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PREDICTING THE EFFECTIVE CHAR DEPTH IN TIMBER ELEMENTS EXPOSED TO NATURAL FIRES, INCLUDING THE COOLING PHASE

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ABSTRACT: This paper presents a numerical study on the effect of the heating and cooling phases on the reduction of the effective cross-section of timber elements, in particular on the evolution of the char depth (300°C isotherm) and zero-strength layer. An advanced calculation method based a finite-difference heat transfer model is compared to the simplified approach suggested by Eurocode 5. For the heating phase, defined as the standard fire curve (ISO 834), the simplified Eurocode 5 method generally provides more conservative char depths, while the zero-strength layer is under-predicted. Nevertheless, the values of effective char depth are comparable. Including the cooling phase evidences that, during this phase, the heat wave penetration leads to a significant increase in the char depth and zero-strength layer. Particularly, this increase directly depends on the fire cooling rate: a slower cooling phase further reduces the effective cross-section of timber members. As a result, this research highlights how the heat wave penetration during the fire cooling phase can significantly reduce the load-bearing capacity of timber elements.

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

1 INTRODUCTION

Urban densification, sustainability drivers and technological advances are fostering the development of high-rise structures using bio-based materials like engineered wood products. Tall mass timber buildings now represent the fastest growing sector in the construction industry [1]. However, challenges related to their fire safety represent a main barrier for the robustness and the success of these structures. The primary difference from traditional construction materials, like steel, concrete, and masonry, is that timber buildings are mainly composed of wood, which is combustible and can contribute to building fires [2]. From a structural engineering perspective, the wood pyrolysis and combustion reduce the effective cross-section and therefore load-bearing capacity of structural elements. Consequently, they can compromise the structural integrity and stability of individual timber components, as well as the whole structural system [3].
The structural performance of timber elements is typically associated with the concept of charring. Charring, considered as the formation of a residual high-carbon char upon pyrolysis, is generally assumed to undergo for temperatures above 300 ºC. Charred wood is typically characterised by low mechanical properties (strength and stiffness), which are normally assumed null [3]. Accordingly, in structural applications, the penetration speed of the char layer, known as charring rate, plays a key role in the evaluation of the load-bearing capacity of timber elements exposed to fire.
The fire performance of structures, as well as the charring rate, is normally defined in a prescriptive manner relying on the standard fire curve, an unrealistic ever-increasing thermal exposure with time, conceived as the worst-case design scenario [4]. Crucially, although a compartment fire within a building enclosure is typically composed of a growth phase, a fully-developed phase, a decay phase and a cooling phase, the standardised fire tests completely ignore what happens after the fully-developed fire phase, deemed less onerous due to its lower temperatures [5,6].
However, during the fire decay and cooling phases, heat continues to penetrate within structural materials through conduction. Consequently, the structural capacity of load-bearing elements gradually continues to reduce [7]. This phenomenon can be more or less significant for various construction materials and systems. This problem is more critical for timber structures because wood loses its mechanical properties in an irreversible manner at relatively low temperatures, compared to traditional construction materials like steel and concrete. For instance, at 100 ºC typical softwood has a compressive strength reduction of about 75%, compared to the value at ambient temperature [4]. Consequently, after the end of the fully-developed fire phase, the load-bearing capacity of timber element can reduce up to an additional 30%

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(compared to the ambient one), and structural failure could occur after fuel burnout, even after a fire seems extinguished [8-12]. The main challenge is related to the fact that, after fire extinction, this hazard cannot be easily detected, and structural collapse may occur with little or no warning. This situation represents a critical scenario for fire brigade interventions.

As a result, this framework leads to an inadequate assessment of timber structures exposed to fire. The precise interaction between fire and structural materials needs to be understood and carefully considered because the temperature propagation through the load-bearing timber can unexpectedly lead to structural collapse [10]. Current regulations simplify the problem by adding a zero-strength layer (ZSL), which is introduced to take into account the reduced mechanical properties of the heated uncharred wood [4,13]. However, the methodology is highly simplified (constant value for ZSL) and typically only carried out for the heating phase of a post-flashover compartment fires. The available literature on the matter is quite limited, but this hazardous issue has been underlined by many researchers [8-12]. Fundamental technical issues still need to be resolved to fundamentally comprehend the heat wave penetration in timber elements during all the fire phases to truly enable the performance-based design of fire-safe tall timber buildings.

This research study investigates the effect of the heating and cooling phases on the reduction of the effective cross-section of timber elements. The study focuses on the evolution of the char layer and zero-strength layer, thus the effective char depth. Simplified (Eurocode 5) and advanced calculation methods (conductive heat transfer model) are employed to estimate their thicknesses and penetration speeds during both the heating and cooling phases. For the cooling phase, the effect of various cooling rates is also investigated.

2 METHODOLOGY

A pure conduction heat transfer model is formulated to investigate the heat penetration within structural timber elements exposed to fire conditions. The finite differences model is based on the numerical method developed by Emmons and Dusinberre, and it explicitly solves a one-dimensional heat conduction problem by resolving energy-balance equations in the main direction of the heat flow [14-16]. The model is discretised into a number of finite elements, associated to nodes.

The heat transfer model is defined in accordance with the Eurocode advanced calculation methods (ACM) [4]. Solid softwood is modelled using the Eurocode 5 effective temperature-dependent material properties, namely mass density ratios, specific heat capacity and thermal conductivity [4]. Common timber density and moisture content are assumed: mass (wet) density equal to 420 kg/m^3 and a moisture content of 12%. The thickness of the timber element is set 200 mm to ensure its thermal thickness (semi-infinite solid), taking into consideration the defined material properties and thermal conditions.

The thermal boundary conditions at the fire-exposed timber surface are also defined according to Eurocode, starting from a defined temperature-time curve: a convective heat transfer coefficient equal to 25 W/m^2K and a timber surface emissivity equal to 0.8 [4,17].

The solid space is discretised in finite elements with a thickness of 1 mm, and the time step is set to 0.025 s, following model stability criteria [14-16].

3 RESULTS FOR STANDARD FIRE (ONLY HEATING PHASE)

The heat transfer in structural timber elements is first investigated considering the fire exposure as the standard fire temperature-time curve for a duration of 2 hours.

3.1 THERMAL CHARACTERISATION AND CHAR DEPTH

The modelling results are first analysed in terms of temperature. Figure 1 shows the temporal evolution of the temperatures at various depths within the timber substrate, while Figure 2 reports the various in-depth temperature profiles at various instants.

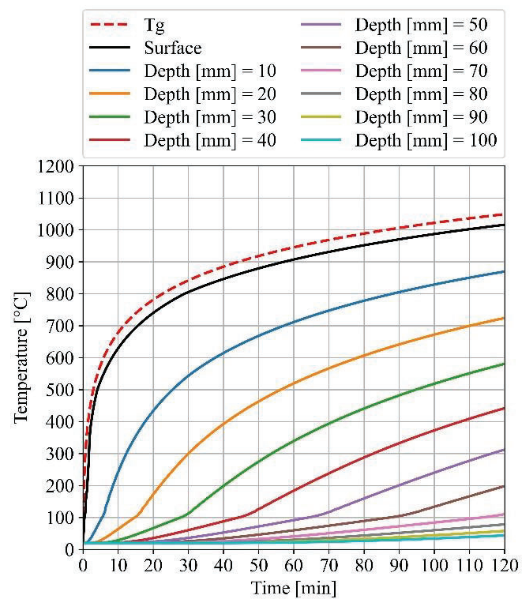

***Figure 1**: Temperature evolution at various depths within the timber substrate.*

The plots highlight how the timber surface closely follows the gas fire temperature and typical thermal gradients within timber elements exposed to fire are shown. These thermal evolutions are directly related to the defined thermo-physical properties of timber at ambient and elevated temperatures (in particular, thermal inertia and thermal diffusivity). It is also important to emphasise that, within the 2 hours of standard fire exposure, the heat wave only slightly penetrates beyond 100 mm in the timber substrate.

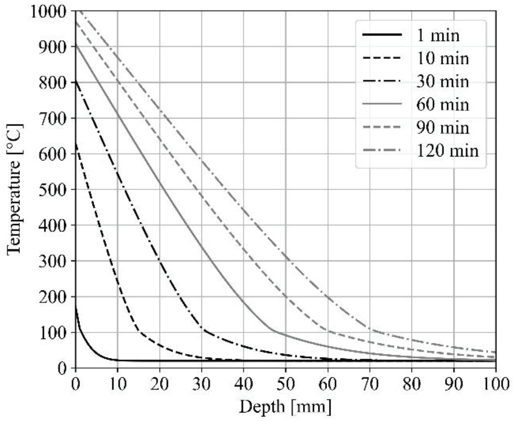

***Figure 2**: Evolution of thermal profiles within the timber substrate at different instants.*

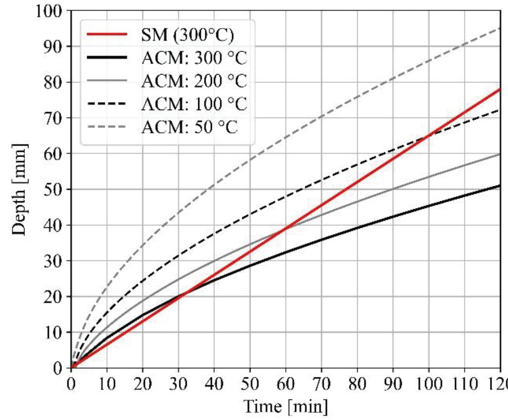

***Figure 3**: Evolution of the isotherms depths (300 ºC, 200 ºC, 100 ºC and 50 ºC) and comparison with EN 1995-1-2 simplified method (SM).*

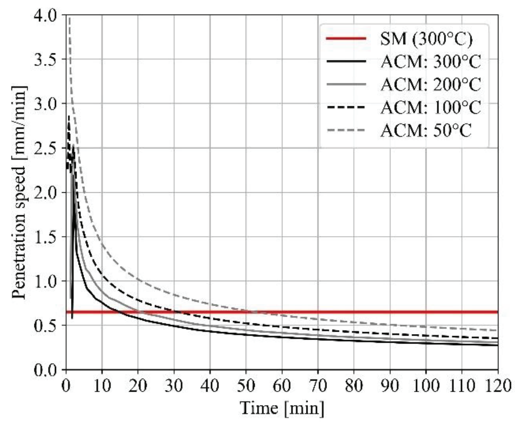

***Figure 4**: Evolution of the isotherms penetration speeds (300 ºC, 200 ºC, 100 ºC and 50 ºC) and comparison with EN 1995-1-2 simplified method (SM).*

The temperature fields shown in Figure 1 and Figure 2 are further analysed to study the thermal penetration of various isotherms within the timber substrate. Figure 3 and Figure 4 report the depths and penetration speeds of the 300 ºC, 200 ºC, 100 ºC and 50 ºC isotherms during the fire exposure. These isotherm curves correspond to various levels of reduced timber mechanical properties, and they are fundamental to quantify the structural capacity of load-bearing timber elements. In particular, the 300 ºC isotherm usually represents the location of the char front and, from its evolution, it is possible to estimate the charring rate within the load-bearing timber cross-section. Beyond this temperature, timber pyrolysis process is typically assumed completed and the resulting charred wood has null strength and stiffness [3].

Figure 3 shows how, for the defined case, the various isotherm curves penetrate the timber substrate, while Figure 4 displays their penetration speeds. It is evident how isotherms of lower temperatures typically have a higher speed compared to isotherms of higher temperatures. At identical instants, 50°C has always the highest penetration speed, while 300°C the lowest. Nevertheless, Figure 4 underlines how the penetration speeds gradually decrease during the fire exposure, all tending to values included between 0.2 and 0.5 mm/min. Accordingly, the distance between the various isotherms increases during the fire exposure, hence the thermal gradient becomes less steep (see Figure 2).

Special attention is paid to the 300°C isotherm depths (i.e. char depth) and penetration speed (i.e. charring rate). In particular, this curve evaluated using the described heat transfer model (advanced calculation method – ACM) is compared to the simplified method (SM) which assumes a constant charring rate [4]. For the case of softwood, this value is set equal to 0.65 mm/min (β_0). Figure 3 and Figure 4 show how this value over-estimates the timber charring rate for standard fire exposures above 15 minutes, while the timber char depth is under-estimated only below 15 minutes.

3.2 ZERO STRENGHT LAYER

Once estimated the char depth, the effect of the heat penetration within the timber cross-section must be considered to assess the load-bearing capacity of timber structural members exposed to fire. Indeed, timber undergoes significant decomposition processes also for temperatures below charring (300°C) and, consequently, important reductions in the mechanical properties.

The Eurocode reduced-cross section method traditionally introduces a "zero-strength layer" (ZSL) to take into account the reduced mechanical properties in the timber heated below charring temperature [4]. This layer is assumed to have null strength and stiffness as charred wood, and it is summed to the char depth to estimate the residual effective cross-section. Eurocode 5 typically prescribes a zero-strength layer of constant thickness: in the current version, this is equal to 7 mm, for fire exposures beyond 20 minutes [4]. In contrast, the new version suggests various constant thicknesses depending on the member types and stress state.

Since the zero-strength layer is linked to the structural capacity of timber members, it is rarely associated with a temperature interval, given the fact that it should theoretically depend on both the mechanical state of the

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cross-section (i.e. stresses) and the thermal gradient within the heated timber. However, using the presented numerical heat transfer model and assuming various constant thicknesses suggested by the Eurocode, it is possible to study the thermal gradient within the zero-strength layer. One edge of the thermal gradient is defined by the charring temperature (300°C), while the other depends on the defined thickness.

Figure 5 shows the evolution of the thermal gradient within zero-strength layers of various thicknesses: 7 mm, 9 mm, 14 mm, and 16 mm. Thicker zero-strength layers have larger thermal gradients and the thermal gradient gradually decreases for longer fire exposures: this is in line with the decreasing thermal gradients observed in Figure 2 and Figure 3. In general, the zero-strength layer extends up to temperatures as low as 70-80°C. This result is in line with what found by Huc *et al.*, who estimated 80-120°C as the edges of the zero-strength layer for timber beams exposed to parametric fire curves [18].

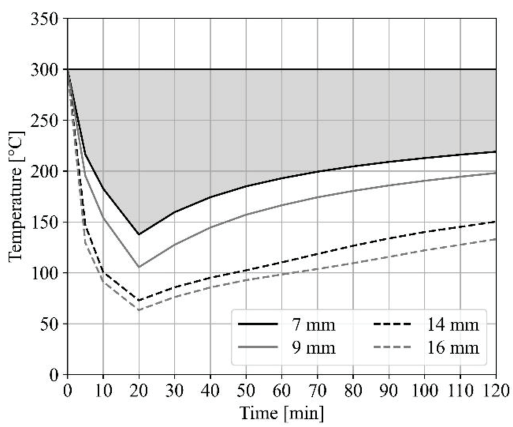

Figure 5*: Evolution of the thermal gradients within the zero-strength layer for different thicknesses (7mm, 9mm, 14mm, and 16 mm).*

Following these considerations, the zero-strength layer is also estimated for the presented case study using two different approaches. The first approach assesses the zero-strength layer based on the in-depth temperatures. Following the previous analysis, the temperature gradient within the zero-strength layer is set to 80-300°C, 100-300°C, and 120-300°C. The second approach calculates the zero-strength layer considering the reduced mechanical properties of the timber section, as shown in Figure 6. Using the reduction factors prescribed by Eurocode 5 (tension and compression) [4], the in-depth thermal gradient shown in Figure 2 can be associated to a distribution of reduced mechanical properties within the timber section (see Figure 7). Assuming the timber cross-section under a homogenous stress state (tension or compression), once estimated the char depth (d_{char}), the zero-strength layer (d_{ZSL}) can be simply calculated based on an effective area equivalence, as shown in Figure 6.

Figure 8 reports the results related to the estimation of the zero-strength layer according to the two methodologies and compared to the current Eurocode 5 simplified method (7 mm). Since temperature continues to penetrate the timber substrate, the zero-strength layer continuously increases during the whole fire exposure. The highest values are calculated for the reduced mechanical properties approach for compression, which induces the highest reductions in the material strength, while the 120-300°C temperature approach represents the least critical conditions. In general, the estimated values are far beyond the 7 mm prescribed by Eurocode 5, ranging between 17 and 34 mm after 2 hour of standard fire exposure. This result again agrees with the research study carried out by Huc *et al.*, who found out thicknesses of zero-strength layer up to 30.5 mm [18].

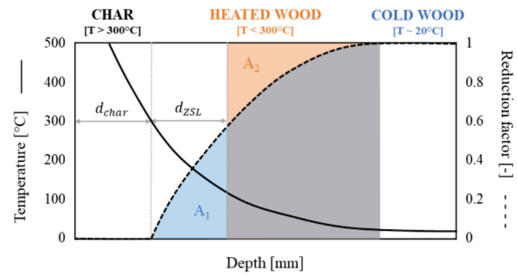

Figure 6*: Schematisation of the methodology to calculate the zero-strength layer based on the reduced mechanical properties, given an in-depth thermal gradient.*

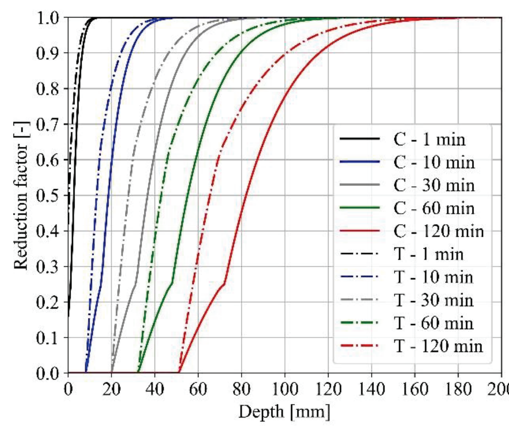

Figure 7*: Evolution of the reduction factor of timber mechanical properties for compression (C) and tension (T) at different instants.*

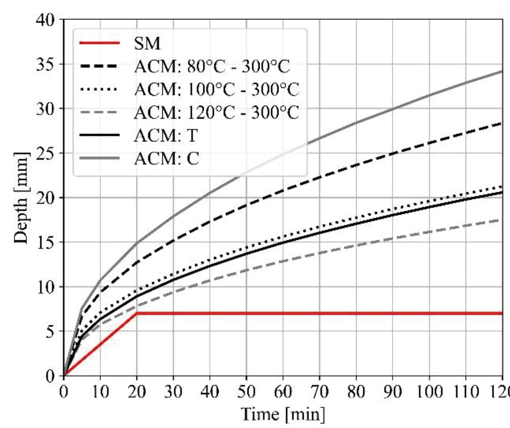

Figure 8*: Evolution of the zero-strength layer according to temperature and reduced mechanical properties approaches, compared to EN 1995-1-2 simplified method (SM).*

3.3 EFFECTIVE CHAR DEPTH

To finally assess the structural capacity of timber members, the effective load-bearing cross-section is obtained considering both the contribution of the charred wood and the wood heated below charring temperature. Indeed, the effective char depth that is assumed to have null strength and stiffness can be calculated as the sum of the char depth and the zero-strength layer. This process can be carried out according to the above-mentioned methodologies. If the results for the char depth (Figure 3) and the zero-strength layer (Figure 8) are merged together, the effective char depth can be evaluated.

Figure 9 shows the effective char depths obtained following the temperature and reduced mechanical properties approaches, compared to the current Eurocode 5 simplified method. The previous sections have highlighted how the Eurocode 5 simplified method generally over-estimates the timber charring rate (beyond 15 min) and under-estimates the zero-strength layer, compared to the results obtained with the presented advanced calculation method based on heat transfer modelling. However, the values of effective char depths appear comparable, as shown in Figure 9. Nevertheless, for the presented case, these results evidence how the Eurocode 5 simplified method is usually less conservative, at least for standard fire durations below 60 minutes.

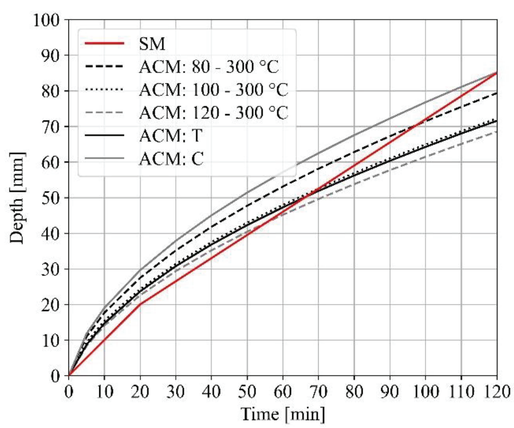

***Figure 9**: Evolution of the effective char depth according to temperature and reduced mechanical properties approaches, compared to EN 1995-1-2 simplified method (SM).*

4 RESULTS FOR NATURAL FIRE (HEATING AND COOLING PHASES)

The previous section has presented the modelling results considering the fire exposure as the standard fire temperature-time curve (ISO 834), hence only analysing the fire heating phase. In this section, a cooling phase is introduced, and the fire exposure is modelled according to the Eurocode parametric fire curves (EPFC) methodology [17]. The case of a squared compartment of 7.5 m × 7.5 m in plan, 3 m in height, with an opening factor of 0.04 $m^{0.5}$, a fuel load density of 720 MJ/m^2 and compartment linings with a thermal inertia of 1160 $J/m^2s^{0.5}K$ is considered. The resulting fire curve is shown in Figure 10. This scenario is chosen to provide a heating phase of 1 hour similar to the standard fire curve (Γ factor equal to 1), followed by a cooling phase from maximum temperature (944°C) to ambient temperature (20°C) of about 2 hours, causing a cooling rate of about 8.3°C/min (linear cooling according to the Eurocode parametric fire curves methodology).

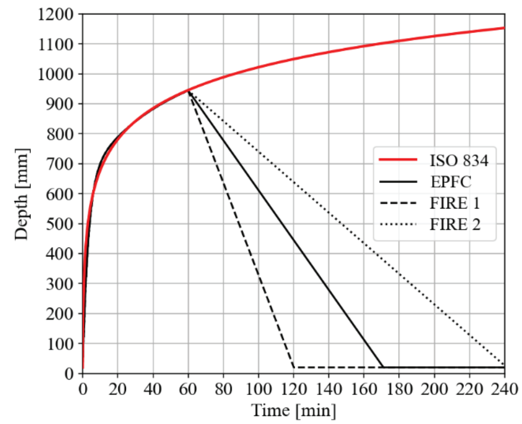

***Figure 10**: Standard fire curve (ISO 834) compared to Eurocode parametric fire curve (EPFC) and other fire curves with different cooling rates (FIRE 1 and FIRE 2, see Section 5).*

The thermal conditions within the timber element are identically calculated using the same heat transfer model in Section 3. Nevertheless, for the cooling phase, various assumptions and simplifications are necessary. The temperature evolution in each investigated node is strongly dependent on material properties, which are temperature-dependent. Once again, the thermo-physical properties of timber at elevated temperature are set according to Eurocode 5 [4]. However, these relationships are relevant and have been validated only for the heating phase, hence it is not known if these material properties can be assumed identical for the cooling phase. This is because certain underlying phenomena are not reversible, for instance water evaporation and thermal decomposition processes. To address this limitation, the timber material properties for the cooling phase are fixed and remain the same depending on the highest temperature reached in each node. This simplification avoids reverse thermal decomposition processes and moisture re-condensation.

4.1 THERMAL CHARACTERISATION AND CHAR DEPTH

The temperature evaluation in the studied material under the exposure of the described Eurocode parametric fire curve (EPFC) is presented in Figure 11. Based on the defined conditions, the heating phase (60 min) is identical to the previous analysis. In contrast, in the cooling phase, the effect of surface cooling on the in-depth temperature and the penetration of the heat wave within the timber element can be observed. The temperature decrease is evident mainly at depths closer to the exposed surface, while this effect decreases with increasing depth. In particular, from 70 mm the temperature evolution almost plateaus within the investigated time period.

The thermal profiles presented in Figure 12 confirm the penetration of the heat wave within the timber cross-section. More specifically, it can be noted the progress of

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the char depth (300°C) for 30 minutes into the cooling phase (note 60 min and 90 min thermal gradients). Similarly, the amount of heated wood slowly increases, causing a further reduction of the in-depth timber mechanical properties and therefore an increase of the zero-strength layer.

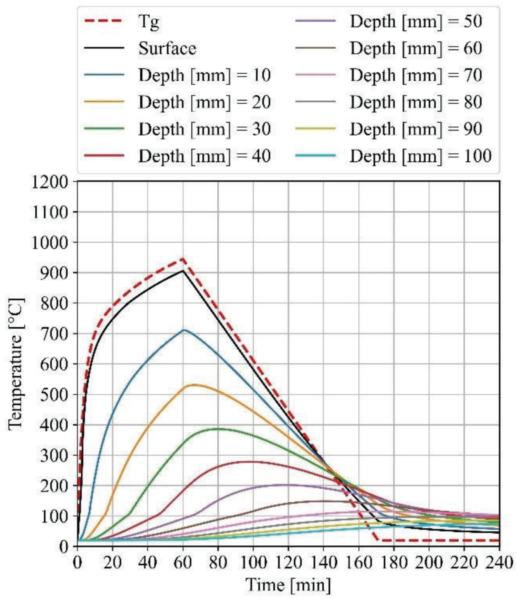

***Figure 11**: Temperature evolution at various depths within the timber substrate.*

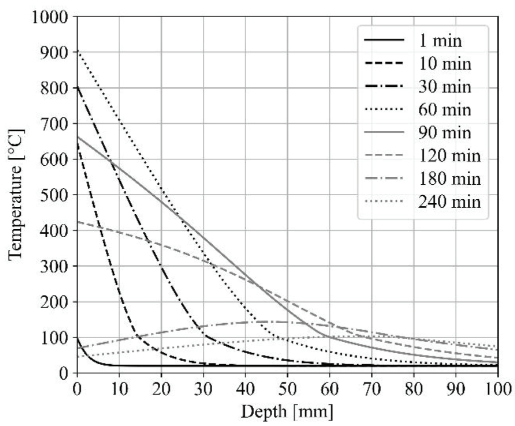

***Figure 12**: Evolution of thermal profiles within the timber substrate at different instants.*

A clearer illustration of this trend is evident through the penetration of the various isotherms (300 ºC, 200 ºC, and 100 ºC) during the fire exposure, presented in Figure 13. The isotherm curves highlight the continuous progression of char front and heat wave into the timber element even during the cooling phase. In particular, the 300°C isotherm evidences how the char front further increase for about 20 minutes during the cooling phase, increasing from 32 mm at the end of the heating phase to the maximum value of 37 mm. Similar conclusions can be drawn for the other isotherm curves, underlying how lower temperatures have a further and longer penetration into the timber cross-section during the cooling phase.

These results are also evident in Figure 14, which displays the penetration speeds of the discussed isotherm curves. Once again, the isotherms of lower temperatures have a higher speed compared to isotherms of higher temperatures, thus the thermal gradients tend to become less steep. In addition, the penetration speeds gradually decrease during the fire exposure. Given the defined thermal boundary conditions, there is a sharp change in the penetration speed of the various isotherm curves a few minutes after the end of the heating phase (note the 300°C isotherm). After this point, the penetration speeds quasi-linearly decrease to zero following specific rates. Consequently, the maximum penetration depths are reached long after the end of the heating phase, causing a further reduction of the timber mechanical properties. For instance, the 100°C isotherm reaches its maximum value about 140 minutes after the end of the heating phase (30 min after the end of cooling phase).

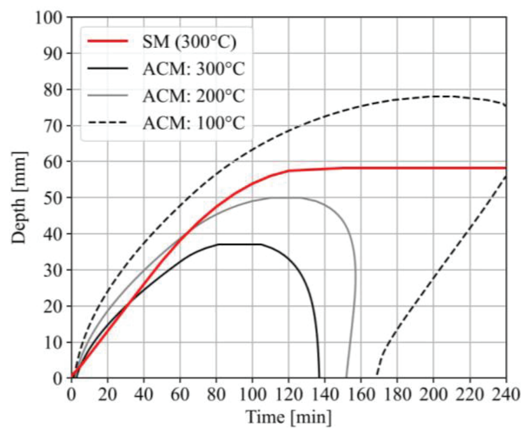

***Figure 13**: Evolution of the isotherms depths (300 ºC, 200 ºC, and 100 ºC) and comparison with EN 1995-1-2 simplified method for parametric fire curves (SM).*

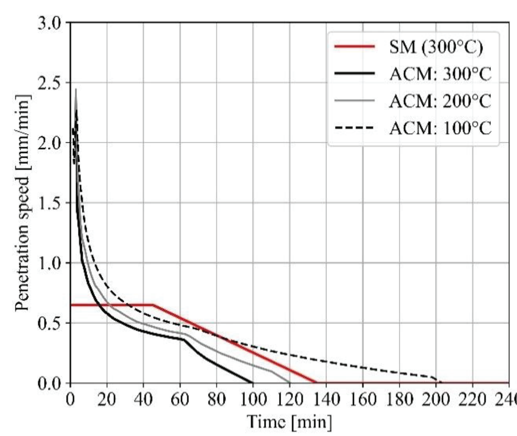

***Figure 14**: Evolution of the isotherms penetration speeds (300 ºC, 200 ºC, and 100 ºC) and comparison with EN 1995-1-2 simplified method for parametric fire curves (SM).*

Special focus is again placed on the 300°C isotherm depths (i.e. char depth) and penetration speed (i.e. charring rate). In particular, in Figure 13, the char depth (300°C isotherm) is compared to the Eurocode 5 simplified method for the parametric fire curve (Annex A) [4]. As in the previous case, the estimation of the char depth and charring rate according to Eurocode 5 (SM) is a more conservative approach compared to the presented advanced calculation method (ACM).

4.2 ZERO STRENGHT LAYER

Similarly to Section 3.2, once estimated the char depth, it is necessary to analyse the effect of heat penetration within the timber cross-section and the consequent reductions in the mechanical properties. This is done again through the concept of the zero-strength layer (ZSL), which is calculated according to the two previously-described approaches.
As regards to the mechanical properties approach, the reduction factors of the timber mechanical properties are estimated assuming their irreversibility. The reduced mechanical properties are based on the maximum temperature reached in each node, hence the reduction factor remains at the lowest attained value even if the node temperature decreases during the cooling phase. Starting from the thermal gradients shown in Figure 12, the distribution of reduced mechanical properties within the timber section can be obtained for tension and compression. As displayed in Figure 15, the effect of the heat penetration on the timber mechanical is evidenced by the lower reduction factors at higher depths.

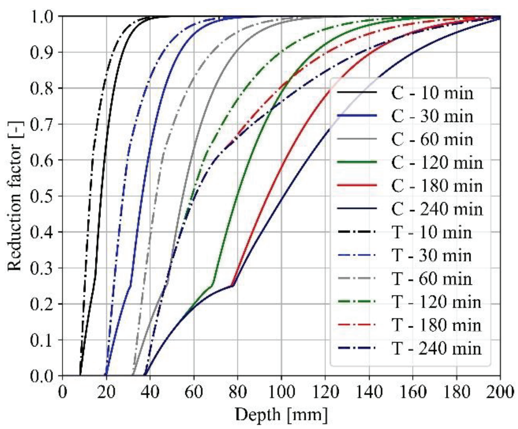

***Figure 15**: Evolution of the reduction factor of timber mechanical properties for compression (C) and tension (T) at different instants*

Figure 16 shows the calculated thicknesses of the zero-strength layer according to the temperature and reduced mechanical properties approaches. As a comparison, the constant value suggested by the Eurocode 5 simplified method (7 mm) is also reported. It is evident how all approaches and assumptions offer different results, with the highest values obtained for the reduced mechanical properties approach for compression and the lowest values for the 120-300°C temperature approach. In general, Figure 16 underlines how the zero-strength layer keeps increasing for a long time after the end of the heating phase and, possibly, the cooling phase. Constant values are achieved for the temperature approaches. In contrast, due to the continuous penetration of the heat wave (and corresponding reduction in the mechanical properties), the zero-strength layer according to the mechanical properties approach does not reach its maximum value even after 1 hour after the end of the cooling phase. Nevertheless, these results evidence how the values of the zero-strength layer at the end of the heating phase are about 2-3 times smaller than the values calculated by including the penetration of the heat wave during and after the cooling phase. When compared to the simplified Eurocode simplified method (SM), it is evident how this approach largely under-estimates the thickness of the zero-strength layer. The presented methodologies predict thickness between 30 and 65 mm, which is up to 10-times greater than the value suggested by the simplified method.

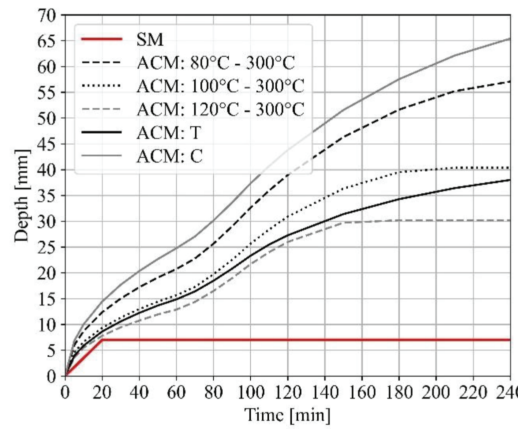

***Figure 16**: Evolution of the zero-strength layer according to temperature and reduced mechanical properties approaches, compared to EN 1995-1-2 simplified method (SM).*

4.3 EFFECTIVE CHAR DEPTH

The results related to the char depth and the zero-strength layer are finally combined to evaluate the structural capacity of timber members. Figure 17 reports the effective char depths obtained following the temperature and reduced mechanical properties approaches, compared to the Eurocode 5 simplified method for parametric fire curves (SM).

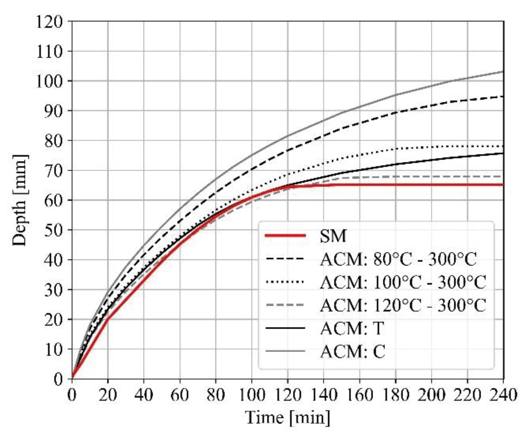

***Figure 17**: Evolution of the effective char depth according to temperature and reduced mechanical properties approaches, compared to EN 1995-1-2 simplified method for parametric fire curves (SM).*

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The Eurocode 5 over-estimation of the char depth and important under-estimation of the zero-strength layer lead to a general under-estimation of the effective char depth. The results are only comparable for the 120-300°C temperature approach, which are the lowest values according to the advanced calculation method. Otherwise, the simplified method generally offers less conservative values. For the highest values obtained for the reduced mechanical properties approach (compression), the final effective char depths differ by more than 34 mm (103 mm vs. 68 mm).

5 PARAMETRIC STUDY: COOLING RATE

The previous section has highlighted how the cooling phase of natural fire exposure have a key role in assessment of the heat penetration and the consequent reduction of the mechanical properties of timber structural elements. For this reason, this section investigates the influence of the cooling phase on this problem. Considering the same heating phase defined in Section 3 and Section 4 (standard fire curve for 1 hour), the two additional curves (FIRE 1 and FIRE 2) are introduced, starting from the previous-adopted Eurocode parametric fire curve (EPFC) as the median case. As the EPFC case, the fire curves are characterised by a constant cooling rate. The considered EPFC has a cooling phase from maximum temperature to ambient temperature of about 2 hours, resulting in a cooling rate of about 8.3°C/min. In constant, FIRE 1 has faster cooling (1 hour) and a cooling rate of about 15.4°C/min, while FIRE 2 slower cooling (3 hours) and a cooling rate of about 5.1°C/min. The defined fire curves are shown in Figure 10.

5.1 THERMAL CHARACTERISATION AND CHAR DEPTH

As in the previous cases, the penetration of the heat wave within the timber cross-section can be investigated by analysing the penetration depths and speeds of the various isotherms. In this case, Figure 18 and Figure 19 displays the results for the 300 ºC and 200 ºC isotherms. Similar conclusions to the cases of the standard fire curve and parametric fire curve can be drawn. However, the fire curves characterised by different cooling rates underline the influence of the cooling phase on the penetration of the heat wave. Indeed, even if the thermal boundary conditions defined for the fire exposure are applied at the element surface, these have an evident effect on the distribution of the in-depth temperatures. Both Figure 18 and Figure 19 highlight how lower cooling rates enable higher penetration depths and speeds, and lower temperatures have a further and longer penetration into the timber cross-section during the cooling phase. The penetration speeds quasi-linearly decrease to zero during the cooling phase, after a clear trend change a few minutes after the end of the heating phase.

Focusing on the 300°C isotherm, it can be observed that the final (maximum) char depth is reached much later than the end of the heating phase. In particular, the difference between the char depth at the end of the heating phase and the maximum char depth is directly related to the cooling rate. A slower cooling phase allows a deeper penetration of the char front: 32 mm at the end of the heating phase and a maximum value of 35 mm, 37 mm, and 41 mm for lower cooling rates, respectively. Similar conclusions can be drawn for the other isotherm curves, emphasising the fact that this effect becomes more important for lower temperatures (higher penetration depths and speeds). As a consequence, it can be expected that the cooling phase has an important impact on the reduction of the mechanical properties in heated timber, therefore the zero-strength layer.

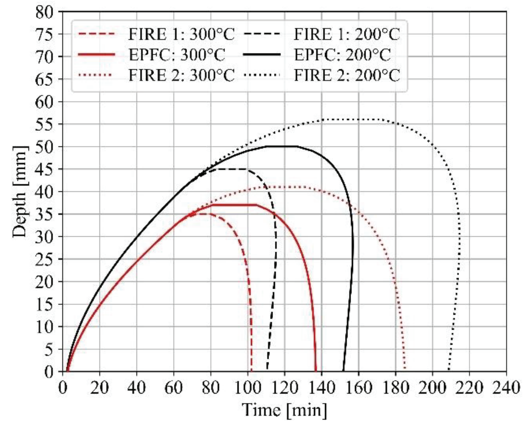

***Figure 18**: Evolution of the isotherms depths (300 ºC and 200 ºC) for different fire exposures.*

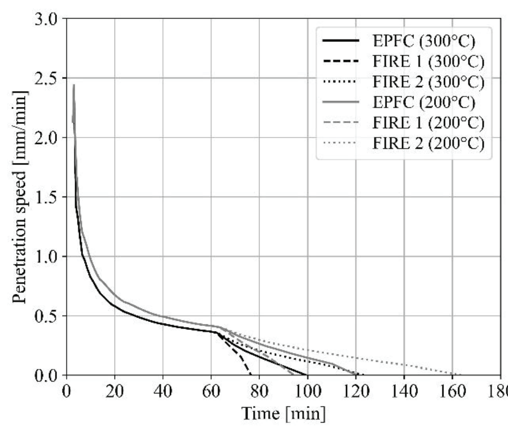

***Figure 19**: Evolution of the 300°C and 200 ºC isotherms penetration speeds for different fire exposures.*

5.2 ZERO STRENGHT LAYER

Starting from the temperature evolutions and in-depth gradients and once estimated the char depth, the zero-strength layer (ZSL) can then be calculated according to the two previous-discussed approaches. Figure 20 displays the calculated thicknesses of the zero-strength layer for the various fire exposures according to the temperature approach, while Figure 21 the ones according to the reduced mechanical properties approach. The results again estimate a large range of thicknesses, from 25 mm to 77 mm), up to more than 10-times the value suggested by the Eurocode 5 simplified method. The numerical results also underline how the zero-strength layer continues to grow for a long duration after the end of the heating phase and the final value directly depends on the cooling phase. A slower cooling leads to a deeper heat penetration, therefore a higher reduction of the timber mechanical properties and higher zero-strength layer (± 5-10 mm). It was also confirmed that the 120-300°C temperature approach is the least conservative approach and the reduced mechanical properties approach for compression the most conservative. This is again related to the continuous penetration of the heat wave, which proceeds differently according to the investigated temperature: lower temperatures have deeper penetration depths and therefore the zero-strength layer reaches its maximum value at a later instant.

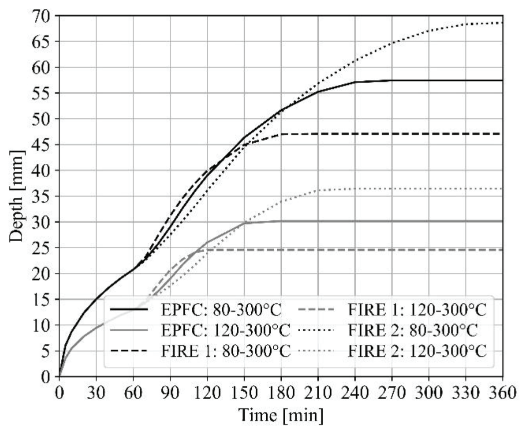

Figure 20*: Evolution of the zero-strength layer according to the temperature approach (80-300°C and 120-300°C) for different fire exposures.*

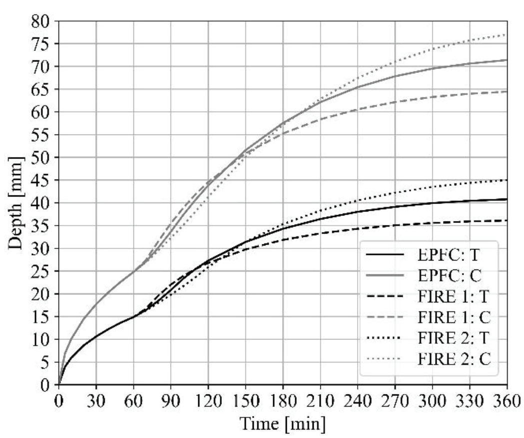

Figure 21*. Evolution of the zero-strength layer according to the reduced mechanical properties approaches (tension and compression) for different fire exposures.*

5.3 EFFECTIVE CHAR DEPTH

The final effective char depths for the different fire exposures, shown in Figure 22 and Figure 23 and obtained by summing the char depths and the zero-strength layers, offer a similar understanding on the influence of the cooling phase on the structural capacity of timber members. The maximum effective char depths, hence the most critical design conditions, are typically achieved after the end of the fire cooling phase and sit within a wide range of values, from 60 mm to 118 mm.

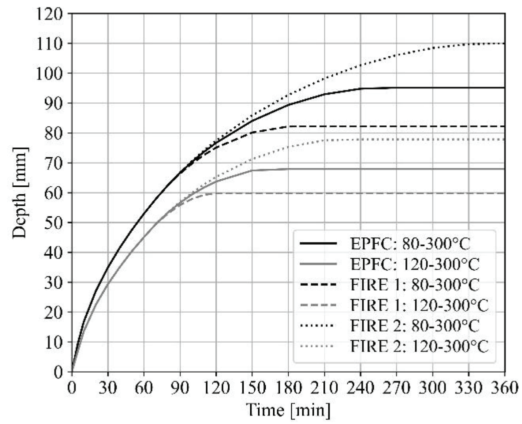

Figure 22*: Evolution of the effective char depth according to the temperature approach (80-300°C and 120-300°C) for different fire exposures.*

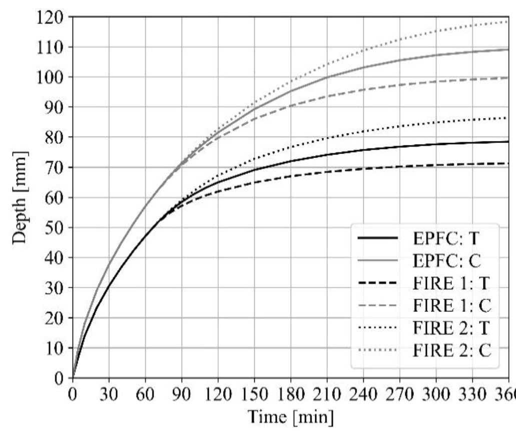

Figure 23*: Evolution of the effective char depth according to the reduced mechanical properties approaches (tension and compression) for different fire exposures.*

6 CONCLUSIONS

The presented research study focuses on the comparison of the char depth and zero-strength layer determined using the simplified approach suggested by Eurocode 5 and those estimated through an advanced calculation method. The advanced calculation method was based on a finite-difference heat transfer model using effective temperature-dependent material properties. The char depth was calculated as the 300°C isotherm, while the zero-strength layer was determined following two approaches: one based on the timber in-depth temperatures, and one based on the timber reduced mechanical properties (tension and compression).

The first comparison investigated the fire heating phase only, defined according to the standard fire temperature-time curve (120 minutes). For the defined case, it was found that the simplified Eurocode 5 method provides more conservative of char depths from 30 minutes onwards, while the zero-strength layer is generally under-predicted (up to 34 mm, instead of 7 mm). However, the overall comparison revealed that the two methods offer comparable results, with Eurocode 5 being usually less conservative, at least for standard fire durations below 60 minutes.

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The influence of the cooling phase on the evolution of the char depth and zero-strength layer was then investigated defining a series of fire exposures: a heating phase of 60 minutes standard fire curve followed by a cooling phase defined according to the Eurocode parametric fire curves, compared to a slower and faster cooling. For all the cooling phases, the heat wave penetration within the timber cross-section led to an increase in the char depth, up to 1 hour after the end of the heating phase. In particular, the difference between the char depth at the end of the heating phase and the maximum char depth is directly related to the cooling rate: a slower cooling phase allowed deeper penetration of the char front. Similar but more pronounced behaviour was also observed for the zero-strength layer. Even for the fastest cooling rate, the zero-strength layer kept increasing for at least 1 hour after the onset of the cooling phase. Accordingly, the maximum effective char depth was typically achieved after the end of the cooling phase.

The research outcomes highlight the importance of including the cooling phase in modern performance-based methodologies for the fire-safe timber structures. It was shown how, during the cooling phase, the load-bearing capacity of timber elements can significantly reduce due to the heat wave penetration and disregarding this phenomenon can lead to important under-estimation, on the unsafe side.

This research study was based on a finite-difference heat transfer model using the effective temperature-dependent material properties suggested by Eurocode 5. Future studies should focus on the effect of various wood species (e.g. density) and wood thermo-physical properties, with various complexities: from various effective material properties for pure conduction heat transfer to the inclusion of models of higher levels of complexity, for instance including the moisture transport and pyrolysis reactions. Also, in this research study, only a few specific heating and cooling phases were investigated, and future studies should cover a broader range of fire exposures to generalise the observed trends. Finally, future research should certainly aim at validating the presented numerical results with experimental data and quantifying the accuracy of the estimated char depth and zero-strength layer approximations, which significantly contribute to the overall effective char depth.

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