Numerical nonlinear structural analysis of a timber truss roof under fire condition

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

[1] *Dept. of Civil Engineering, Federal University of Ouro Preto*
Morro do Cruzeiro, 35400-000, Ouro Preto/MG, Brazil
caroline.af@aluno.ufop.edu.br, jackson.segundo@aluno.ufop.edu.br, ricardo@ufop.edu.br, luis.queiroz@aluno.ufop.edu.br
[2] *Department of Engineering, Federal University of Lavras*
Trevo Rotatório Professor Edmir Sá Santos, 37203-202, Lavras/MG, Brazil
igor.lemes@ufla.br
[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] *Concremat Engineering & Technology*
34006-056, Nova Lima, Minas Gerais, Brazil
rafaelcesario@hotmail.com

Abstract. Historically, timber has been associated with fire due to its flammability, and numerous incidents of uncontrolled fires underscore the need fire safety measures. This study aims to evaluate the fire resistance of a timber truss roof. As temperatures rise, the physical and mechanical properties of timber members change, leading to a loss of strength and rigidity in parts or the entire truss. This research utilizes the SAFIR® computer program to perform the timber cross-section thermal analysis and timber truss thermomechanical analysis. By conducting the first analysis, it becomes possible to calculate the temperature field of timber members' cross-section in a transient regime, while also obtaining information about the degradation of material properties. The second analysis provides the critical time of the timber truss during collapse. The numerical results obtained here were compared and validated with those from the literature (experimental results). The truss collapse time predicted by SAFIR®'s model was quite similar to the one observed in the laboratory. The addressed numerical methodology allows for more realistic studies of timber isolated element and structural system.

Keywords: thermal and thermomechanical analysis, fire, timber, truss, SAFIR®.

1 Introduction

As greenhouse gases continue to rise and environmental impact reduction gains global attention, timber buildings have emerged as a vital asset in the pursuit of a sustainable future. One of the main benefits of timber construction is its carbon sequestration potential. As trees grow, they absorb carbon dioxide from the atmosphere and store it in their fibers. When this wood is used in buildings, the carbon remains trapped, helping to mitigate greenhouse gas emissions. Additionally, timber buildings require less energy compared to traditional materials like concrete and steel, leading to lower carbon emissions during the manufacturing process. Another advantage is the potential for timber to be reused or recycled at various stages of its lifecycle, significantly reducing solid waste generation.

Throughout history, wood has been associated with being a combustible material due to reports of major fires, such as the Great Fire of London in 1666, which destroyed much of the city. Following this event, Buchanan and Abu [1] reported the emergence of the first fire brigades and fire codes promoted by insurance companies that were more interested in protecting property than in the safety of life. Since then, the importance of fire safety has been recognized as fundamental to reducing, to acceptable levels, the risk of death, injury, property loss and environmental damage during a fire.

As temperatures increase, the physical and mechanical properties of timber elements change, resulting in a loss of strength and rigidity. Therefore, it is important to evaluate the capacity of an isolated element or structural system to continue performing the functions for which it was designed for a given period of time when exposed to fire.

Therefore, the aim of this study is to evaluate the thermal and thermomechanical performance of a timber truss subjected to high temperatures, based on experimental tests carried out by Jessop [2]. Using the SAFIR® [3] computer software, idealized numerical analyses were conducted, which include: the thermal analysis of the timber cross-sections and the thermomechanical analysis of the timber truss. By performing the thermal analysis, it becomes possible to calculate the temperature distribution within the timber cross-section, in a transient regime, and the degradation of the material properties. Then, using the data from the first analysis, the thermomechanical analysis is performed, where the critical time of collapse of the structural system due to exposure to fire is obtained. The numerical results obtained were compared and validated with those obtained experimentally.

2 Problem investigated

Jessop [2] experimentally investigated the fire behavior of a light timber-framed compartment constructed with a timber truss roof and plasterboard ceiling. That work investigated the fire resistance of pine timber trusses composed of a bottom chord, top chord and three diagonal members, as shown in Figure 1. Figure 2 shows the cross sections of the top and bottom chords, which are 45 mm x 90 mm, and three diagonal sections, with 45 mm x 70 mm in height and width, respectively. Each member of the truss system is subjected to fire on all faces.

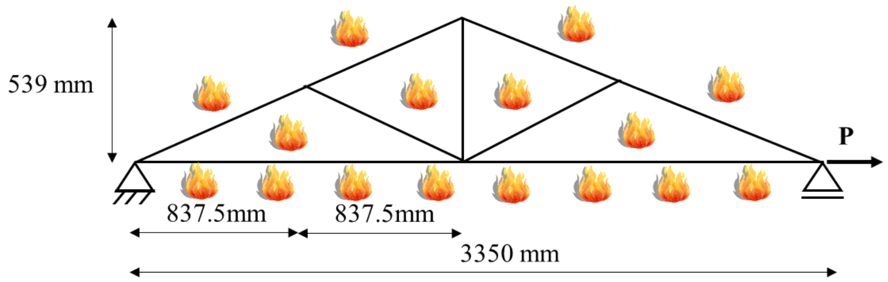
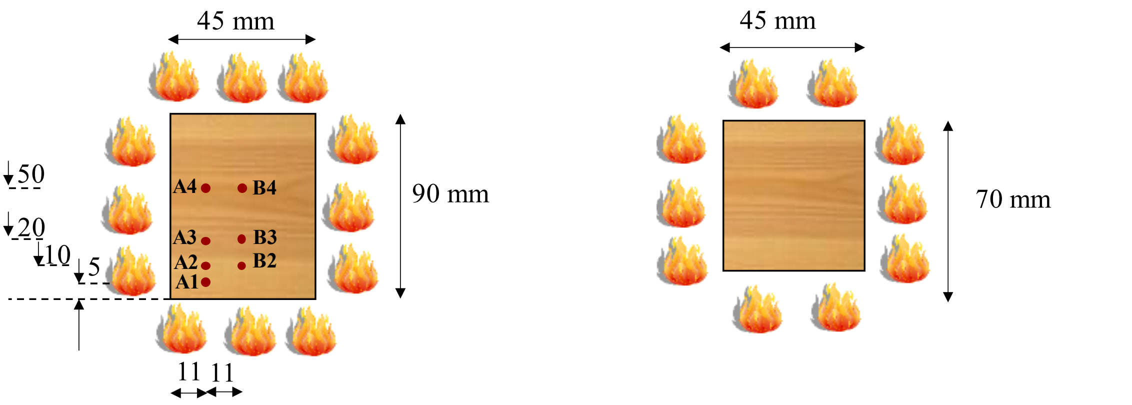


Figure 1. Timber truss system: geometry, loading and support conditions



a) Bottom and top chord: section 45 x 90 mm b) Diagonal members: section 45 x 70 mm

Figure 2. Timber truss members cross-sections

The thermal and mechanical properties of the timber used in the truss at room temperature were experimentally obtained. The values of these properties were: timber moisture content of 11.2%, specific mass of 550 kg/m³, tensile strength of 6 MPa, compressive strength of 6 MPa, and modulus of elasticity of 8000 MPa. For the numerical analysis performed in this work, the exposure time to fire of 40 minutes and the time interval of 15 seconds in the transient sectional analysis were considered. The values for the load P applied to the truss are presented in Table 1.

Table 1. Values for the load P applied to the timber truss (Figure 1)

Truss	Load P (kN)
T1	855
T2	738
T3	561

3 Thermal analysis

When dealing with structural engineering problems in fire conditions, transient thermal analysis is necessary, considering time-dependent boundary conditions. Furthermore, the analysis takes on a non-linear character because the properties of the materials are temperature-dependent. Consequently, FEM-based numerical solutions are typically utilized to discretize continuous domains, making it easier to analyze non-linear systems.

Often, it is not possible to fully scale every physical phenomenon that occurs in a real and complex fire scenario [4]. To simplify the analysis, mathematical models are used to describe the temporal variations in temperature. The representation of these models can be achieved through standardized curves [5-7] (standard curve) or customized natural curves based on the fire's specific properties. The purpose of standardized curves was to unify furnace tests and enable the comparison of experimental findings from various laboratories, although their physical representation is somewhat restricted.

Although the experiment was designed to follow the ISO-834-1:1999 [5] standard fire curve, there was a large variation in furnace temperature along the height of the truss. Therefore, the temperature variation measured by Jessop [2] was used and is shown in Figure 3. During the first 10 minutes of the experiment, increasing amounts of steam rising from the compartment were observed. After approximately 16 minutes from the start of the experiment, significant increases in the amount of steam and smoke rising from the compartment were observed.

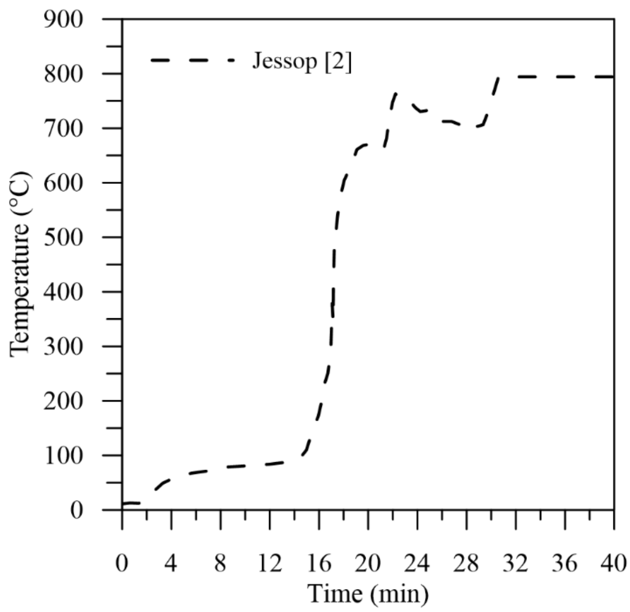


Figure 3. Gas temperature assessed in the Jessop experiment [2]

The temperature was evaluated in the 45 x 90 mm cross-section at 11 mm from the left lateral face at points A1, A2, A3 and A4 for depths of 5, 10, 20 and 50 mm, respectively (Figure 2). Points B1, B2 and B3 were also evaluated for the same depth at 22 mm from the left lateral face, as detailed in Figure 2. The results of the sectional thermal analyses are presented in Figures 4 and 5, where it is possible to verify the good agreement between the results found in the literature and those obtained in this research.

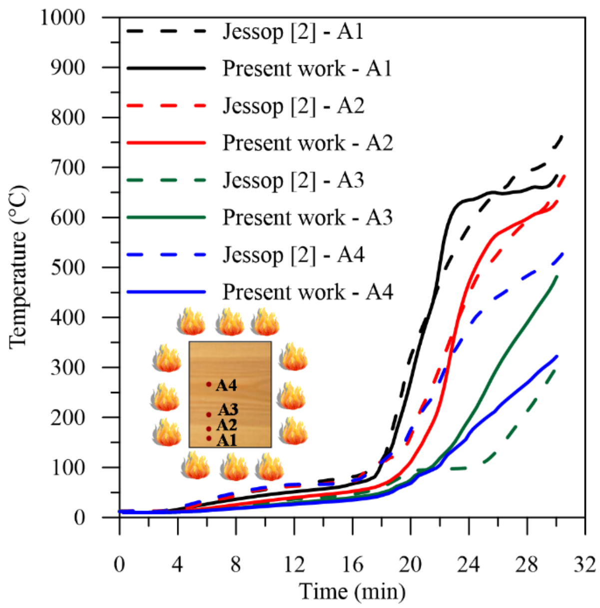


Figure 4. Temperature *vs.* time curve for points A of the 90 x 45mm cross section

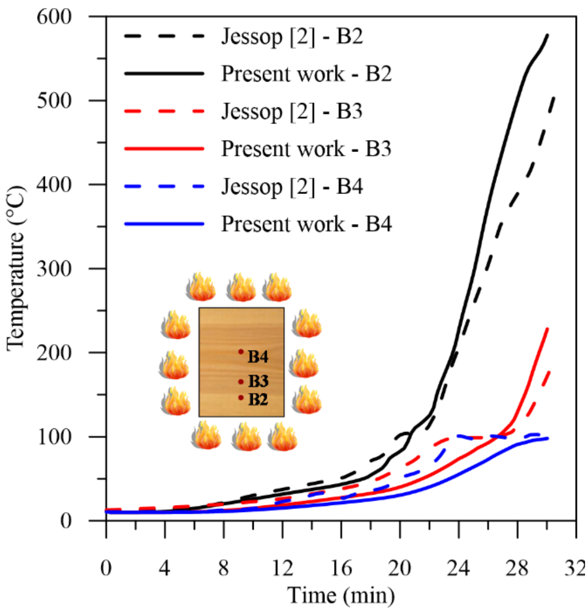


Figure 5. Temperature *vs.* time curve for points B of the 90 x 45mm cross section

The depth of carbonization at the end of the experiment was measured and the values are presented in Table 2. When comparing the experimental data with the results obtained through the numerical methodology, a good agreement is observed. This indicates that the numerical model used was able to predict the real behavior of carbonization during the fire.

Table 2. Measured (laboratory) and calculated (numerical) char depth on the bottom chord

	Jessop [4] - experimental			SAFIR® - numerical		
	T1	T2	T3	T1	T2	T3
Final char depth (mm)	30	35	37.5	26	28	31
Charring rate (mm/min)	1.1	1.2	1.3	0.93	0.98	1.05

4 Thermomechanical analysis

The interaction between mechanical and thermal analyses involves different physical phenomena. The temperature field induces thermal strain in the structure, while structural strain generally does not impact the temperature distribution. Consequently, there is no need for simultaneous iterations between the two fields.

In this way, after defining the temperature field in the sectional thermal analysis, it is possible to determine the reduction in the mechanical (strength and stiffness) and thermal (coefficient of expansion) properties of the timber as the temperature varies. Through the FEM, the thermal and structural analyses establish a connection by integrating these variations. The strength and stiffness parameters decrease as soon as the temperature exceeds 20°C, and when it reaches 300°C they reduce to zero. In the range from 20°C to 300°C, we apply different reduction factors to tension and compression for strength and modulus of elasticity. The behavior is not reversible during cooling.

During thermomechanical analysis, the increase in temperature generates thermal strain in the structure, and consequently thermal forces arise to balance the system. In the analysis of structures under high temperatures, the external load acting remains unchanged once the fire has started. The solution of the nonlinear transient problem is obtained for each time increment, where the temperature field in the cross section and the resistance parameters are determined. These parameters are updated according to the reduction factors presented by the EN 1995-1-2:2004 [7] standard.

Thus, by considering the data in Table 2, it is possible to find the fire resistance time of the timber truss system and presented in Table 3 for different values of the applied load P (see Figure 1 and Table 1). The error was calculated considering the relative difference between the result obtained by SAFIR® and the experimental one.

Table 3. Fire resistance time for timber trusses

Truss	Collapse time (min)		Error (%)
	Jessop [4] - experimental	SAFIR® - numerical	
T1	27.27	27.87	2.19
T2	29.17	28.50	2.28
T3	28.85	29.49	2.20

It can be seen that the failure times of the trusses obtained in this research through SAFIR® are close to those from laboratory. Buchanan and Abu [1] described that light timber trusses exposed to post-flashover fire conditions have poor fire resistance. The strength and stiffness of the system are predominantly determined by the behavior of the truss connections and these are highly vulnerable when exposed to high temperatures. Therefore, the bottom flange of the trusses failed due to tension.

5 Conclusions

The building's stability in fire situations involves understanding the consequences of rising temperatures on structures, which has been achieved through laboratory experiments and the use of increasingly sophisticated numerical models. Such models allow for a greater understanding of structural behavior in situations of high temperatures.

The results obtained through the thermal and thermomechanical analyses of timber trusses, although not exact, are within an acceptable range and are satisfactory. These differences arise due to the heterogeneity and orthotropic properties of wood. Wood is a natural material with composition and properties that vary in different directions (longitudinal, radial and tangential). This variability, combined with the presence of natural defects and differentiated responses to heat, makes the numerical modeling challenging. To simplify, models often assume effective properties, which can cause discrepancies between the numerical results and the actual behavior of timber exposed to fire.

Therefore, in this work, it is concluded that it is possible to simulate timber structures in the SAFIR® software with a good degree of accuracy, since the errors obtained were less than 3%.

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