department of Engineering, Federal University of Lavras*
Campus Universitário Kennedy, 37200-000, Lavras/MG, Brazil
igor.lemes@ufla.br

Abstract. When exposed to high temperatures, such as in a fire situation, the physical and resistance characteristics of the materials employed in the structure deteriorate as the temperature increases. This fact promotes a considerable loss in the bearing capacity and stiffness of the structural system. The verification of a structure exposed to fire depends primarily and principally on the thermal analysis of the cross-section of the structural element. This analysis permits the determination of the temperature variation or temperature range in the element from the boundary conditions provided by the fire model adopted. Timber, being an anisotropic material, with irregular fibers, presence of knots and flammable, and widely used in civil construction, becomes a target for the study of realistic behavior in fire. As such, this study has the objective of performing a thermal analysis in a transient regime utilizing the finite element method on timber cross-sections that are employed in civil construction through use of the Computational System for Advanced Structural Analysis/Fire Analysis (CS-ASA/FA module). Two cross-sections were analyzed, and the results obtained were very satisfactory. Therefore, it is possible to conclude that the CS-ASA/FA module can yield the necessary information when a thermo-structural analysis is performed for the evaluation of strength and stiffness losses of the structural material when exposed to fire.

Keywords: Thermal analysis, Fire situation, Timber cross-section, FEM, CS-ASA/FA.

1 Introduction

The thermal analysis of a structural element consists of determining the variation of the temperature field when they are exposed to fire, as a function of the elapsed time of the fire. Such analysis involves two steps: determining the heat transferred by convection and radiation, resulting from the fire, in the boundary of the element of interest; and determining the heat transfer by conduction within the structural elements. Thus, it is necessary to properly understand the heat transfer processes (convection, radiation, and conduction), which make it possible to determine the transfer of energy to anybody. Additionally, it is necessary to consider the variation of thermal properties as a function of the temperature of the component materials.

The objective of the thermal analysis presented in this work is to determine the temperature distribution in the timber structural elements submitted to high temperatures to provide the necessary resources to evaluate the loss of strength and stiffness of the structural material with the increase of temperature in mechanical or structural analysis. It is also noteworthy that the temperature distribution along each element is considered uniform and equal to that estimated in its cross-section. Thus, the sectional analysis through numerical heat transfer models provides the determination of the temperature field at different points of the timber cross-section.

Therefore, the present work aims to determine the temperature variation in structural elements with timbered cross-sections through thermal analysis via the finite element method (FEM). The methodology used through the FEM is applied in a transient regime and considers relevant factors such as the heat transfer mechanisms and the variation of the material's thermal properties as a function of temperature. To this end, the expansions made in the CS-ASA/FA (Computational System for Advanced Structural Analysis/Fire Analysis) computational module are used for sections of timbered elements. The thermal analyzes of this study are then compared with those available in the literature, allowing the validation of the method and the implementations carried out.

The CS-ASA/FA module was designed by Barros [1, 2] and Pires [3] who implemented detailed numerical formulations for the advanced analysis of steel, concrete, and composite structures (steel-concrete) in a fire situation. Thus, this module performs a thermal analysis of cross-sections through the FEM in steady and transient conditions.

2 Thermal analysis

Simulating the conditions and development of a real fire is a complex task. Consequently, determining the effects caused by increasing temperatures on structures is also not trivial. In fire, the temperature of the structural elements depends directly on the temperature of the gases in the compartment. The temperature *versus* time curve that characterizes a fire depends on several factors, such as compartment geometry, characteristics of the sealing materials, degree of ventilation of the environment, and disposition and quantity of the combustible material. The current regulations present, in a simplified way, ways to model the variation of the temperature of the gases in a compartment on fire through nominal and parametric curves.

For this work, in the thermal analysis, the standard fire curve available in ISO 834-1 [4] was adopted and it is given by:

$$T_g = T_0 + 345 log \left(8t + 1 \right) \tag{1}$$

in which T_g is the temperature of the gases in °C, T_0 is the initial ambient temperature, usually taken as 20 °C, and t is the fire exposure time in minutes.

In this present work, the computational module CS-ASA/FA received interventions to perform the thermal analysis of timber cross-sections in transient regimes. This module, designed to perform thermal analysis of cross-sections in transient and steady state, is part of the CS-ASA computer system, being also developed based on the FEM. When coupled to the CS-ASA/FSA (Fire Structural Analysis) module, it allows performing thermo-structural analysis of structures.

Numerical modeling of thermal analysis consists of solving the differential equation of heat conduction for solid bodies. This research uses the Weighted Residuals Method, specifically the Galerkin Method, to obtain this equation in terms of FEM, which is given in matrix form for each element by:

$$\boldsymbol{C}^e \left\{ \frac{\partial \boldsymbol{T}}{\partial t} \right\} + \boldsymbol{K}^e \left\{ \boldsymbol{T} \right\}^e = \boldsymbol{R}^e \tag{2}$$

where: $\mathbf{C}^e$ is the capacitance matrix; $\mathbf{T}^e$ is the nodal temperature vector; $\mathbf{K}^e$ is the thermal conductivity matrix; $\mathbf{R}^e$ is the nodal heat flux vector. Considering the contribution of all elements adopted to model the timber cross-section, the equation that describes the global equilibrium of the transient heat conduction problem is expressed by:

$$\boldsymbol{C} \left\{ \frac{\partial \boldsymbol{T}}{\partial t} \right\} + \boldsymbol{K} \left\{ \boldsymbol{T} \right\} = \boldsymbol{R} \tag{3}$$

in which: **C**, **K, T** and **R** are, respectively, the global matrices and vectors of the system.

To obtain the solution of Eq. (3), that is, to calculate the temperature field, a numerical model of integration based on the Finite Difference Method is used, which was previously presented by Lewis *et al.* [5], Rigobello [6] and Nunes [7]. Due to the dependence of the material properties on the temperature, the problem equation presents a non-linear character. Therefore, it is necessary to adopt numerical solution strategies, essentially based on linear integration in time and also to use iterative processes.

The CS-ASA/FA module has two procedures for solving the system of equations: simple incremental and iterative-incremental. For the second option, the iterations can be performed using the classical Newton-Raphson method or the Picard algorithms (Successive Approximation Method). For the analysis of this work, the simple incremental system was chosen, according previously Barros [1, 2] and Pires [3] research.

The variation of the thermal properties of timber as a function of temperature, in this work, is adopted as indicated by Eurocode [8]. Figures 1, 2, and 3 show, respectively, the variation of thermal conductivity, specific heat, and specific mass ratio to dry specific mass, as a function of temperature, for softwoods adopted in the following analyzes.

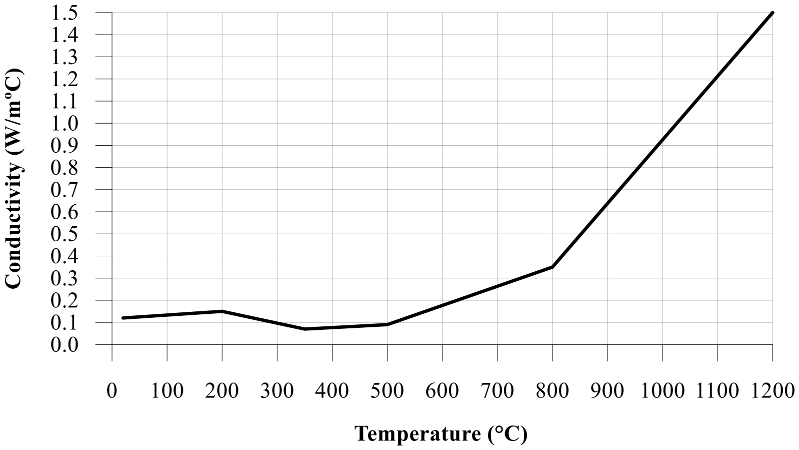


Figure 1. Temperature-thermal conductivity relationship for softwood

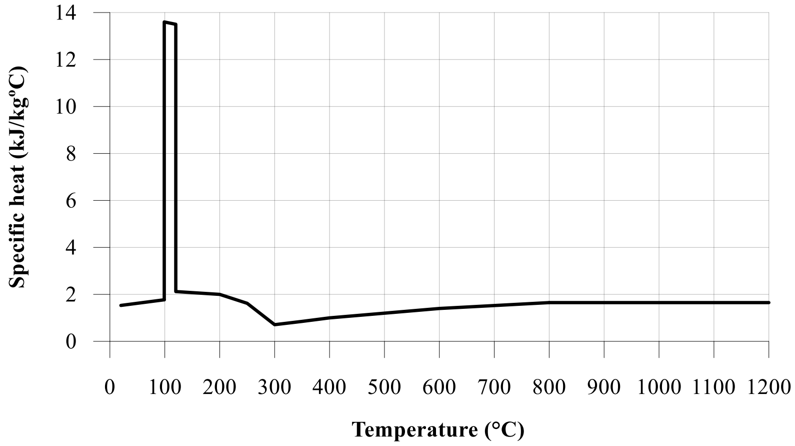


Figure 2. Temperature-specific heat relationship for softwood

3 Numerical Examples

In this section, thermal analyzes will be carried out on timber cross-sections, using the CS-ASA/FA computational module, considering the results presented in other literature works. The main objective is to verify the behavior of the temperature distribution in the timber and the validity of the implementations carried out for this simulation. Thus, two cross-sections previously studied by Thi *et al*. [9] and Dârmon and Lalu [10] were studied. The examples present their characteristics to timber properties and geometry, providing an adequate initial view of the thermal problem in timbered elements. The analyzes were performed with linear quadrilateral elements for the cross-section discretization and the numerical solution adopted was the simple incremental strategy. In each example, the parameters adopted for the numerical model are highlighted.

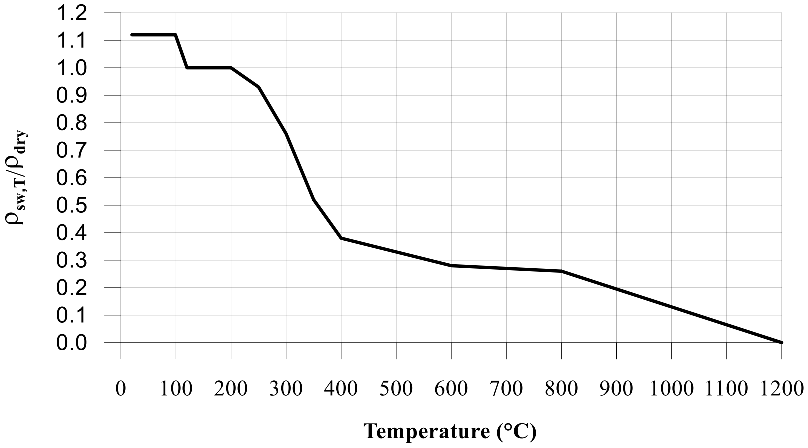


Figure 3. Temperature-density ratio relationship for softwood with an initial moisture content of 12%

3.1 Rectangular section of laminated veneer lumber

The first model analyzed by this research is a veneered laminated timber panel. Thi *et al.* [9] studied experimentally and numerically the behavior of this section under standard fire situations through fire and finite element tests, respectively.

The experimental configuration was set up with a cross-section measuring 146 mm wide and 60 mm thick, with a length equal to 1000 mm and all sides exposed to fire. For the finite element model, in turn, symmetry was used to model a quarter of the total cross-sectional area (73mm wide and 30mm thick). Figure 4 illustrates the model described. Temperatures were calculated for depths of 5 mm and 15 mm vertically (P_1 and P_2, respectively) and horizontally (P_3 and P_4, respectively) on the faces not exposed to fire.

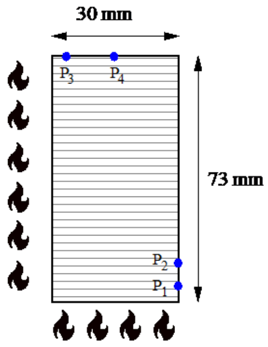


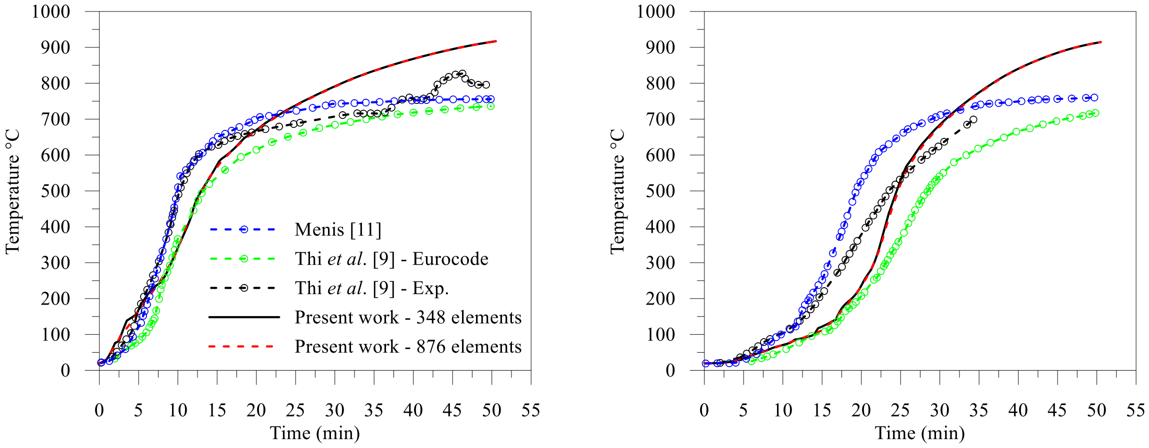
Figure 4. Cross-section of laminated veneer lumber

The timber moisture content considered was equal to 12% and the dry density equal to 570 kg/m³. The result for the thermal analyzes are shown in Figures 5a, 5b, 6a and 6b, in the form of temperature *versus* time graphs. Two meshes were used to numerically simulate this problem using the CS-ASA/FA module: the first one with 348 quadrilateral elements, the same amount used by Thi *et al.* [9]; and the second, more refined, with 876 elements. The time increment for the analyzes was equal to 15 seconds.

Through these figures, it is possible to perceive a good agreement between the results found in the literature and those obtained by this research. Another positive indication is the fact that the temperature *versus* time curves present similar behavior for the different points when their locations in the cross-section are placed in perspective.

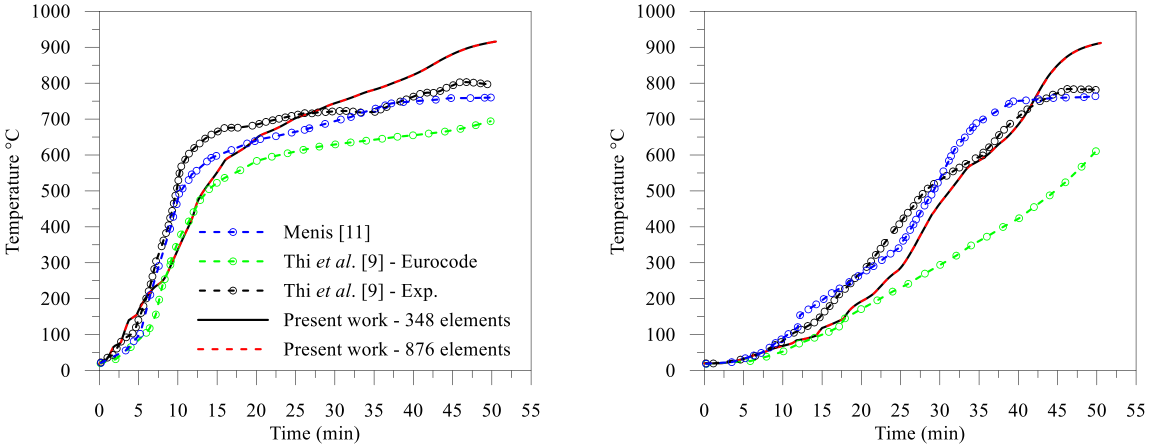
It is also possible to notice that the curves present well-defined levels in the initial heating phase and similar behavior for the two meshes. This fact may be related to the behavior change in the thermal properties of the timber described in the previous sections, evidencing the model's conformity with the expected behavior.

The effect of timber carbonization may be the cause of the small differences found between the model and the references. Thi *et al.* [9] indicate that this phenomenon occurs in the range of 300° Celsius, precisely where the differences are accentuated. It should be noted that the influence of this phenomenon is progressive since it causes a decrease in the heat propagation. Therefore, more external elements are less affected by this effect than internal elements, since carbonization occurs in the same direction as the fire propagation.



a) Temperature *versus* time: P_1 b) Temperature *versus* time: P_2

Figure 5. Thermal analysis for cross section of laminated veneer lumber



a) Temperature *versus* time: P_3 b) Temperature *versus* time: P_4

Figure 6. Thermal analysis for laminated veneer lumber cross-section

3.2 Rectangular laminated timber cross-section

The second example analyzed is the cross-section of a glued laminated timber beam. Dârmon and Lalu [10] studied experimentally and numerically this section under standard fire on three faces under the fire (experiment) and finite element tests, respectively.

The experimental configuration was set up with a cross-section measuring 180 mm wide and 440 mm high, with a length equal to 3500 mm and three faces exposed to fire (the upper face was not exposed to fire). The same cross-section was used for the numerical model. Figure 7 illustrates the model described. Temperatures were evaluated for depths of 20 mm and on the outer surface (0 mm) of the center of the cross-section, as indicated in the same figure.

The timber moisture content considered was equal to 11.6% and the dry density equal to 338 kg/m³. The results obtained for the thermal analysis are shown in Figures 8a and 8b in the form of temperature *versus* time graphs. Two finite element meshes were used to numerically simulate this problem using the CS-ASA/FA module:

the first with 396 quadrilateral finite elements, the same amount used by Dârmon and Lalu [10]; the second, more refined, with 792 finite elements. The time increment used for the analyzes was equal to 15 seconds.

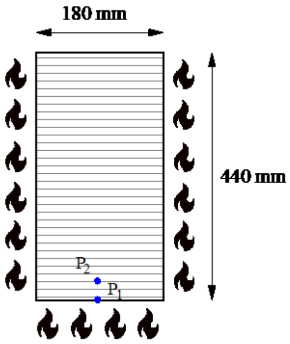
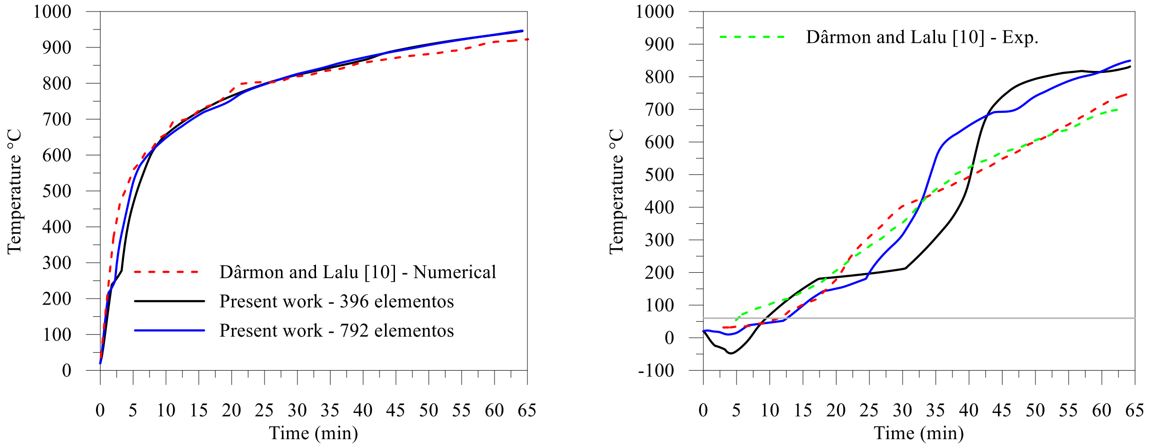


Figure 7. Laminated timber cross-section



a) Temperature *versus* time: P_1

b) Temperature *versus* time: P_2

Figure 8. Thermal analysis for laminated veneer lumber cross-section

It is possible to observe that similar behavior of the temperature *versus* time curves for the two meshes. However, for lower temperatures at the beginning of the analysis, the behavior of the finer mesh is more precise. The investigations carried out by this research indicate that in elements with larger dimensions for timbered sections, due to the unique behavior of the material at initial temperatures, they lead to an irregular behavior in heat transmission, especially at points close to elements with a large temperature variation.

The temperature *versus* time curves presents good agreement with the behavior of the timber properties described by Eurocode [8], showing the same ranges of behavior change and confirming the validity of the implementations carried out. The carbonization effect considered by Dârmon and Lalu [10] explains the difference in behavior since this phenomenon acts directly on the heat flow.

4 Final Remarks

Two cross-section analyzes of structural elements in fire situation were performed through the expansion made in the CS-ASA/FA module. The examples were determined considering their practical application. With this, it was possible to perceive the difference in behavior between timber species under high temperatures and different fire conditions. The results obtained were compared with results from other authors, and answers were satisfactory and consistent, showing the program's ability to perform timber thermal analysis. The carbonization effect, not yet introduced in the model used on this research, explains the differences observed to the literature, since this phenomenon has impact on the behavior of timber in fire situations.

This research will continue to treat the timber structures thermo-mechanical analyzes. Therefore, among the future steps still to be developed, the following stand out: determining the behavior of the stiffness and resistance of timber at high temperatures, considering more complex thermal effects (such as carbonization) and assembling the material degradation compatible with the finite element formulations.

Acknowledgements. This work was made with the support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais), PROPEC/UFOP, PROPPI/UFOP, UFSJ and UFLA.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Barros, R.C., *Avaliação Numérica Avançada do Desempenho de Estruturas de Aço Sob Temperaturas Elevadas*. Dissertação de Mestrado, Programa de Pós-Graduação em Engenharia Civil, Deciv/EM/UFOP, Ouro Preto, MG, Brasil, 2016.
[2] Barros, R.C., *Avaliação numérica do comportamento não linear e resistência de estruturas mistas de aço e concreto em situação de incêndio*. Tese de Doutorado, Programa de Pós-Graduação em Engenharia Civil, Deciv/EM/UFOP, Ouro Preto, MG, Brasil, 2021.
[3] Pires, D., *Análise numérica avançada de estruturas de aço e de concreto armado em situação de incêndio*. Tese de Doutorado, Programa de Pós-Graduação em Engenharia Civil, Deciv/EM/UFOP, Ouro Preto, MG, Brasil, 2018.
[4] ISO 834-1, *Fire resistance tests - elements of buildings construction, Part 1: General requirements*. ISO - International Organization for Standardization. Geneva, 1999.
[5] R.W. Lewis, P. Nithiarasu and K.N. Seetharamu, *Fundamentals of the Finite Element Method for Heat and Fluid Flow*. John Wiley & Sons, Chichester, 2004.
[6] R. Rigobello, *Desenvolvimento e aplicação de código computacional para análise de estruturas de aço aporticadas em situação de incêndio*. Tese de Doutorado, Programa de Pós-Graduação em Engenharia de Estruturas, Escola de Engenharia de São Carlos da Universidade de São Paulo. São Carlos, SP, Brasil, 2011.
[7] N.E.M. Nunes, *Código computacional para análise térmica tridimensional de estruturas em situação de incêndio*. Dissertação de Mestrado, Programa de Pós-Graduação em Engenharia de Estruturas, Escola de Engenharia de São Carlos da Universidade de São Paulo. São Carlos, SP, Brasil, 2014.
[8] European Committee for Standardization – EN 1994-1-2:2005. Eurocode 4: *Design of composite steel and concrete structures, Part 1-2: General rules, Structural Fire Design*, Bruxelas, 2005.
[9] V.D. Thi, M. Khelifa, M. Oudjene, M.E. Ganaoui and Y. Rogaume, "Finite element analysis of heat transfer through timber elements exposed to fire". *Engineering Structures*, 143, 11-21, 2017.
[10] R. Dârmon and O. Lalu, "The fire performance of Cross Laminated Timber beams". *Procedia Manufacturing*, 32, 121-128, 2019.
[11] A. Menis, "Fire resistance of Laminated Veneer Lumber (LVL) and Cross-Laminated Timber (XLAM) elements. Italy: Università degli studi di Cagliari, PhD Thesis, 2012