XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

Numerical evaluation of timber as passive fire protection for steel structural profiles

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

[1]*Department of Civil Engineering, School of Mines, Federal University of Ouro Preto (UFOP)*
Campus Morro do Cruzeiro s/n, CEP: 35.400-000, Ouro Preto/MG, Brasil
caroline.af@aluno.ufop.edu.br, ricardo@ufop.edu.br, jacksonsrsegundo@gmail.com
[2]*Department of Engineering, Federal University of Lavras (UFLA)*
Trevo Rotatório Professor Edmir Sá Santos Universidade Federal de Lavras, CEP: 37200-900, Lavras/MG, Brasil
igor.lemes@ufla.br
[3] *Department of Technology in Civil Engineering, Computing, Automation, Telematics and Humanities (DTECH), Federal University of São João del-Rei (UFSJ)*
Fazenda do Cadete - Lobo Leite, CEP: 36415-000, Ouro Branco/ MG, Brasil
dalilah@ufsj.edu.br
[4]*Sereng Engineering and Consulting, Nova Lima, Brasil*
rafaelcesario@hotmail.com

Abstract. Steel is extensively used in civil construction due to its high strength, durability, and versatility. However, its intrinsic vulnerability to elevated temperatures — characterized by rapid loss of mechanical strength and high thermal conductivity — makes fire protection essential to ensure structural safety. In this context, timber has emerged as a promising passive fire protection material, capable of delaying heat transfer and extending the resistance time of steel elements. This study investigates the effectiveness of timber encapsulation as fire protection for steel I-beam profiles through advanced numerical modeling. Using the SAFIR® software, transient thermal analyses were performed to simulate different encapsulation configurations (unprotected, partially encapsulated, extended partial encapsulation, and fully encapsulated) combined with various timber species (Douglas, Silver fir, and Pine). The numerical approach was validated against experimental results available in the literature, demonstrating close agreement and confirming the reliability of the methodology. The results show that timber significantly increases the fire resistance of steel sections, with full encapsulation delaying the attainment of the critical steel temperature (550 °C) by more than two hours. These findings highlight the potential of steel–timber composite solutions as sustainable, cost-effective, and safe alternatives for structural fire protection. Furthermore, the validated computational strategy provides a robust tool for future parametric studies and design improvements, supporting the development of innovative guidelines for hybrid structural systems under fire conditions.

Keywords: Steel-timber composite cross-sections; Transient thermal analysis; Passive fire protection; Numerical modeling; SAFIR® software

1 Introduction

Steel is one of the most widely adopted construction materials worldwide, largely due to its combination of high mechanical strength, lightness, versatility, and durability. These properties enable the design of slender structural elements capable of resisting large loads and spans, while also facilitating prefabrication and rapid assembly on construction sites. Additionally, the recyclability and reusability of steel contribute to reducing environmental impacts, positioning it as a key material in the transition toward sustainable construction practices [1,2]. Despite these well-recognized advantages, steel remains particularly vulnerable when exposed to fire: as

temperature rises, its mechanical resistance deteriorates rapidly, while its high thermal conductivity accelerates heat transfer, threatening the integrity of the entire structure in a short period of time.

In response to this limitation, different fire protection strategies have been developed and integrated into design practice. These include active protection systems, such as sprinklers, and passive solutions, such as insulating coatings, concrete encasements, and fire-resistant boards. Among these alternatives, the use of timber as a natural thermal barrier has gained increasing attention in recent years. Timber, although combustible, presents a comparatively low thermal conductivity and develops a protective char layer when exposed to fire, which slows heat penetration and protects the underlying material. Consequently, it can function not only as a structural component but also as an efficient means of delaying the thermal degradation of steel elements [3–5].

The hybridization of steel and timber in composite elements has been explored by several researchers, who point to the potential of combining the high strength of steel with the insulating capacity of wood to achieve safer and more sustainable fire-resistant systems. Nguyen *et al*. [3], for example, conducted experimental investigations on steel profiles protected by timber layers, demonstrating the ability of timber encapsulation to significantly delay the attainment of critical steel temperatures. Other studies, such as those by Saulnier *et al*. [4] and Béreyziat *et al*. [5], have reinforced these findings, highlighting that timber protection can extend the fire resistance of steel beams without resorting to conventional insulation systems, while also reducing costs and environmental impacts. Nevertheless, the literature indicates that the number of experimental studies remains limited, and the complex thermo-mechanical interactions between steel and timber under fire conditions still demand deeper numerical and analytical investigation

Given this context, the present study aims to contribute to the understanding of the fire performance of steel-timber composite sections by means of advanced computational modeling. Numerical simulations were carried out using the SAFIR® software [6], a tool widely recognized for transient thermal and structural analyses under fire conditions. The models were validated against experimental results reported by Nguyen *et al*. [3], ensuring reliability in the adopted methodology. The objective is to assess different timber encapsulation configurations and wood species, quantifying their effect on delaying heat propagation and increasing the fire resistance of steel sections. In doing so, this work seeks to provide a more accurate basis for design procedures, supporting safer, more economical, and sustainable engineering practices aligned with the growing use of hybrid structural systems.

2 Transient thermal analysis of composite cross-sections

The fire performance of composite structural members depends primarily on the evolution of temperature within their cross-sections. In order to evaluate the efficiency of timber as a passive fire protection material for steel profiles, it is necessary to accurately reproduce the transient heat transfer phenomena that occur during fire exposure. This section presents the theoretical formulation adopted for the thermal analysis, which serves as the basis for the numerical simulations developed in Section 3.

The problem of heat conduction is governed by Fourier's law, expressed in the form of a partial differential equation (PDE) that relates the spatial and temporal evolution of temperature to the thermophysical properties of the material. For engineering applications, the direct analytical solution of this PDE is rarely feasible due to the geometric complexity of cross-sections and the temperature-dependent behavior of materials. Consequently, the Finite Element Method (FEM) provides a robust framework to discretize the domain, approximate the temperature field, and obtain solutions in a stepwise manner for transient conditions

In this study, the Galerkin method of weighted residuals was employed to derive the finite element equations, ensuring temperature continuity across the discretized cross-section. The resulting system of equations can be expressed in matrix form as:

$$\mathbf{K}\mathbf{T} + \mathbf{C}\dot{\mathbf{T}} = \mathbf{g} \tag{1}$$

where **C** represents the capacitance (thermal capacity) matrix, **K** is the thermal conductivity matrix, **g** represents the vector of heat fluxes imposed at the boundaries, **T** is the nodal temperature vector, and $\dot{\mathbf{T}}$ denotes its time derivative. The transient problem was solved through a numerical integration scheme based on the Finite Difference Method (Newmark's solution), which divides the fire exposure into small time increments. At each increment, the solution is updated iteratively by imposing thermal equilibrium, typically through Newton–Raphson iterations.

A fundamental aspect of fire analysis is the strong dependence of material properties on temperature. In this work, the thermal conductivity, density, and specific heat of both steel and timber were updated at each time step according to the reduction factors recommended by Eurocode 3 [8] and Eurocode 5 [7], respectively. This approach ensures that the degradation of material properties under elevated temperatures is realistically captured, which is particularly relevant for timber due to its anisotropy and charring behavior.

The formulation described herein establishes the computational foundation for simulating hybrid steel-timber cross-sections under fire. In Section 3, this model is applied to IPE 240 profiles with different levels of timber encapsulation. By combining the high conductivity of steel with the insulating properties of timber, the analyses highlight the distinct thermal response of each configuration, providing insights into the effectiveness of timber as a passive fire protection material.

3 Simulation of steel-timber composite cross-sections

The fire performance of steel-timber composite (STC) cross-sections was investigated through advanced simulations using the SAFIR® software, which allows coupled thermal and structural analyses under transient fire conditions. Building upon the formulation presented in Section 2, the finite element models were developed to replicate the experimental and numerical conditions reported by Nguyen *et al*. [3], thereby ensuring a reliable validation of the adopted approach. The analyses focused on evaluating the influence of different timber encapsulation strategies on the heating rate of the steel web, as illustrated in Figure 1, which presents the four cross-sectional configurations considered in this study.

Material properties were defined according to data available in the literature and complemented by recommendations from Eurocode 3 [8] for steel and Eurocode 5 [7] for timber. To reduce computational complexity while maintaining physical consistency, the interface between steel and timber was modeled as a perfect bond, assuming no relative slip or detachment during heating. Although this idealization neglects potential effects such as adhesive failure or irregular charring, it enables isolating the influence of encapsulation geometry and timber species on thermal performance, which is the primary focus of this study.

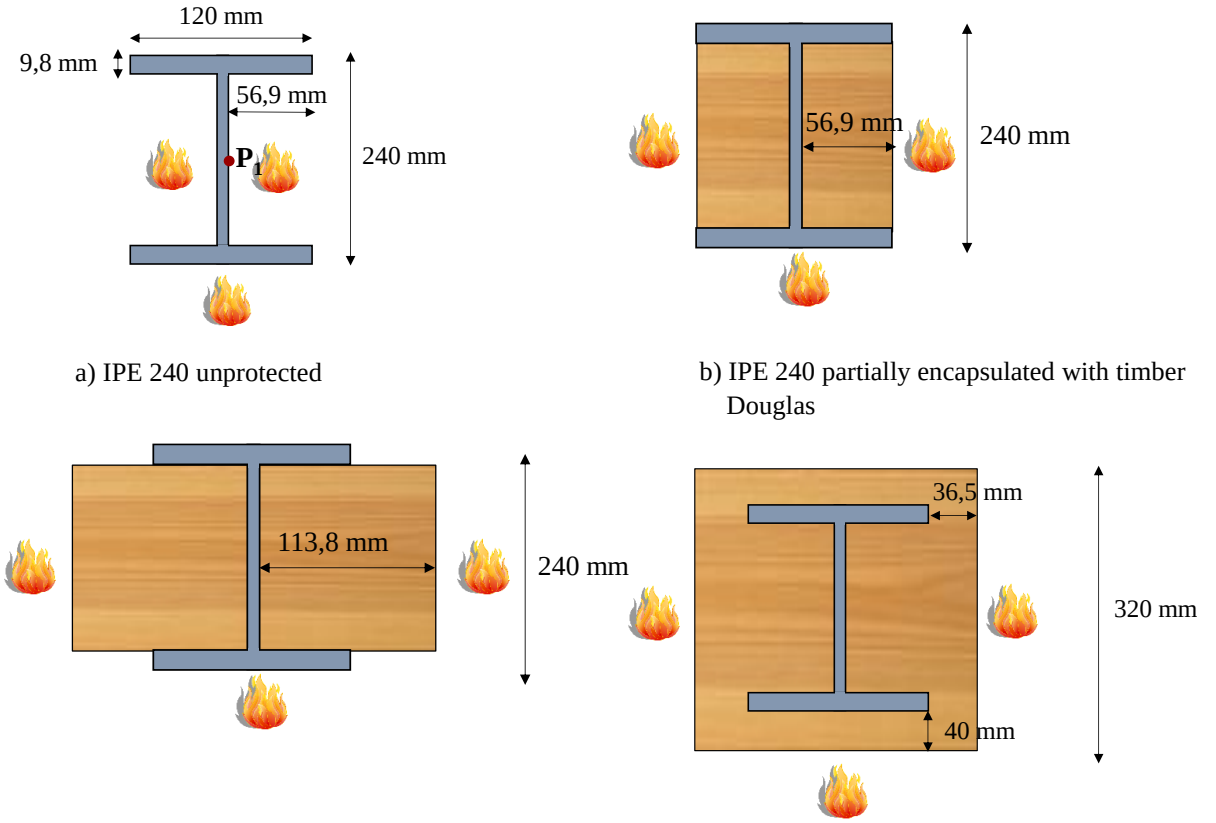
The numerical models considered the IPE 240 steel profile subjected to the ISO 834-1 standard fire curve [9]. Three encapsulation strategies were examined — partial, extended partial, and full protection — together with three timber species commonly found in construction: Douglas (density $\rho = 496$ kg/m³, 8% moisture), Silver fir ($\rho = 425$ kg/m³, 10%), and Pine ($\rho = 430$ kg/m³, 9%). These variations were selected to reproduce the conditions of Nguyen *et al*. [3], facilitating direct comparison between numerical predictions and experimental observations. In this way, the simulations provide a consistent framework for evaluating the potential of steel-timber composite sections as sustainable and efficient alternatives for fire-resistant structural systems

3.1 Results and discussion

The numerical simulations performed in this study reproduced with good accuracy the experimental trends reported by Nguyen *et al*. [3]. Figure 2 shows the temperature evolution at point P1, located at the web-timber interface, for the four encapsulation configurations. In general, the curves demonstrate strong agreement between the present numerical model and the literature data, with only minor deviations in the heating rates. These differences are mainly associated with the orthotropic and heterogeneous nature of timber, as well as local irregularities observed in experimental tests, which are not explicitly captured in the idealized computational models. Nevertheless, the consistency of the overall trends confirms the reliability of the SAFIR-based approach for simulating hybrid steel-timber sections under fire.

A quantitative comparison of the results is presented in Table 1, which summarizes the time required for the steel web to reach 550 °C — the critical temperature associated with significant loss of mechanical resistance. The unprotected IPE 240 profile reached this threshold in less than 10 minutes, highlighting the extreme vulnerability of bare steel. By contrast, the partially encapsulated section with Douglas timber increased fire resistance to nearly one hour, while the extended partial encapsulation with Silver fir further delayed heating to values above 100 minutes. The best performance was achieved with full encapsulation using Pine, where the critical temperature was not attained until more than two hours of fire exposure. These results emphasize that the degree of encapsulation is the dominant factor in enhancing fire resistance, with timber species exerting a secondary

influence linked to density and moisture content.



a) IPE 240 unprotected

b) IPE 240 partially encapsulated with timber Douglas

c) IPE 240 partially encapsulated extend with timber Silver fir

d) IPE 240 fully encapsulated with timber Pine

Figure 1. Configurations of steel-timber composite cross-sections with different encapsulation level

It is also important to recognize the limitations of the adopted numerical assumptions. The perfect bond hypothesis, the omission of defects such as cracks or delamination at the steel-timber interface, and the simplified treatment of the charring process may all contribute to discrepancies between numerical and experimental outcomes. Even so, the deviations observed remained relatively small and did not compromise the identification of clear performance hierarchies among the studied configurations. From an engineering perspective, the findings confirm the potential of timber as an efficient and sustainable passive fire protection system, capable of substantially extending the safe use period of steel structures during fire and providing valuable additional time for evacuation and firefighting interventions.

Table 1. Time required for the steel web to reach 550 °C: experimental *vs*. numerical results

Specimen	Nguyen *et al.* [3]	Present work
IPE 240 unprotected	11 min	8 min
IPE 240 partially encapsulated (Douglas)	62 min	55 min
IPE 240 partially encapsulated extend (Silver fir)	120 min	107 min
IPE 240 fully encapsulated (Pine)	147 min	137 min

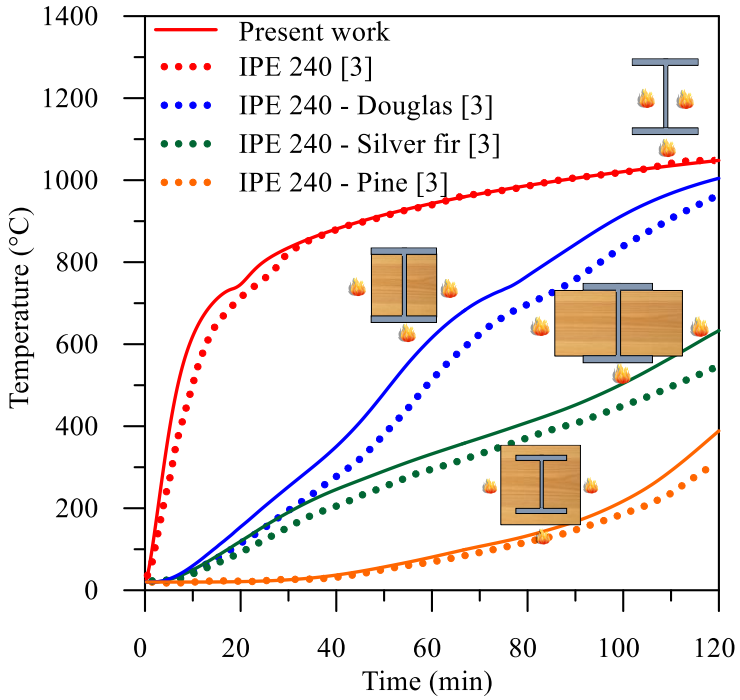


Figure 2. Temperature-time response of steel web (numerical *vs.* experimental)

3.2 Parametric study

After validating the computational model, a parametric study was conducted to further explore the effect of timber encapsulation using Silver fir as the reference material, given its intermediate density and moisture content compared with Douglas and Pine. Figure 3 illustrates the temperature-time response of the steel web under the ISO 834-1 fire curve for the four protection configurations. As expected, the unprotected profile exhibited the steepest temperature rise, surpassing 550 °C in only a few minutes. The partially encapsulated configuration provided noticeable improvement by introducing a thermal barrier, yet the steel temperature still increased rapidly, approaching critical values within the first hour. The extended partial encapsulation resulted in a much slower heating rate, evidencing the importance of protecting not only the web but also part of the flanges. Finally, the fully encapsulated section achieved the best performance, maintaining the steel temperature well below the critical threshold for more than two hours.

The comparison among these configurations highlights two key findings. First, the extent of encapsulation is the governing parameter in improving fire resistance, with the transition from partial to extended partial protection producing a disproportionately large increase in resistance time. Second, while Silver fir was used as the baseline species, the relative trends observed are consistent with those obtained for Douglas and Pine, reinforcing the robustness of the numerical model. From an engineering standpoint, these results underline the potential of targeted timber encapsulation strategies as efficient and sustainable alternatives to conventional fireproofing materials. In practical terms, they indicate that even partial protection can provide valuable additional safety time, whereas full encapsulation may guarantee compliance with stringent fire resistance requirements in building design.

4 Conclusions

This study presented a numerical investigation of the fire performance of steel beam cross-sections protected with timber encapsulation, using transient thermal analyses carried out in the SAFIR® software. The computational models were validated against experimental data from Nguyen *et al*. [3], showing strong agreement and confirming the robustness of the adopted methodology.

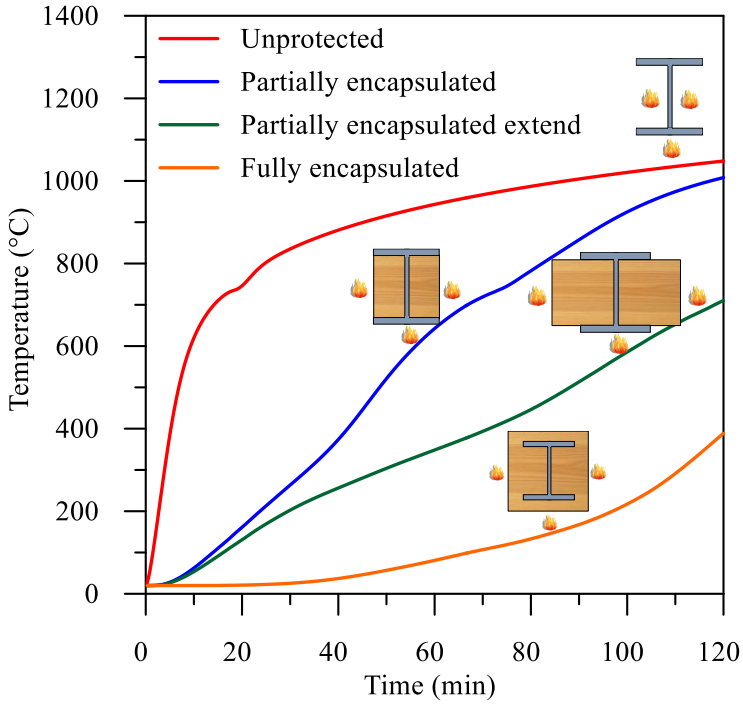


Figure 2. Parametric study: steel temperature-time response with silver fir encapsulation

The results demonstrated that timber can significantly delay the heating of steel sections, thereby acting as an efficient passive fire protection material. The degree of encapsulation proved to be the most influential factor: while the unprotected IPE 240 reached the critical temperature of 550 °C in less than 10 minutes, partial protection extended fire resistance to nearly one hour, extended partial protection to almost two hours, and full encapsulation to more than two hours. Although the wood species had a secondary role, differences in density and moisture content produced measurable effects, with Pine achieving the longest resistance times.

From an engineering perspective, these findings provide evidence that timber encapsulation can substantially improve the fire resistance of steel profiles, ensuring additional safety margins that are critical for evacuation and firefighting operations. Moreover, by substituting or complementing conventional fireproofing methods, steel-timber composite solutions represent a sustainable, cost-effective, and innovative alternative for building design.

Nevertheless, some limitations should be acknowledged. The assumptions of perfect bond at the steel-timber interface, the simplified representation of the charring process, and the omission of potential defects such as cracks, gaps, or adhesive failure may explain the minor discrepancies between simulations and experimental results. Addressing these aspects requires refined experimental data and more advanced numerical modeling.

Future research should therefore focus on: (i) detailed investigation of the steel-timber interface, including the role of connectors, adhesives, and possible detachment during fire; (ii) coupled thermo-mechanical analyses that account for load-bearing capacity in addition to heat transfer; (iii) studies of the influence of timber properties (density, moisture, anisotropy) on fire resistance; and (iv) the development of design-oriented parametric models to support the drafting of practical guidelines and code provisions.

In summary, this work validates the use of SAFIR® for simulating steel–timber sections under fire and demonstrates the potential of timber encapsulation to extend fire resistance times by more than two hours. The study contributes to advancing the understanding of hybrid structural systems and establishes a strong basis for future research, aiming to bridge the gap between laboratory-scale investigations and real design applications.

Acknowledgements. The authors gratefully acknowledge the financial and institutional support that made this research possible. This work was supported by CAPES – Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Brazil), CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico (Brazil), and FAPEMIG – Fundação de Amparo à Pesquisa do Estado de Minas Gerais, as well as by the Gorceix Foundation. The authors also express their appreciation to the graduate support programs PROPEC/UFOP and PROPPI/UFOP,

and to the partner institutions UFSJ and UFLA, for their continuous encouragement and provision of resources that contributed to the development of this study.

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] B. Liu. "Progress of research on fire-resistant steel in civil engineering." *Applied and Computational Engineering*, 2025.
[2] A. Aghayere. *Structural steel design*. Walter de Gruyter GmbH & Co KG, 2025.
[3] M. H. Nguyen, S. E. Ouldboukhitine, S. Durif, V. Saulnier, A. Bouchair. "Passive fire protection of steel profiles using wood." *Engineering Structures*, v. 275, p. 115274. 2023.
[4] V. Saulnier, S. Durif, S. Oulboukhitine, A. Bouchaïr, G. Bihina. "Wood as Fire Protection of Steel in Hybrid Structural Elements." In: *International Scientific Conference on Woods & Fire Safety*. Cham: Springer International Publishing, 2020.
[5] A. Béreyziat, M. Audebert, S. Durif, A. Bouchaïr, A. Si Larbi, D. Dhima. "Fire Protection of Steel Beams by Timber: Thermomechanical Analysis." *International Scientific Conference on Woods & Fire Safety*. Cham: Springer International Publishing, 2020.
[6] J. M. Franssen. "SAFIR: A thermal and struc-tural program for modeling structures under fire". *Engineering Journal*, 42(3), 143-158, 2005.
[7] European Committee for Standardization. "EN 1995-1-2 - Eurocode 5 - Design of timber structures - Part 1-2: General - Structural fire design", 2004.
[8] European Committee for Standardization. "EN 1993-1-2 - Eurocode 3 - Design of steel structures - Part 1-2: General rules - Structural fire design", 2005.
[9] International Organization for Standardization. "ISO 834-1, Fire Resistance Tests - Elements of Buildings Construction, Part 1: General Requirements", Geneva, 1999.