

Advancing Timber for the Future Built Environment

CHARRING CHARACTERISTICS OF TIMBER ELEMENTS EXPOSED TO NATURAL FIRE

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ABSTRACT: To evaluate the charring characteristics of timber elements exposed to natural fire, a numerical analysis was conducted using the advanced numerical model PYCIF. This model provides a detailed physical description of the phenomena by coupling heat and mass transfer with the pyrolysis reaction of timber at elevated temperatures. The analysis was performed on a timber cross-section subjected to various natural fire curves generated using the Ozone software. During the analysis, several quantities were examined, including the final charring depth, the onset time of charring and the end time of charring. The main goal was to determine if any correlation exists between the charring characteristics and the properties of the natural fire curves. The results revealed a strong correlation between the final charring depth and the maximum temperature of the fire curve. Additionally, there was a strong correlation between the onset time of charring and the time when the fire curve reached 300 °C during the heating phase. Finally, a strong correlation was observed also between the end time of charring and the time when the fire curve reached 300 °C during for timber elements exposed to natural fire.

KEYWORDS: charring characteristics, advanced numerical analysis, natural fire, simplified method of charring

1 – INTRODUCTION

The increasing use of timber as a sustainable building material of the future requires comprehensive knowledge of the material to ensure its safe application. As a combustible material, understanding the behavior of timber under fire conditions and ensuring the fire safety of timber structures is of utmost importance. One of the most important phenomena which determine the behavior of timber structures in case of fire is charring. Charring leads to a loss of stiffness and strength of the timber structure during fire exposure, which eventually leads to failure. Numerous studies have been conducted to determine the charring of timber exposed to the standard fire curve, usually yielding simplified charring rates as provided by EN 1995-1-2 [1]. However, natural fires can deviate significantly from the standard temperature-time relationships, resulting in higher or lower charring depths than predicted by current models or codes [2].

Recent advances in performance-based fire design highlight the importance of numerical modeling to better capture the complexity of timber behavior under natural fire conditions [3]. Advanced numerical tools, such as the PYCIF model, enable detailed simulations that couple heat transfer, moisture movement and pyrolysis reaction, and allow more accurate prediction of charring [4,5].

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In this study, the charring behavior of timber elements exposed to natural fire conditions is investigated using a numerical simulation approach. By analyzing correlations between fire curve characteristics and charring parameters (e.g., depth, onset, and end time of charring), the research shows a great potential for the development of a simplified charring model that is applicable to natural fire scenarios.

2 – BACKROUND

In the past, the charring of timber under standardized fire conditions has been studied in detail, primarily using the ISO 834 fire curve, which led to the development of empirical charring models. Such a model is also defined in the Eurcode standard EN 1995-1-2:2005 [1], which specifies constant charring rates for softwood, hardwood and other timber products exposed to the ISO 834 fire. However, the conditions in natural fires often lead to variable heating and cooling rates that affect the charring process and the structural performance of timber [6].

Recent studies have shown that natural fires have higher heating rates and maximum temperatures compared to the ISO 834 fire curve [7], leading to differences in charring rates and depth predictions [2]. Experiments by Bartlett and Bisby [8] showed that average charring rates ranged from 0.36 to 0.79 mm/min, with peaks exceeding 2.0 mm/min, indicating significant differences depending on the fire conditions.

With advances in computational fire engineering, models such as PYCIF [4, 5] have been developed to simulate the coupled heat and mass transfer mechanisms and pyrolysis reaction in timber during fire exposure. Such models allow more detailed and general predictions of charring depth, thermal degradation and moisture redistribution compared to empirical methods.

This study uses the PYCIF model to numerically analyze timber charring in 20 different natural fire scenarios and investigates correlations between charring parameters and fire curve characteristics to develop a simplified charring model for timber exposed to a natural fire.

3 – PROJECT DESCRIPTION

This research employs a numerical approach to evaluate the charring characteristics of timber elements exposed to natural fire conditions. The methodology consists of two main steps: (i) generation of natural fire curves and (ii) numerical analysis of charring.

3.1 GENERATION OF NATURAL FIRE CURVES – OZONE SOFTWARE

OZone is a zone model which can be used to simulate the temperature development within a fire compartment. It is a model for determination of natural fire curves. It combines two-zone and one-zone models to simulate fire dynamics. The two-zone model divides the compartment into upper and lower layers with uniform temperatures, while the one-zone model assumes a uniform temperature throughout the entire compartment. The OZone model includes sub-models for ventilation, combustion, heat and mass transfer, which are crucial for accurately predicting fire dynamics.

For ventilation, models for vertical, horizontal, and forced ventilation are included. These models simulate the heat and mass transfer between the compartment and the external environment.

The default combustion process in OZone is the extended fire duration model. This model increases the fire duration until the fuel is depleted. The pyrolysis rate is proportional to the mass of oxygen entering the compartment, ensuring that all the fuel within the compartment is burned. This approach extends the fire duration compared to the initial input. The OZone model also includes an oxygen balance to account for the mass of oxygen entering and leaving the compartment. This balance affects the combustion process and determines whether the fire is fuel or ventilation controlled. In ventilation-controlled scenarios, the rate of heat release is limited by the available oxygen, which affects the intensity and duration of the fire. The combustion reaction in the OZone V2 model is based on the stoichiometric combustion of wood. The reaction takes into account the heat release rate and the production of combustion products, which are essential for simulating the effects of the fire on the fire compartment.

Heat transfer through walls, floors, and ceilings is simulated by the partition model, which is based on a one-dimensional finite element approach. The model ensures energy balance between the gas and the partitions and provides a realistic simulation of the heat transfer dynamics.

3.2 NUMERICAL ANALYSIS OF CHARRING – PYCIF MODEL

To determine the charring of timber exposed to natural fire curves, the PyCiF model was used. PyCiF model couples a 2D heat-mass transfer model with a pyrolysis model, and implements a charring criterion based on physical phenomena. This approach offers a significant advantage over conventional methods that rely on an empirical charring temperature, often referred to as the char front temperature. Unlike the conventional assumption of a fixed char front temperature of 300 °C, the PyCiF model does not require this empirical value to determine the char layer thickness.

The pyrolysis reaction of timber is modelled by the Broido-Shafizadeh (hereafter BS) pyrolysis model [9]. The BS model describes cellulose pyrolysis with three reactions. The first reaction, which leads to active cellulose, is followed by two competing reactions, the first of which leads to the formation of volatiles and the second to the formation of char and gases. The kinetics of the reaction are shown in Fig. 1., where the kinetic parameters k_i follow the Arrhenius law:

$$k_i = A_i \exp\left(\frac{-E_i}{RT}\right),\tag{1}$$

where A_i represents the pre-exponential factor, E_i is activation energy, R is the universal gas constant and T is the temperature (measured in K).

The equations describing coupled heat-mass-pyrolysis phenomena consists of three continuity equations describing the conservation of bound water (c_b), water vapour ($\tilde{\rho}_v$) and the residual gas mixture (air and pyrolytic gases, $\tilde{\rho}_g^*$), and energy conservation equation. Mass and energy conservation equations are:

$$\frac{\partial c_{\rm b}}{\partial t} = -\nabla \cdot \mathbf{J}_{\rm b} + \dot{c},\tag{2}$$

$$\frac{\partial(\varepsilon_{\rm g}\,\tilde{\rho}_{\rm v})}{\partial t} = -\nabla \cdot \mathbf{J}_{\rm v} - \dot{c},\tag{3}$$

$$\frac{\partial (\varepsilon_{\rm g} \, \tilde{\rho}_g^*)}{\partial t} = -\nabla \cdot \, \mathbf{J}_{\rm g},\tag{4}$$

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (\mathbf{k} \nabla T) - (\rho C \mathbf{v}) \nabla T - \Delta H_{\rm s} \dot{c} - Q. \quad (5)$$

In equations (2) – (5), ε_g denotes the porosity of timber, J_i (*i* = b, v, g) are mass fluxes of each moving medium (bound water, water vapour and residual gas mixture) and *c* is the sorption rate. ρC is the heat capacity of timber, **k** is the matrix containing thermal conductivities in different directions, **v** is the velocity of gaseous mixture which follows Darcy's law, ΔH_s is the latent heat of sorption and *Q* is the energy sink or release due to the pyrolysis reaction The boundary conditions prescribed at the contact between the timber body and the surroundings are the following:

$$h_{\rm cr} = k \frac{\partial T}{\partial n},$$

$$\mathbf{n} \cdot \mathbf{J}_{\rm v} = \beta \left(\tilde{\rho}_{\rm v,\infty} - \tilde{\rho}_{\rm v} \right),$$

$$\mathbf{n} \cdot \mathbf{J}_{\rm b} = 0,$$

$$P_{\rm g} = P_{\rm g,\infty}$$

(6)

where $h_{\rm cr}$ is the heat flux due to convection and radiation, $\tilde{\rho}_{\rm v,\infty}$ and $P_{\rm g,\infty}$ are the vapour concentration and the gas pressure in the ambient, respectively, β is the mass transfer coefficient and **n** is the unit vector normal to the outer surface of timber volume.

The solution to Eqs. (2)-(5), along with the boundary and initial conditions, is obtained numerically using a Galerkin-type finite element method. This method is implemented by our own code developed within the Matlab environment. Further details on the PYCIF model and the solution procedure can be found in [4,5]

Cellulose
$$k_1$$
 Active cellulose k_2 (Tar)
 k_3 Char + Gas

Figure 1. Broido-Shafizadeh pyrolysis kinetics.

4 – DESIGN PROCESS

The first step of the numerical methodology involves generating fire curves using the Ozone software. A total of 20 natural fire curves were generated. In all cases, the same compartment was used, with a length of 20 m, a width of 15 m, and a height of 4 m. The maximum fire area $A_{\rm f}$ corresponds to the floor area of the compartment (300 m^2) . To ensure the diversity of the natural fire curves, various quantities were varied in the fire scenarios. These included the thermal properties of the boundary encloser, i.e. the thermal conductivity of the roof, ceiling and walls λ , the area of the openings (with a fixed height of 3 m, while the opening length l_0 varied) and the fire load density. All other parameters remained constant, i.e. specific heat of the enclosure c = 1000J/kgK, density of the enclosure $\rho = 1000$ kg/m³, fire growth rate $t_{\alpha} = 150$ s, maximum heat release rate per unit area $RHR_f = 250 \text{ kW/m^2}$.

Table 1: Range of varied parameters

Parameter	Range
λ [W/mK]	0.25 - 2.25
<i>l</i> _o [m]	7 – 34
$q_{\rm fd} [{ m MJ/m^2}]$	300-1300

The second step of the numerical methodology represents the analysis with the coupled hygro-thermopyrolysis model PYCIF. For the analysis, a cross-section with a height of 100 mm was considered, exposed to natural fire from one side. The cross-section was discretized with 100 finite elements. The most important parameters for the analysis include the density of timber of 420 kg/m³ and the initial moisture content of 12 %. A surface emissivity ε_m of 0.8 and the convective heat transfer coefficient α_c of 35 W/m²K, were specified for the boundary conditions. The numerical model and other data for the boundary conditions are shown in Fig. 2.



Figure 2. Numerical model and data for boundary conditions

The kinetic parameters used for the analysis are listed in Table 2.

Reaction #1	Reaction #2	Reaction #3
$E_1 = 242.6 \text{ kJ/mol}$	$E_2 = 153.1 \text{ kJ/mol}$	$E_3 = 197.9 \text{ kJ/mol}$
$A_1 = 1.7 \cdot 10^{21} \text{ s}^{-1}$	$A_1 = 7.9 \cdot 10^{11} \text{ s}^{-1}$	$A_1 = 1.9 \cdot 10^{16} \text{ s}^{-1}$

Table 2: Kinetic parameters for pyrolysis reaction

For all other parameters, please refer to [4,5].

5 – RESULTS

The 20 natural fire curves generated with the Ozone model are shown in Figure 3. The curves were generated to represent a wide range of possible temperature developments in natural fire scenarios. In particular, these include fire curves with temperatures above 1100°C and very fast heating rates but shorter exposure

times, as well as curves with lower maximum temperatures but longer exposure times.



Figure 3. Generated fire curves in Ozone

The main objective of this study was to observe the relationships between the characteristics of charring (final charring depth, onset and end time of charring) and the characteristics of natural fire curves. Several variables were analyzed, of which the most evident correlations were between: (*i*) final charring depth ($d_{ch,end}$) and the maximum fire curve temperature ($T_{g,max}$), (*ii*) the onset time of charring ($t_{ch,on}$) and the time at which the fire curve reaches 300 °C during the heating phase ($t_{300,heat}$) and (*iii*) the end time of charring ($t_{ch,end}$) and the time at which the fire curve reaches 300 °C during the cooling phase ($t_{300,cool}$).

In the fire design for structures exposed to natural fire, the primary objective is to ensure structural survival, which largely depends on the final charring depth, as one of the most critical factors determining fire resistance. However, obtaining the final charring depth for natural fire exposure is challenging. For instance, standards such as EN 1995-1-2 [1] only outline performancebased methods for its determination, without providing simplified approaches. To address this, advanced numerical simulations are conducted to establish a basis for simplified estimation. In this study, the most straightforward method for determining the final charring depth is by linking $d_{ch,end}$ directly to the maximum fire temperature $T_{g,max}$, which is presented in Figure 4. The data points represent the calculated values. In general, it is seen that the thickness $d_{ch,end}$ increases with the increasing maximum fire temperature $T_{g,max}$. The dotted trend line follows an exponential function given by:

$$d_{\rm ch,end} = 0.0056 \exp(0.002T_{\rm g,max}),$$
 (7)

The goodness of fit of the proposed equations is assessed by the R^2 measure (the coefficient of determination), which is equal to 0.9048. This indicates a strong correlation between the two variables, suggesting that as the maximum fire temperature increases, the final charring depth increases exponentially.



Figure 4. The relationship between the maximum fire temperature $(T_{g,max})$ fire and the final charring depth (d_{chend})

The relationship between the onset time of charring $(t_{ch,on})$ and the time when the fire curve reached 300 °C during the heating phase $(t_{300,heat})$ is presented in Figure 5. This relationship is important to better predict and understand the behavior of timber under fire conditions. The figure clearly demonstrates a strong linear relationship between these two variables, as confirmed by the trend line:

$$t_{\rm ch,on} = 1.06 \cdot t_{\rm 300,heat} + 1.1732 \,. \tag{8}$$

This is further affirmed by the high R^2 value of 0.9971. The results also indicate that, on average, charring starts approximately two minutes after the fire curve reaches 300°C during the heating phase.



Figure 5. The relationship between the onset time of charring $(t_{ch,on})$ and the time when the fire curve reached 300 °C during the heating phase $(t_{300,heat})$

In Figure 6, the relationship between the end time of charring $(t_{ch,end})$ and the time when the fire curve reached 300 °C during the cooling phase $(t_{300,cool})$ is

given. A strong linear correlation is found here as well, described by the trend line:

$$t_{\rm ch,end} = 0.7053 \cdot t_{300,\rm cool} + 8.23 \tag{9}$$

with a high coefficient of determination (\mathbb{R}^2) of 0.9612 Additionally, it is evident that the charring ends before the fire curve reaches 300 °C during the cooling phase. On averages, it is reached 15 minutes earlier.



6 – CONCLUSION

In this study, the charring of timber elements exposed to natural fire conditions was investigated using the advanced numerical model PYCIF. The results showed strong correlations between the characteristics of the natural fire curves and the charring parameters, such as the final charring depth, onset time of charring and end time of charring. It was discovered that the final charring depth increases exponentially with the maximum fire temperature. A simple exponential function was provided to represent this relationship, allowing for the estimation of final charring depth even in natural fire scenarios that were not specifically examined in this study. Additionally, we identified linear relationships between the onset time of charring and the time when the fire curve reaches 300°C during the heating phase, as well as between the end time of charring and the time when the fire curve reaches 300°C during the cooling phase. These linear relationships are important because they allow the estimation of the beginning and end times of charring, which is crucial for the appropriate assessment of the fire resistance of timber elements.

These findings highlight the importance of considering the specific characteristics of natural fire scenarios when assessing the fire performance of timber structures. The ability to predict charring behavior accurately under varying fire conditions is crucial for ensuring the safety and integrity of timber buildings. The advanced numerical simulations conducted in this study provide a robust framework for developing simplified methods that can be applied in practical engineering design.

The results indicate significant potential for developing simplified methods for determining the charring of timber elements exposed to natural fires. Future research should explore the impact of different timber species, moisture content, and structural configurations on charring behavior. Additionally, more analyses with a wider range of possible fire scenarios are needed, including the charring of elements exposed to fire from multiple sides, where the rounding effect is significant. Understanding these variables will enhance the accuracy and applicability of the simplified methods developed.

7 – REFERENCES

[1] EN 1995-1-2. "Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design (2004)

[2] J. Liu, E. C. Fischer. "Review of the charring rates of different timber species." In: Fire and Materials 48 (2024), pp. 3–15

[3] T. Gernay. "Performance-based design for structures in fire: Advances, challenges, and perspectives." In: Fire Safety Journal 142 (2024), pp. 104036

[4] R. Pečenko, T. Hozjan. "A novel approach to determine charring of wood in natural fire implemented in a coupled heat-mass-pyrolysis model." In: Holzforschung 75.2 (2020), pp. 148-158.

[5] R. Pečenko, T. Hozjan and S. Huč. "Modelling charring of timber exposed to natural fire." In: Journal of Wood Science 69 (2023), pp. 1–14.

[6] J. König. "Effective thermal actions and thermal properties of timber members in natural fires." In: Fire and Materials 30 (2006), pp. 51–63.

[7] A. Hofmann, A. Klippel, T. Gnutzmann, S. Kaudelka, F. Rabe. "Influence of modern plastic furniture on the fire development in fires in homes: large-scale fire tests in living rooms." In: Fire and Materials 45 (2021), pp. 155-66

[8] A. I. Bartlett, R. M. Hadden, L. A. Bisby, A. Law. "Analysis of Cross-Laminated Timber Charring Rates upon Exposure to Nonstandard Heating Conditions." In: Fire and Materials 2015 - 14th International Conference and Exhibition, Proceedings (2015), pp. 667-681 [9] A. Bradbury, S. Yoshio, F. Shafizadeh. "A Kinetic Model for Pyrolysis of Cellulose." In: Journal of Applied Polymer Science 23.11 (1979), pp. 3271-3280.