Timber Cross-Section Verification in Fire Situation

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Abstract. Temperature has a significant influence on the timber structural elements behavior. Such material, anisotropic, with irregular fibers and the presence of knots, and flammable, when exposed to high temperatures (fire situation), has its physical and resistance properties deteriorated. This deterioration leads to a considerable loss of stiffness and strength of timber structural systems. During a fire, the thermal analysis of the structural element cross-section becomes dominant, since the behavior of the beam, column, truss or frame under high temperature depends directly on this phase. This thermal analysis allows for determining the temperature field variation through the boundary conditions adopted for the timber cross-section model. Therefore, the objective of this study is to carry out transient thermal analysis, via FEM, of a timber cross-section widely used in civil construction. Such numerical analysis will be carried out through the CS-ASA/FA module with additions of graphical interfaces via GiD platform. Thus, a more complete and accurate visualization of the temperature field variation in the timber cross-section is expected. Finally, comparisons are made with other literature or software results, as SAFIR, to prove the capability of the CS-ASA/FA module and GiD graphical interfaces.

Keywords: thermal analysis, fire situation, timber cross-section, CS-ASA/FA, SAFIR.

1 Introduction

With the use of flammable materials such as timber, the fire concern becomes quite relevant. Modern human society had its development closely related to the knowledge and mastery of fire. Morris and Mouço [1] point out that out-of-control fires have caused considerable human and material losses throughout history, emphasizing the importance of considering fire safety in civil engineering projects. Among historical fires in wooden structures, we can highlight: the great fire of Meireki, in 1657, which lasted three days, destroying two-thirds of the city of Edo (today Tokyo), causing about 100 thousand deaths. This city buildings were made of paper and timber, which contributed to the disaster; the great fire of Rome, dating from the year 64, affected 10 of the 14 zones of the city and destroyed three of them. The fire started from the port area and had its spread favored by most Romans living in insulas, wooden buildings with up to five floors. At the Brazilian national level, Gouveia [2] highlights the flammable architectural complexes, placing the Minas Gerais cities of Estrada Real, characterized by expressive Mineiro Baroque ensembles, as vulnerable and insecure. The fire at the Pilão Hotel in Tiradentes Square, in Ouro Preto/MG, in 2003, illustrates this vulnerability well. Another fire, now in 2012, in one of the large houses that make up the architectural complex of Tiradentes Square, but which was quickly brought under control by firefighters and had no victims, illustrates this risk.

In current times, with the increase in greenhouse gases and the global concern with reducing the environmental impact, wooden constructions have become popular again due to their important role in the search for a more sustainable future in harmony with the environment. One of the biggest contributions of timber construction is its carbon sequestration potential. As trees grow, they capture carbon dioxide from the atmosphere and store it in their grains. When the material is used in buildings, this carbon remains retained, helping to reduce the emission of greenhouse gases in the atmosphere. Additionally, wooden buildings consume less energy when compared to traditional materials such as concrete and steel, which result in lower carbon gas emissions during the manufacturing process. Another additional consideration is the possibility of reusing or recycling the material at all stages of production, resulting in a considerable reduction in the generation of solid waste.

Understanding the behavior of timber in situations of high temperatures is of vital importance in the design of structural systems that use this material. Its physical properties and resistance, when exposed to high temperatures, are deteriorated, and consequently, there is a considerable reduction in the rigidity and bearing capacity of such structures. Therefore, this work proposes to carry out a non-linear transient thermal analyzes of a timber cross-section, with the objective of evaluating the evolution of the temperature field and the behavior of this material under high temperatures. This way, it will be possible to adequately understand the behavior of timber cross-sections in a fire situation and provide additional information to designers, aiming to ensure greater safety in the design of structural elements and system with this material.

2 Thermal analysis

For structural engineering problems in fire condition, the thermal analysis is transient with boundary conditions that depend on time and the material properties depend on temperature, giving the analysis a non-linear character [3]. Thus, computational numerical models based on the Finite Element Method (FEM) are usually used to discretize the element or continuous medium and obtain approximate numerical solutions.

The computational module CS-ASA/FA received interventions to perform the thermal analysis of timber cross-sections in transient regimes, as see in [4]. This module, designed to perform thermal analysis of cross-sections in transient and steady state, is part of the CS-ASA computer system [5], being also developed based on the FEM. When coupled to the CS-ASA/FSA (Fire Structural Analysis) module, it allows performing thermo-mechanical analysis of structures.

The heat conduction problem solution basically refers to solving a partial differential equation, considering the constitutive relationship of the material (Fourier's Law), and satisfying the initial and boundary conditions. In this work, the Weighted Residuals Method, in particular the Galerkin Method, is used to arrive at the equilibrium equation for the heat conduction problem via FEM, which is given in matrix form for each element by:

$$\boldsymbol{C}^e\dot{\boldsymbol{T}}^e + \boldsymbol{K}^e\boldsymbol{T}^e = \boldsymbol{R}^e \tag{1}$$

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

$$\boldsymbol{C}\dot{\boldsymbol{T}} + \boldsymbol{K}\boldsymbol{T} = \boldsymbol{R} \tag{2}$$

in which $\boldsymbol{C}$, $\dot{\boldsymbol{T}}$, $\boldsymbol{K}$, $\boldsymbol{T}$ and $\boldsymbol{R}$ are the global matrices and vectors of the system.

The solution of eq. (2) is obtained through a time integration strategy based on the Finite Differences Method, which allows the consideration of the variation in the thermal properties of timber as a function of temperature rise, following the recommendations of EN 1995-1 -2:2004 [6] for advanced analysis models. The CS-ASA/FA module [7-9] provides two procedures to solve systems of nonlinear equations: the simple incremental and the iterative-incremental. In the case of the latter, the iterations can be performed using the Picard's algorithm (Successive Approximations Method [10]) and the Newton-Raphson Method (NRM) [11].

The SAFIR program [12] uses two iterative methods (the traditional NRM and the modified NRM) to solve non-linear problems. When using the computational programs, Werther *et al*. [13] explains that to have sufficient knowledge of the material and structural response under fire exposure, it is necessary experience of user to assess the simulation results, an understanding of the boundary conditions for heat transfer and structural calculations and, especially, to know the thermal and physical properties of timber material. Thus, the variation of the thermal properties of timber as a function of temperature, in this work, is adopted as indicated by [6] and the standard fire curve available in ISO 834-1: 1999 [14], which is expressed by:

$$T_g = T_0 + 345\log(8t+1) \tag{3}$$

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

3 Numerical example

The cross laminated timber (CLT) beam section, which is 600 mm wide and 150 mm high with the lower surface exposed to fire, was analyzed by Tran *et al*. [15], as illustrated in Fig 1. These researchers investigated numerically this timber cross-section in a standard fire situation, according to [14].

The numerical model built via CS-ASA/FA and SAFIR considered the timber moisture content of 12% and specific dry mass of 450 kg/m³, and the time interval for the transient thermal analyzes was 15 sec. The temperature was evaluated at the cross-section center (300 mm) and depth of 21 mm. For the SAFIR software, the temperature was calculated at a depth of 20 mm. A mesh with 1200 quadrilateral finite elements (Q4) was used in both computational systems.

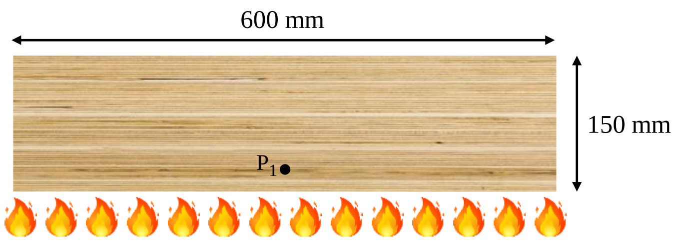
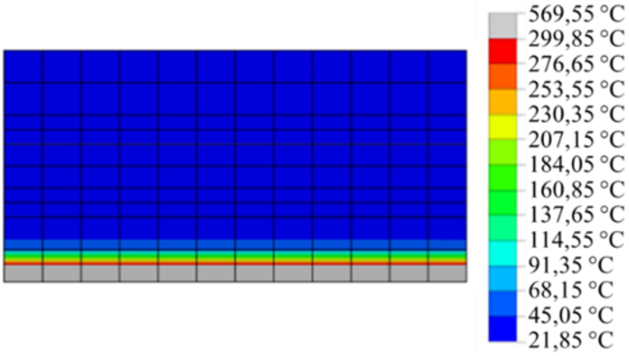


Figure 1. CLT beam cross-section exposed to fire [15]

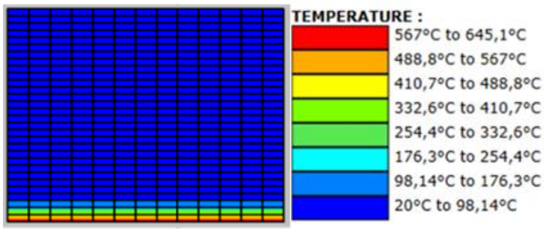
Figures 2 and 3 bring the cross-section temperature variation at 10 and 40 min, respectively, of exposure to fire obtained by softwares CS-ASA/FA, SAFIR and literature [15]. Figures 2a and 3a were adapted from [15] by changing the temperature from Kelvin (K) to Celsius (°C). The results presented indicate the good agreement between the software's and literature [15], and therefore the ability of these two numerical tools in evaluate the progress of temperatures field in timber cross-sections.

Figure 4a represents the temperature *versus* time curve for the thermal analysis. Again, the results indicate the good agreement between the literature and the numerical tools. The temperature remains constant at 20°C in the first few minutes of exposure to fire. Soon after, the temperatures begin to increase progressively. In turn, Fig. 4b shows the progression of the timber carbonization layer. It is known that the formation of the carbonized layer starts at temperatures above 300°C. As the time of fire exposure increases, a reduction in the thickness of the residual section (unaffected by carbonization) is observed and when this residual thickness is not sufficient to cope with the applied moment, the beam collapses. The progression of carbonization in CS-ASA/FA and SAFIR follows the same trend, pointing out the similarity between the results of these two programs. The table in Fig. 4b indicates the relationship between the depth measured in CS-ASA/FA and SAFIR. See that in 10 min this ratio dropped below of 80%. The other values are close to 90%, demonstrating the compatibility of these two numerical tools.

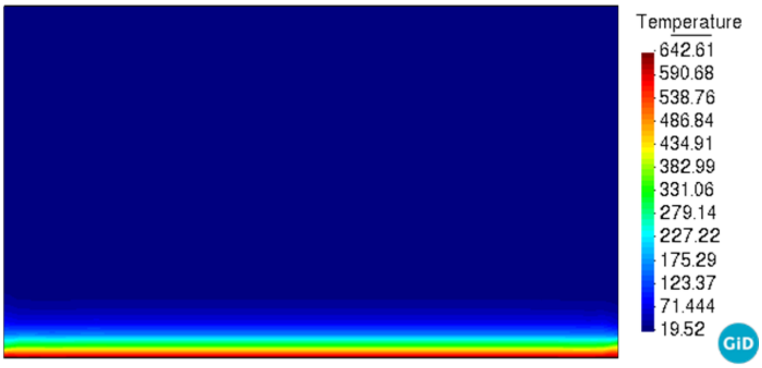
The small differences between the thermal analysis results found using CS-ASA/FA and SAFIR softwares can be explained by the differences of how the thermal problem is handled in each one. Detailed information on how these programs solve the non-linear transient thermal problems can be seen in [7-9, 12].



a) Tran *et al.* [15]

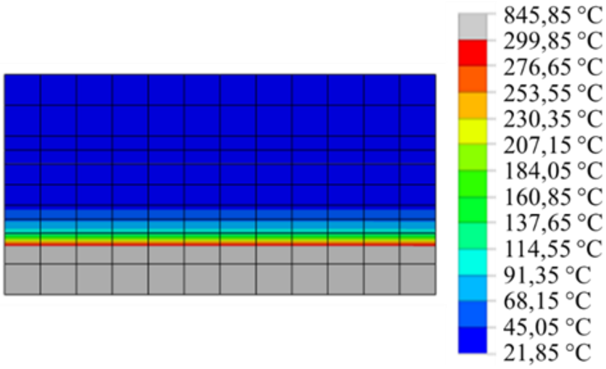


b) SAFIR [12]

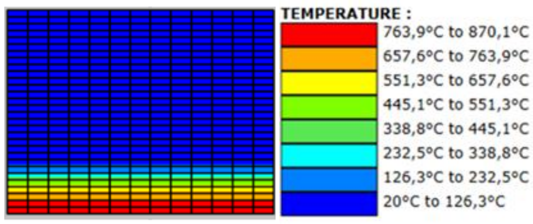


c) CS-ASA/FA

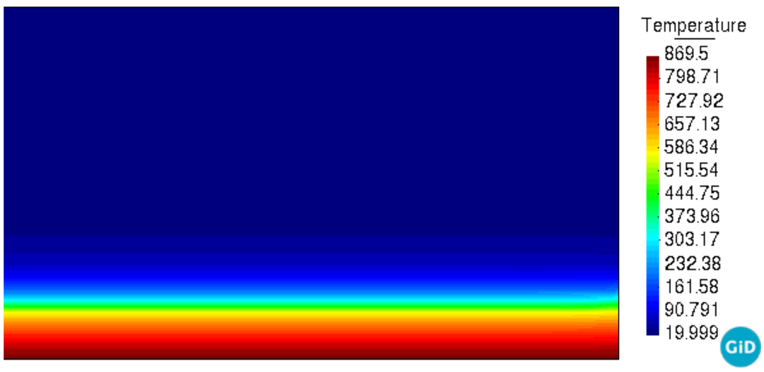
Figure 2. Temperature field in 10 minutes



a) Tran *et al.* [15]

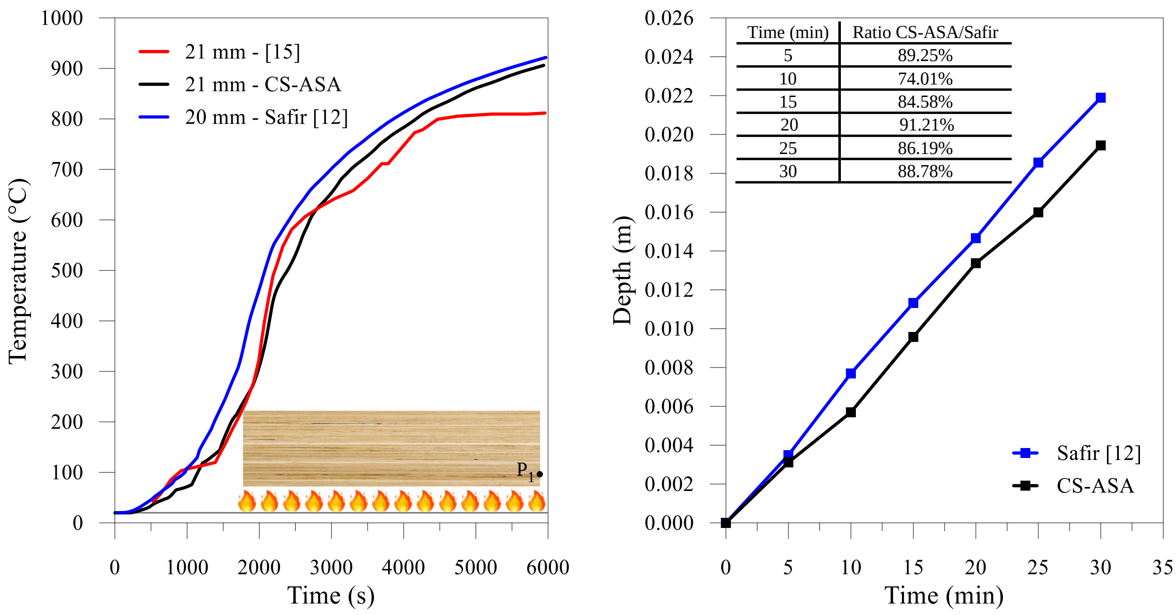


b) SAFIR [12]



c) CS-ASA/FA

Figure 3. Temperature field in 40 minutes



a) Temperature *x* time curve (Point P_1)

b) Charring depth after fire-exposure

Figure 4. Cross laminated timber (CLT) beam section thermal analysis

4 Conclusions

It is essential to comprehend how materials respond to high temperatures to ensure structural safety during fires. Therefore, non-linear thermal analyzes that capture the progression of the temperature field in structural cross-sections are crucial in allowing engineers to design buildings with more safety. When timber is exposed to fire, its physical characteristics and resistance deteriorate due to the increase in temperature, which compromises the material strength capacity.

This work evaluated the performance of a CLT beam cross-section under high temperatures. Using the CS-ASA/FA computational module and SAFIR software, we carried out the thermal analysis of the timber cross-section proposed by Tran *et al*. [15]. The results found were satisfactory and consistent, demonstrating the ability of the CS-ASA/FA module to conduct a non-linear transient thermal analysis of timber cross-sections.

This research will continue to treat the timber structures (beams, columns, truss and frames) thermo-mechanical analyzes. There are still some steps to be developed in the future, such as determining how timber behaves at high temperatures considering more complex thermal effects, and putting together the material degradation that is compatible with finite element formulations.

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