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INVESTIGATING THE THERMAL PENETRATION IN STRUCTURAL TIMBER ELEMENTS EXPOSED TO NATURAL FIRES

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ABSTRACT: This study investigates fire-induced charring and thermal penetration in structural timber elements exposed to natural fire conditions, with a focus on the critical role of the cooling phase. A simplified 1D heat transfer model, based on Eurocode 5 temperature-dependent material properties, is implemented to simulate the thermal response of timber members subjected to Eurocode parametric fire curves. The analysis quantifies the char depth (300 °C isotherm) and the zero-strength layer, using both temperature-based (80-300 °C and 120-300 °C) and reduced mechanical properties approaches (tension and compression). Results show that, while the char depth predominantly develops during the heating phase, the zero-strength layer continues to grow during cooling, often reaching a thickness comparable to the char layer. The effective char depth (char depth + zero-strength layer) typically reaches its maximum towards the end of the cooling phase, representing the most critical condition for load-bearing capacity. The most severe conditions arise in low ventilation and high fuel load scenarios, characterised by long-duration fires rather than the highest temperatures. The findings highlight the need to explicitly consider the cooling phase in performance-based fire design for timber structures.

KEYWORDS: timber structures, fire safety, charring, zero-strength layer, cooling

1 – INTRODUCTION AND BACKGROUND

Urban densification, sustainability drivers, and advancements in building technologies are driving a renewed interest in high-rise construction using bio-based materials. Among these, engineered wood products such as cross-laminated timber (CLT) and glulam are central to the rapid expansion of mass timber buildings, which now represent one of the fastest-growing sectors in the construction industry [1]. Mass timber offers several environmental benefits, including a lower carbon footprint, renewability, and reduced construction time compared to traditional steel and concrete systems. However, despite these advantages, fire safety remains one of the principal barriers to the widespread adoption and acceptance of tall timber structures [2].

The primary distinction between timber buildings and those constructed from non-combustible materials such as steel and concrete, lies in the combustibility of wood. Timber acts not only as a structural material but also as a potential source of fuel in the event of a fire. From a structural engineering perspective, wood undergoes pyrolysis and combustion when exposed to elevated temperatures [3]. Pyrolysis leads to the formation of a char layer, typically assumed to occur at temperatures above 300°C, which reduces the effective cross-section of load-bearing elements [4-5]. The charred wood is considered to have null strength and stiffness. As a result, structural integrity and stability can be compromised, both at the component and system levels.

In standard design practice, the charring rate is a key parameter in evaluating the fire performance of timber elements [4-5]. This rate determines the progression of the char front and, consequently, the reduction in the load-bearing effective cross-section. However, conventional fire resistance design, including the Reduced Cross-Section Method (RCSM) outlined in EN 1995-1-2, typically focuses on prescriptive methods

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based on standard fire exposure, such as the ISO 834 fire curve [4-6]. This exposure is characterised by a monotonically increasing temperature-time relationship, conceived as a worst-case design scenario for post-flashover fires during the growth and fully-developed phases.

However, real compartment fires follow a more complex thermal development, consisting of a growth phase, a fully-developed phase, a decay phase, and ultimately a cooling phase [7]. Despite this, most standardised fire tests and design approaches neglect the decay and cooling phases, assuming them to be less critical due to the lower temperatures [8]. Nevertheless, this assumption does not hold for timber structures and, even after the peak fire temperatures are achieved and the fire appears extinguished, the heatwave continues to propagate deeper into timber members (see Figure 1). As a result, load-bearing capacity can continue to deteriorate during the fire decay and cooling phase, posing a risk of delayed structural failure, often with little or no warning.

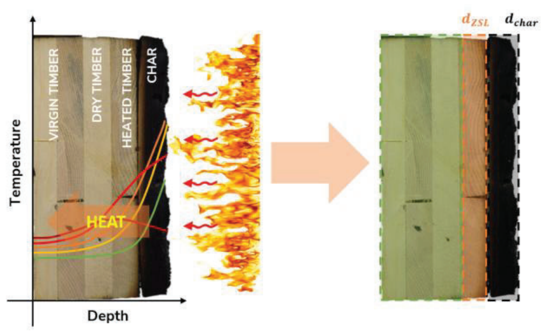

Figure 1. Heatwave propagation within the structural timber element during the fire exposure (heating and cooling phases), and simplified method to estimate the load-bearing capacity based on the char depth (d_{char}) and zero-strength layer (d_{ZSL}).

Timber's susceptibility to irreversible loss of mechanical properties at relatively low temperatures exacerbates this problem, compared to traditional construction materials (refer to EN 1995-1-2 and see Figure 2). For example, typical softwood may exhibit a compressive strength reduction of up to 75% at just 100°C, even if it has not yet charred [6]. Accordingly, structural timber exposed to temperatures between 100°C and 300°C experiences substantial degradation in strength and stiffness. This is particularly critical for columns and load-bearing walls, where compressive loads dominate [9-11].

Current simplified design approaches, such as the RCSM, address this issue by introducing the concept of the zero-strength layer to account for the heated but uncharred timber with reduced mechanical properties [6, 12]. The zero-strength layer, assumed to have zero strength and stiffness like charred wood, is added to the char depth when determining the effective load-bearing cross-section. According to the current Eurocode 5, the zero-strength layer thickness is a constant 7 mm for fire exposures exceeding 20 minutes [6]. In the proposed second-generation Eurocode, different thicknesses are suggested, depending on member type and stress state, with values up to 16 mm for CLT floor elements under compression [13]. However, these simplified methods only account for heating phases and neglect cooling effects, potentially underestimating damage in performance-based designs.

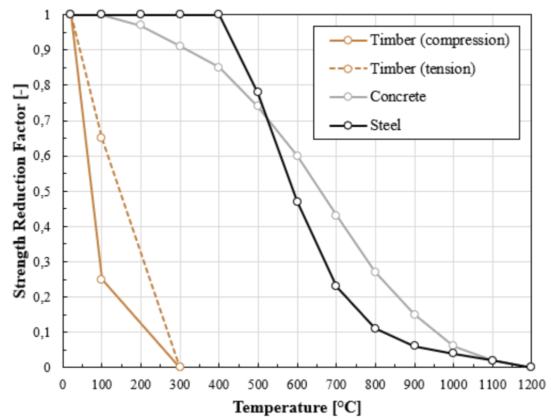

Figure 2. Comparison of the strength reduction factor of steel, concrete and timber at elevated temperatures (based on EN 1992-1-2:2023, EN 1993-1-2:2024, and EN 1995-1-2:2009).

Recent research highlights the continued thermal penetration and mechanical degradation of timber elements during the cooling phase [9-11, 14-20]. Numerical and experimental studies have demonstrated that the zero-strength layer can grow substantially during the cooling phase, even matching or exceeding the thickness of the char layer by the end of the fire exposure [14-17].

Despite growing recognition of these issues, there remain significant knowledge gaps and technical challenges in comprehensively assessing the fire performance of timber structures, particularly during the cooling phase. There is a pressing need to move beyond prescriptive design approaches towards performance-based methods that account for the entire fire duration, including the fire decay and cooling phases [7]. Such methods will enhance the reliability and safety of fire-exposed timber structures, especially in tall timber buildings, where the consequences of delayed structural failure can be severe.

This study addresses these challenges by investigating fire-induced charring and heat penetration in timber members exposed to natural fire conditions (i.e., Eurocode parametric fire curves). Using a simplified one-dimensional heat transfer model and effective

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temperature-dependent material properties, the research aims to quantify the impact of both the heating and cooling phases on the char depth, zero-strength layer thickness, and effective residual cross-section of load-bearing timber elements. The findings provide new insights to support the development of modern performance-based fire design strategies for fire-safe timber buildings.

2 – METHODOLOGY

A one-dimensional heat transfer model based on pure conduction is formulated to investigate heat penetration in structural timber elements exposed to fire, following an approach analogous to a previous study [14]. The finite difference model is based on the numerical method developed by Emmons and Dusinberre [21-22]. The model domain is discretised into a series of finite elements associated with nodes, explicitly solving the one-dimensional heat conduction equation by applying energy balance equations along the primary heat flow direction (from the exposed surface towards the substrate). An in-house Python code is developed to solve the numerical problem.

The heat transfer model follows the Eurocode advanced calculation methods (ACM) [6]. Solid softwood is modelled as an isotropic and homogeneous material with temperature-dependent effective properties as defined in Eurocode 5, including mass density ratios, specific heat capacity, and thermal conductivity [6]. The timber is assumed to have a wet density of 420 kg/m³ and a moisture content of 12% at ambient temperature. During the cooling phase, the material properties (both thermo-physical and mechanical ones) remain dependent on the highest temperature reached at each node, implying that thermal decomposition phenomena (e.g., water evaporation, pyrolysis, and charring) are irreversible and do not degrade further during cooling [9].

The timber element thickness is set at 250 mm to ensure its thermal thickness (semi-infinite solid) based on the defined material properties and thermal conditions. The spatial domain is discretised into finite elements of 1 mm thickness, with a time step set to a minimum of 0.0125 s, subject to numerical stability criteria [21-22].

Regarding the fire-exposed surface, thermal boundary conditions (radiation and convection) are defined according to Eurocode, based on a temperature-time curve. A timber surface emissivity of 0.80 is assumed, with a convective heat transfer coefficient of 35 W/m²K on the fire-exposed surface and 4 W/m²K on the unexposed surface [6, 23]. Fire temperature-time curves are derived using the Eurocode parametric fire curve (EPFC) methodology [23], including both heating and cooling phases. Consistent with previous studies [14, 24], fire conditions are parameterised for a reference compartment with two degrees of freedom: an opening factor varying between 0.02 and 0.20 m^{½} and a fuel load density ranging from 50 to 2000 MJ/m² (see Figure 3). The reference compartment is assumed to be square, with a floor area of 7.5 × 7.5 m², a height of 3 m, and lining thermal inertia of 1160 J/m²s^{½}K (EPFC reference value). The parametric analysis is carried out at sampling steps of 0.05 m^{½} and 50 MJ/m^2 for the opening factor and fuel load density, respectively, and the contour plots presented in the results section are smoothed to improve their readability.

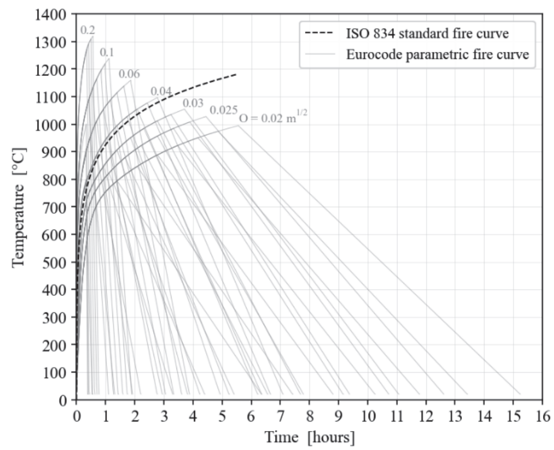

Figure 3. Standard fire curve (ISO 834) compared to the considered series of Eurocode parametric fire curves (EPFC).

Using the described heat transfer model, numerical results are analysed to investigate fire-induced heat transfer within the timber substrate, with a focus on the penetration of various isotherms. These isotherms can be associated with different levels of reduced mechanical properties in timber and are used to quantify the load-bearing capacity of timber elements exposed to fire.

Following a common simplification, the char depth (d_{char}) is determined based on the location of the 300°C isotherm [4-5]. Beyond this temperature, the pyrolysis process is typically assumed to be complete, and the resulting charred wood is considered to have null strength and stiffness [6].

In addition to charring, the zero-strength layer thickness (d_{ZSL}) is determined to account for the reduction in mechanical properties of timber heated below the charring temperature, following two different approaches [14]. The first approach determines the zero-strength layer based on the in-depth temperature distribution, defining the temperature range within this layer as 80-300 °C and 120-300 °C [15]. In contrast, the second approach calculates the zero-strength layer by considering the reduction in timber's mechanical properties (tension and compression) as recommended in Eurocode 5 [6], alongside the computed in-depth thermal profiles. This approach assumes that the timber cross-section is subjected to a uniform stress state (tension or compression, no combined actions).

Finally, the effective load-bearing cross-section of the timber member is determined by considering the combined effect of the char depth and the zero-strength layer, both of which are assumed to have null strength and stiffness. The effective char depth (d_{eff}) is calculated as the sum of the char depth and the zero-strength layer.

3 – RESULTS

3.1 EXEMPLARY CASE

The numerical analysis of fire-induced thermal penetration in timber structures is first presented for a case study. The case study considers the reference compartment described in Section 2, with an opening factor of 0.04 m^{½} and a fuel load density of 714 MJ/m^2. The resulting fire curve, compared to the ISO 834 standard fire curve, is shown in Figure 4. Following the Eurocode parametric fire curve (EPFC) methodology, these conditions define a fire scenario with a heating phase of 1 hour, closely resembling the ISO 834 standard fire curve (Γ factor equal to 1), followed by a cooling phase lasting approximately 2 hours, during which the temperature decrease from the maximum value of 944°C to ambient temperature (20°C) at a constant cooling rate of about 8.3°C/min.

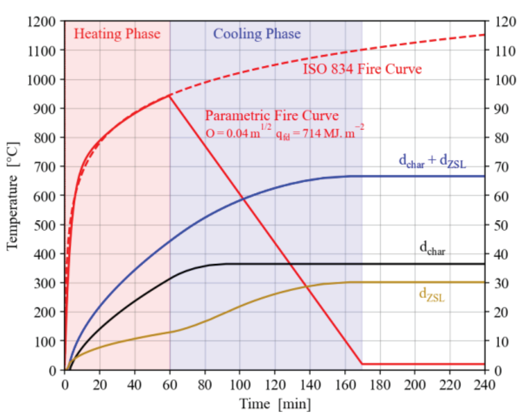

Figure 4. Evolution of the char depth (d_{char}), zero-strength layer thickness (d_{zsl}, according to the 120-300 °C temperature approach), and effective char depth (d_{char}+d_{zsl}) during the considered parametric fire exposure (heating phase and cooling phase).

The results presented in Figure 4 illustrate how the char depth (300 °C isotherm) increases predominantly during the heating phase. However, it continues to penetrate the timber substrate during the cooling phase: in this case, it reaches its maximum value after about 20 minutes in the cooling phase. On the contrary, the zero-strength layer thickness has a secondary impact during the heating phase but becomes more significant during the cooling phase, continuously increasing throughout the whole fire duration (heating and cooling phases). At the end of the fire exposure, the resulting zero-strength layer thickness is comparable to the char depth. In this case study, the zero-strength layer is estimated according to the 120-300 °C temperature approach [14].

As a result, the maximum value of the effective char depth is reached near the end of the cooling phase, which represents the most critical condition for the load-bearing timber structure.

3.2 PARAMETRIC STUDY

Eurocode parametric fire curves (EPFC)

A parametric study is conducted to examine how various input parameters related to the compartment and fuel characteristics affect the estimation of the natural fire conditions using the Eurocode parametric fire curves (EPFC) methodology [23]. For the reference compartment, the opening factor and fuel load density are systematically varied to determine the maximum temperature, cooling rate and duration of the fire phases (heating, cooling, and total). The results, presented in Figure 5, highlight the distinction between ventilation-controlled and fuel-controlled fires, separated by the diagonal dashed line.

Fuel-controlled fires generally reach lower maximum temperatures than ventilation-controlled fires. Their fire phases are relatively short, with a total duration typically below half an hour. However, their cooling rates vary significantly, ranging from below 1 °C/min to over 4.0 °C/min. In contrast, ventilation-controlled fires can attain maximum temperatures exceeding 1300 °C, in case of high opening factor and fuel load density. Their cooling rate is typically below 1.5°C/min and is directly influenced by ventilation conditions (i.e., the opening factor). Ventilation also plays a crucial role in determining the fire phase durations, with the longest fire durations (heating, cooling, and total) occurring at very low opening factors and very high fuel load densities.

After having investigated the thermal boundary conditions defined according to the Eurocode parametric fire curves (EPFC) methodology, the thermal penetration in the timber substrate is examined by analysing the development of the char depth (d_0), the zero-strength

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layer thickness (d_{ZSL}) and the effective char depth (d_{eff}) for varying opening factors and fuel load densities.

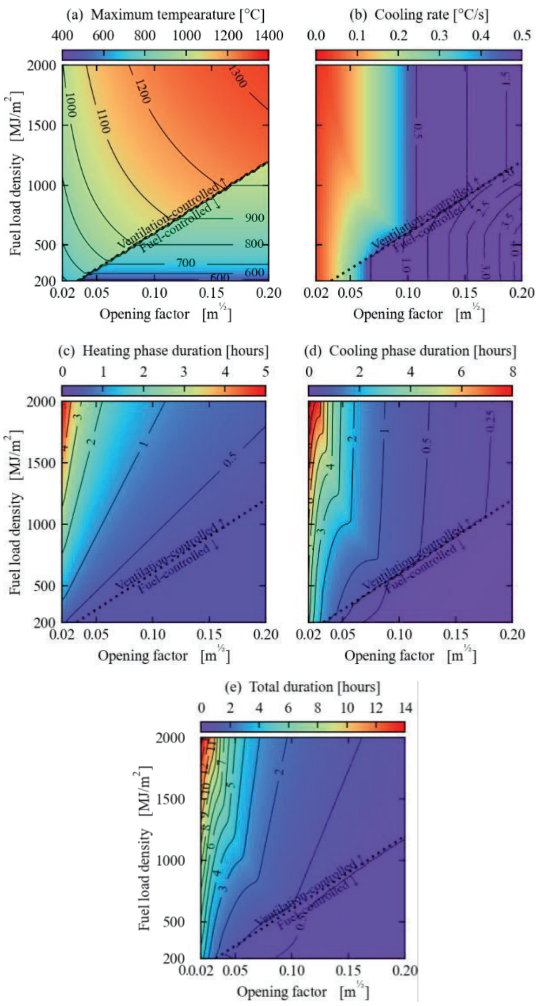

Figure 5. Maximum temperature (a), cooling rate (b), heating phase duration (c), cooling phase duration (d), and total duration (e) according to the Eurocode Parametric Fire Curves (EPFC) methodology as a function of opening factor and fuel load density, for ventilation- and fuel-controlled conditions.

Char depth

The char depth (d_{char}) results for the heating phase, cooling phase, and final fire exposure are presented in Figure 6(a)–(c). As previously noted, the char depth develops predominantly during the heating phase, with values generally ranging between 10 and 70 mm, while only minor increases (mostly below 10 mm) occur during the cooling phase. The highest char depths are typically observed under low ventilation – high fuel load density conditions. However, as shown in Figure 5, this region does not correspond to fires with the highest maximum temperatures but rather to those with the longest heating phase duration. In conclusion, the final char depth is primarily determined by the char formation during the heating phase. However, the cooling phase also contributes, albeit to a lesser extent, and this non-negligible effect should always be considered.

Zero strength-layer

Following the determination of char depth, the zero-strength layer thickness (d_{ZSL}) is calculated using the previously described approaches: the 80–300 °C and 120–300 °C temperature-based approaches (Figure 7(a)–(c) and Figure 8(a)–(c), respectively) and the reduced mechanical properties approach for compression and tension (Figure 9(a)–(c) and Figure 10(a)–(c), respectively).

Similar to the trends observed for char depth, the development of the zero-strength layer during different fire phases is directly linked to the duration of the heating and cooling phases (refer to Figure 5). However, unlike charring, the cooling phase plays a more significant - or at least comparable - role in the formation of the zero-strength layer, depending on the approach followed. The results indicate that the zero-strength layer at the end of the heating phase represents approximately 50% of the thickness of the total zero-strength layer when the penetration of the heat wave during the cooling phase is also considered. Indeed, Figure 11 highlights how, since the heat wave continues to penetrate the timber substrate during the whole fire exposure, the zero-strength layer continuously increases as well, usually for a considerable duration after the end of the heating phase and into the cooling phase and, possibly, also after the cooling phase. In terms of specific values, the zero-strength layer thickness can exceed 50 mm during the heating phase and 60 mm during the cooling phase, resulting in total values exceeding 110 mm.

Comparing the various approaches, the highest values are obtained using the reduced mechanical properties approach for compression, whereas the 120–300 °C temperature-based approach produces the least critical conditions. This result is directly related to the fact that, according to Eurocode 5 [6], compression induces a greater reduction in material strength than tension at the same temperature. Among the temperature-based approaches, the 80–300 °C range results in larger values than the 120–300 °C range, as the inner zero-strength layer boundary temperature of 80 °C results in longer and hence deeper heat wave penetration, compared to 120 °C. Additionally, the 120–300 °C temperature approach and the reduced mechanical properties approach for tension yield comparable results, as do the 80–300 °C temperature approach and the reduced mechanical properties approach for compression.

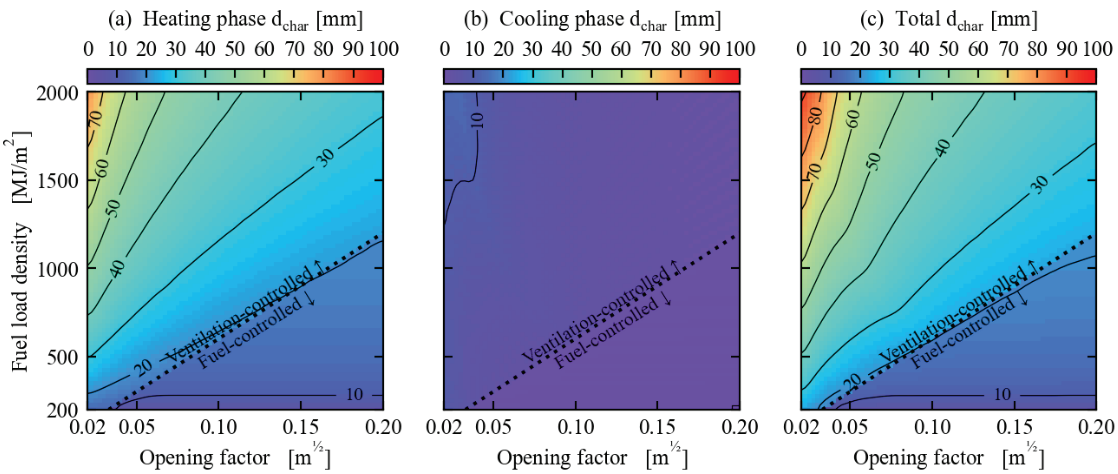

Figure 6. Char depth d_{char} (300 °C isotherm) as a function of opening factor and fuel load density during the heating phase (a), the cooling phase (b), and at the end of the fire exposure (c).

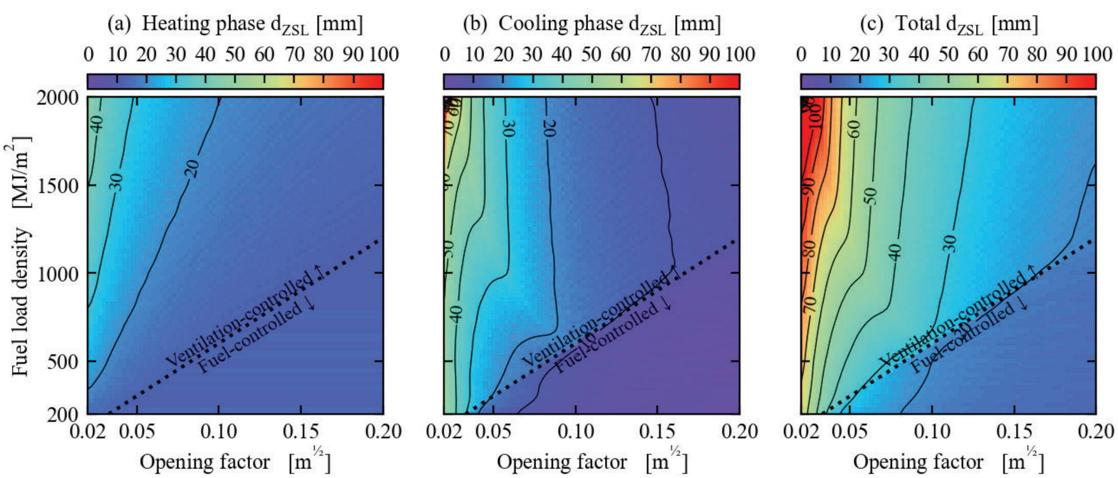

Figure 7. Zero-strength layer thickness d_{ZSL} (80-300 °C temperature approach) as a function of opening factor and fuel load density during the heating phase (a), the cooling phase (b), and at the end of the fire exposure (c).

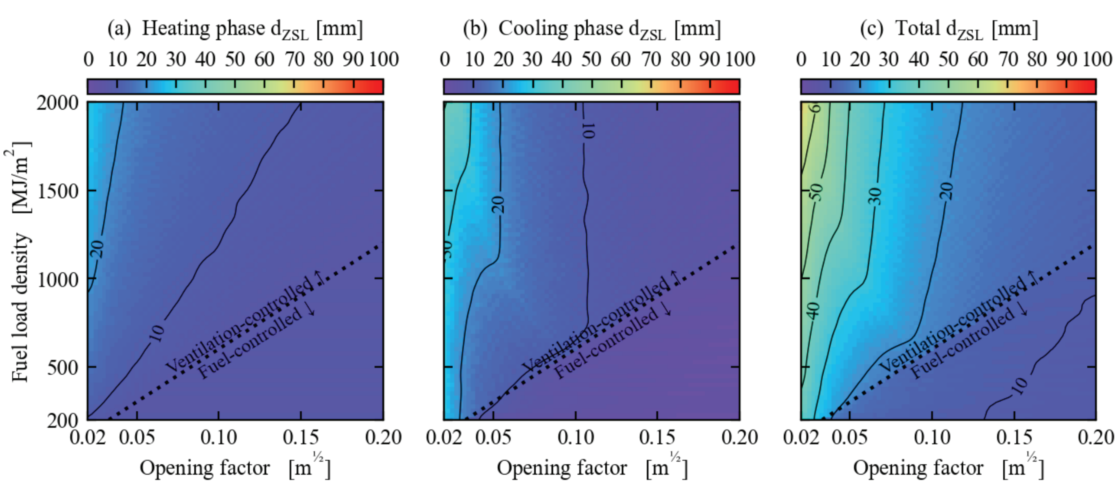

Figure 8. Zero-strength layer thickness d_{ZSL} (120-300 °C temperature approach) as a function of opening factor and fuel load density during the heating phase (a), the cooling phase (b), and at the end of the fire exposure (c).

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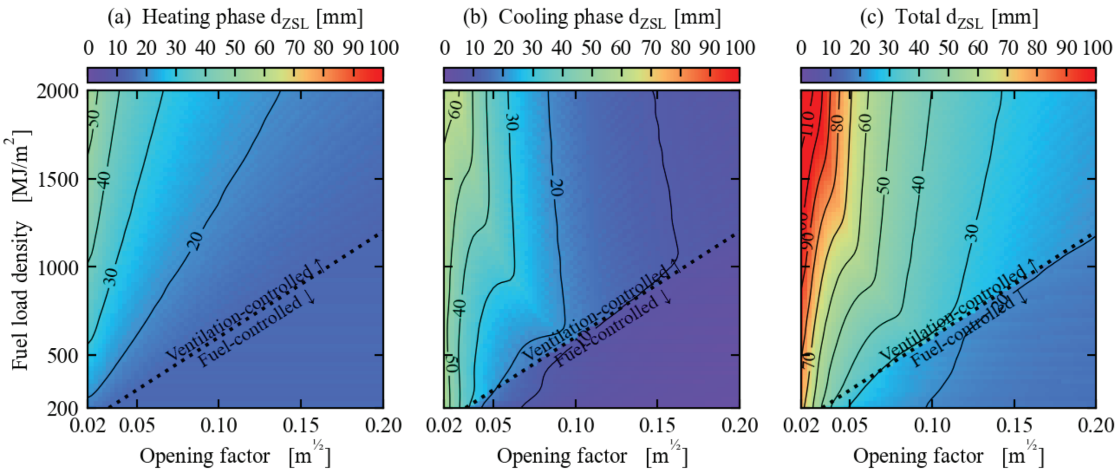

Figure 9. Zero-strength layer thickness d_{ZSL} (reduced mechanical properties approach for compression) as a function of opening factor and fuel load density during the heating phase (a), the cooling phase (b), and at the end of the fire exposure (c).

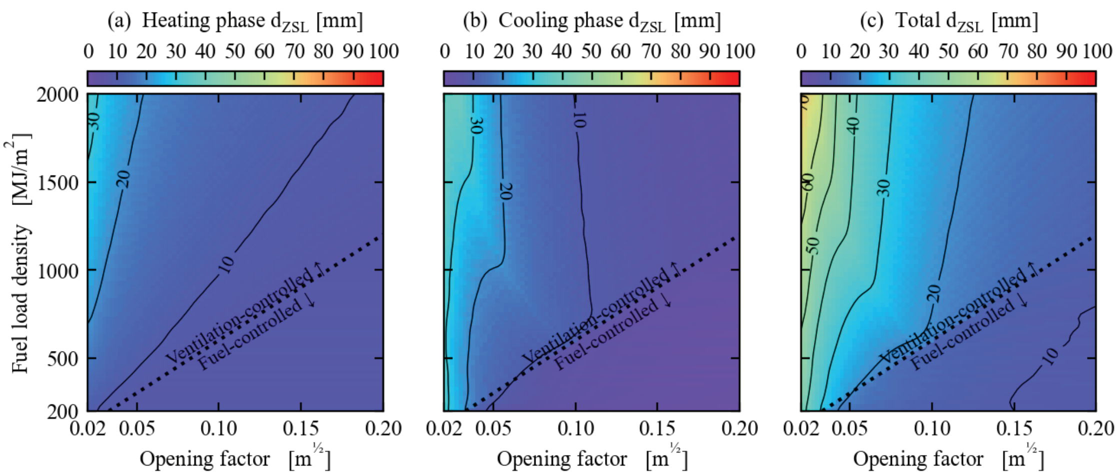

Figure 10. Zero-strength layer thickness d_{ZSL} (reduced mechanical properties approach for tension) as a function of opening factor and fuel load density during the heating phase (a), the cooling phase (b), and at the end of the fire exposure (c).

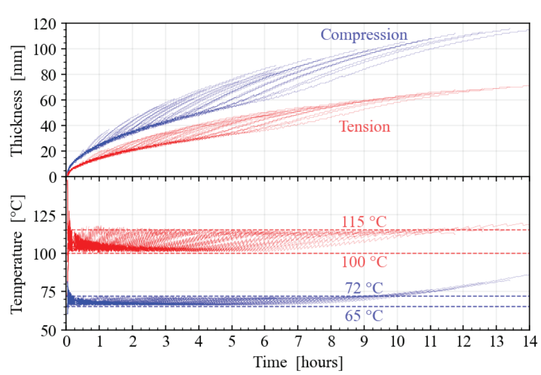

Figure 11. Evolution of the zero-strength layer thickness (above) and the corresponding equivalent temperature ranges (below) according to the reduced mechanical properties approach for compression (blue) and tension (red) under different fire exposures.

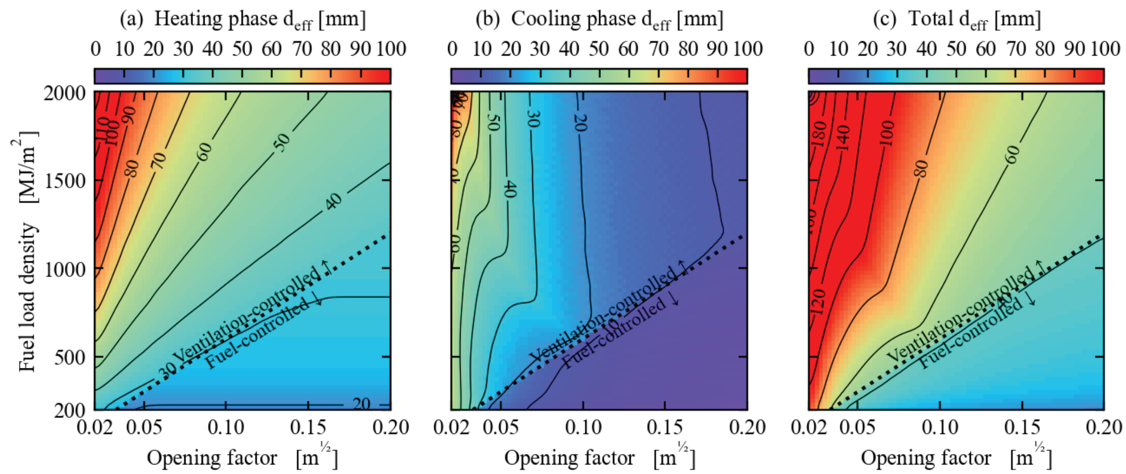

Figure 12. Effective char depth d_{eff} [mm] (zero-strength layer according to temperature approach 80-300 °C) as a function of opening factor and fuel load density during the heating phase (a), the cooling phase (b), and at the end of the fire exposure (c).

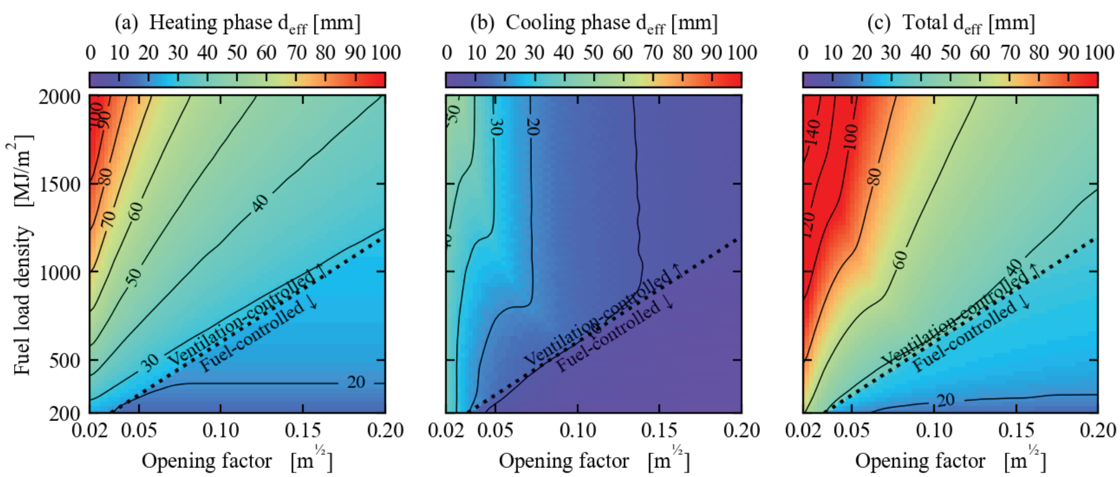

Figure 13. Effective char depth d_{eff} [mm] (zero-strength layer according to temperature approach 120-300 °C) as a function of opening factor and fuel load density during the heating phase (a), the cooling phase (b), and at the end of the fire exposure (c).

To further verify this relationship, Figure 11 illustrates the equivalent temperature ranges corresponding to the zero-strength layer thicknesses estimated according to the reduced mechanical properties approaches for compression and tension. Notably, the resulting temperature ranges are highly specific and to a large extent only marginally influenced by the duration and the severity of the fire exposure: 65-72 °C for compression, and 100-115 °C for tension. This finding confirms that, due to the characteristic reduction factors recommended by Eurocode 5 [6], the temperature-based and reduced mechanical properties approaches yield comparable results and, given the defined thermo-physical timber properties, the reduced mechanical properties can be directly associated with a thermal gradient in uncharred timber.

Finally, when compared to the current Eurocode simplified method, which assumes a constant zero-strength layer thickness of 7 mm [6], it is evident that the calculated values are, in most severe cases. More than an order of magnitude higher, exceeding 100 mm. Consequently, the Eurocode simplified method significantly underestimates the zero-strength layer thickness and is therefore unsuitable for assessing natural fire exposures, particularly when both the heating and cooling phases are considered.

Effective chat depth

To finally assess the actual load-bearing capacity of timber members, the effective load-bearing cross-section is determined by considering the combined effects of charred wood and degraded wood heated below the

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charring temperature. Accordingly, the effective char depth (d_{eff}), which is assumed to have no strength or stiffness, is calculated as the sum of the char depth and the zero-strength layer. The results, presented in Figure 12 and Figure 13, are reported only for the temperature-based approaches (120-300 °C and 80-300 °C) due to the similarity between the zero-strength layer estimations obtained from the temperature-based and reduced mechanical properties approaches.

The numerical results indicate that the effective char depth can exceed 180 mm by the end of fire exposure, in the most severe cases. Consistent with the results for the zero-strength layer, the 80-300 °C temperature approach yields higher values of effective char depth than the 120-300 °C approach, with an increase of approximately 20%.

The most critical conditions are observed in ventilation-controlled fires, particularly in low-ventilation, high-fuel load density scenarios. Again, these conditions do not correspond to the highest fire temperatures but rather to fires with the longest duration, including both the heating and cooling phases. Conversely, in fuel-controlled fires, the effective char depth is typically below 40 mm.

When considering the heating and cooling phases separately, the heating phase contributes the most significantly, accounting for approximately 2/3 of the total effective char depth. However, the cooling phase also plays a notable role, contributing to about 1/3 of the total thermal degradation of timber elements.

4 – CONCLUSIONS

This research study investigates fire-induced charring and heat penetration in timber elements exposed to natural fire conditions, represented by the Eurocode parametric fire curves (EPFC). A simplified one-dimensional heat transfer model, employing effective temperature-dependent material properties, is developed to simulate the thermal response of solid timber sections under such conditions.

The results demonstrate that char depth, defined by the 300°C isotherm, increases predominantly during the heating phase. However, it continues to penetrate the timber substrate during the cooling phase, resulting in a minor yet non-negligible additional increase in char depth after the peak temperature is reached.

The zero-strength layer thickness was estimated using both temperature-based approaches (80-300 °C and 120-300 °C) and the reduced mechanical properties approaches for tension and compression. While the zero-strength layer has a secondary impact during the heating phase, it becomes more significant during the cooling phase, continuing to increase throughout the entire fire exposure. At the end of the heating phase, the zero-strength layer is typically about half the thickness of its final value and, by the end of the fire exposure, its thickness is generally comparable to the char depth. It was also found that, for the adopted timber material properties, the zero-strength layer estimated using the reduced mechanical properties approaches corresponds to specific temperature ranges, namely 65-72 °C for compression and 100-115 °C for tension.

The maximum value of the effective char depth (the sum of the char depth and the zero-strength layer) is typically reached near or after the end of the cooling phase, representing the most critical condition for the load-bearing capacity of timber structures. In general, the heating phase contributes approximately 2/3 of the total effective char depth, while the cooling phase accounts for about 1/3, confirming the significant influence of the latter. The most critical conditions for timber elements exposed to natural fires are associated with low ventilation and high fuel load densities, which correspond to fires with the longest durations (both heating and cooling phases), rather than the highest maximum temperatures.

In conclusion, this study highlights the importance of explicitly including the cooling phase in modern performance-based approaches for the fire-safe design of timber structures. It was shown that, during the cooling phase, the load-bearing capacity of timber elements can continue to degrade significantly due to ongoing heat penetration. Disregarding this phenomenon can lead to a substantial underestimation of damage, resulting in unsafe design assumptions.

5 – ACKNOWLEDGEMENTS

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6 – REFERENCES

[1] Ramage M, Foster R, Smith S, Flanagan K, Bakker R. Super Tall Timber: design research for the next generation of natural structure. *The Journal of Architecture*, 22, 104–122, 2017.

[2] Law A., Hadden R. We need to talk about timber: fire safety design in tall buildings. *The Structural Engineer*, 3, 2020.

[3] Bartlett A., Hadden RM., Bisby L.A. "A Review of Factors Affecting the Burning Behaviour of Wood". *Fire Technology*, 55, 1–49, 2019.

[4] Buchanan A.H., Abu A.K. Structural design for fire safety. *John Wiley & Sons*, 2nd Edition, 2017.

[5] LaMalva K., Hopkin D. *International handbook of structural fire engineering*. Springer, 2021.

[6] European Committee for Standardization (CEN). EN 1995-1-2 Eurocode 5: Design of timber structures – Part 1.2: General – Structural fire design. Brussels, Belgium, 2004.

[7] Lucherini A., Torero J.L. Defining the fire decay and the cooling phase of post-flashover compartment fires. *Fire Safety Journal*, 141, 103965, 2023.

[8] Gernay T., Franssen J.M. A performance indicator for structures under natural fire. *Engineering Structures*, 100, 94-103, 2015.

[9] Gernay T. Fire resistance and burnout resistance of timber columns. *Fire Safety Journal*, 122, 103350, 2021.

[10] Gernay T., Zehfuß J., Brunkhorst S., Robert F., Bamonte P., McNamee R., Mohaine S., Franssen J.-M. Experimental investigation of structural failure during the cooling phase of a fire: Timber columns. *Fire and Materials*, 1-16, 2022.

[11] Wiesner F., Hadden R., Deemy S., Bisby L. Structural fire engineering considerations for cross-laminated timber walls. *Construction and Building Materials*, 323, 126605, 2022.

[12] Schmid J., Just A., Klippel M., Fragiacomo, M. The reduced cross-section method for evaluation of the fire resistance of timber members: discussion and determination of the zero-strength layer. *Fire Technology*, 51, 1285-1309, 2015.

[13] European Committee for Standardization (CEN). prEN 1995-1-2:2025 Eurocode 5: Design of timber structures – Part 1-2: General - Structural fire design. Brussels, Belgium, 2025.

[14] Lucherini A., Šejnová Pitelková D., Mozer V. Estimating the effective char depth in structural timber elements exposed to natural fires, considering the heating and cooling phase. *Engineering Structures*, 323(A), 119255, 2025.

[15] Huc S., Pečenko R., Hozjan T. Predicting the thickness of zero-strength layer in timber beam exposed to parametric fires. *Engineering Structures*, 229, 111608, 2021.

[16] Huč S., Hozjan T., Pečenko R. Effective cross-section of a timber beam exposed to natural fires. *European Journal of Wood and Wood Products*, 83(2), 1-16, 2025.

[17] Lange D., Boström L., Schmid J., Albrektsson J. The Reduced Cross Section Method Applied to Glulam Timber Exposed to Non-standard Fire Curves. *Fire Technology*¸ 51, 1311–1340, 2015.

[18] Wiesner F., Bartlett A., Mohaine S., Robert F., McNamee R., Mindeguia J.C., Bisby L. Structural capacity of one-way spanning large-scale Cross-Laminated Timber slabs in standard and natural fires. *Fire Technology*, 57, 291-311, 2021.

[19] Wiesner F., Bisby L.A., Bartlett A.I., Hidalgo J.P., Santamaria S., Deeny S., Hadden R.M. Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces. *Engineering Structures*, 179, 284-295, 2019.

[20] Wiesner F., Randmael F., Wan W., Bisby L., Hadden R.M. Structural response of cross-laminated timber compression elements exposed to fire. *Fire Safety Journal*, 91, 56–67, 2017.

[21] Emmons H.W. "The numerical solution of heat conduction problems". *Transactions of the American Society of Mechanical Engineers*, 65(6), 607-615, 1943.

[22] Dusinberre G.M. "Heat Transfer Calculations by Finite Differences". *International Textbook Company*, Pennsylvania, USA, 1961.

[23] European Committee for Standardization (CEN). EN 1991-1-2 Eurocode 1: Actions on structures – Part 1.2: General actions – Actions on structures exposed to fire. Brussels, Belgium, 2002.

[24] Thienpont T., Van Coile R., Caspeele R., De Corte W. Burnout resistance of concrete slabs: Probabilistic assessment and global resistance factor calibration. Fire Safety Journal, 119, 103242, 2021.

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