31st International Conference
ENGINEERING MECHANICS 2025
Medlov, Czech Republic, May 12 –14, 2025
Paper **#56,** pp. 173–176, doi: 10.21495/em2025-173

CHARRING RATE OF WOOD AND DEVELOPMENT OF CRACKS IN THE CHARRED LAYER

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Abstract: *The paper presents a part of research focused on the influence of cracks on the fire resistance of wooden structures and their potential integration into numerical models. The increasing interest in using wood as a sustainable construction material emphasizes the necessity of a detailed investigation of its behavior during fire exposure. Existing analyzed methods often rely on conservative charring rates under standard fire conditions, which are not remotely similar to natural fire conditions and at the same time do not describe the reality of the development of the charred layer and formation of cracks in the layer. A numerical model was developed to incorporate an equation for a more realistic charring rate based on a probabilistic approach and crack distances. This allowed the inclusion of the effect of anisotropic wood properties, moisture, density, and oxygen content, which led to a better description of the wooden structure's behavior during fire exposure. Results of the model show good consistency of the prediction with the data measured during the experiment.*

Keywords: charring rate, crack, charred layer, wood, probability, fire

1. Introduction

With the increasing use of wood in construction, it is essential to conduct detailed research of the fire behavior of wooden structures. Advanced methods and their refinement can reflect the variability of the material properties of wood at elevated temperatures and allow sufficiently accurate determination of fire resistance to ensure economically viable construction. The issue of fire resistance of timber structures is complex and requires a combination of theoretical knowledge with numerical calculations and experimental data.

The main parameter influencing fire resistance is the charred layer that is formed on the surface when exposed to fire. It works as a thermal barrier between the rough wood and the flame. The char depth in the cross-section can vary considerably. The charring layer and its development is directly proportional to the charring rate (Huč et al., 2021), which is not constant when exposed to a natural fire and shows a non-linear progression in time, this phenomenon cannot be described by simplified methods (Šejna et al., 2024b). There are calculation procedures ranging from simplified linear, non-linear, and probabilistic which can be used to determine the final depth of the charred layer. Simplified approaches cannot include the re-ignition of the wood due to burning, changes in the percentage of oxygen in the air, or the moisture content of the wood. For more accurate calculations, it is appropriate to use advanced methods, for example as proposed in (Hietaniemi, 2005), see equation (1), and methods including the effect of probability.

$$\beta = f(\chi_{O_2}, t) \cdot \frac{C \cdot \dot{q}_e^n(t)^p}{(\rho + \rho_0) \cdot (A + B \cdot \omega)} \cdot e^{-\frac{t}{\tau}} \qquad (1)$$

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One of the key factors which can significantly affect behaviour of wooden structures during a fire is the presence of cracks. Cracks are a natural part of wooden structures and they are caused by tension exceeding the strength limit. Such tension can occur in wood during tree growth, harvesting and manipulation, and drying. Cracks are formed at elevated temperatures due to volume loss and thermal tension at high temperatures, and additional cracks are gradually formed in the charred layer (Šejna et al., 2024a). Cracks disrupt the thermal barrier function, resulting in increased heat transfer to the structure and accelerated burning. In addition, cracks allow the escape of volatiles which, when in contact with oxygen, support further flame spread. Despite this important influence, the issue of the effect, formation, and behaviour of cracks in the char layer is often neglected in current methods.

The formation of cracks when subjected to thermal load was studied in (Šejna et al., 2024a; Li et al., 2017; Rinta-Paavola et al., 2024). Li et al. (2017) state a critical heat flux for the creation and formation of cracks, which is 15 kW/m^2, cracks form at once and then only expand. Larger cracks can be found in the vertical direction than in the horizontal direction (Li et al., 2017). For mechanically unloaded elements, it has been confirmed that there is a relationship between the number of cracks and heat flux and between the number of cracks and the ambient pressure (Šejna et al., 2024a). The number of cracks increases with increasing heat flux, while it decreases with increasing ambient pressure (Li et al., 2017, 2021). The paper (Rinta-Paavola et al., 2024) shows how the pattern of cracks also varies significantly for different wood species (spruce, pine, birch). Experimental research presented in (Šejna et al., 2024a) has shown that the distances between cracks decrease with increasing fire exposure time (valid for 19 mm thick samples).

The distance of cracks in the charred layer can be predicted using the analytical method introduced in (Baroudi et al., 2017), see equation (2). The method has been validated using several experiments (Šejna et al., 2024a; Rinta-Paavola et al., 2024) and shown good results for the given conditions.

$$n_i = \frac{\sqrt[4]{12}}{\pi} \cdot \frac{l_i}{h} \cdot \sqrt[4]{\frac{E_R(T_0)}{E_i(T^*)}} \cdot \sqrt[4]{\frac{1}{\omega^3} \cdot \frac{h}{1m'}} \tag{2}$$

2. Calculation of charring rate

In order to determine the exact depth of the charring layer which is one of the input value of the crack distance calculation in equation (2), a comparison of several methods for determining the charring rate has been made. The standard equations according to (ČAS, 2004) and an advanced calculation using a probabilistic approach according to (Hietaniemi, 2005) were used for comparison. Calculations were performed in Python 3.10 to follow the progression with probability effects, with approximately 30 variables entering the calculation.

In Fig. 1 it can be seen that in the probabilistic approach, see (Hietaniemi, 2005), taking into consideration the time-varying properties of the wood at elevated temperature, a more accurate charring rate can be achieved than in the simplified standard methods. In real situations, the charring layer forms a thermal barrier, the wood burns more slowly, the charring rate decreases and is therefore neither constant nor linear. The results according to (Hietaniemi, 2005) also correspond with the simulations that were performed in the work (Šejna et al., 2024b). It was further confirmed that the method according to (Hietaniemi, 2005) is sufficiently functional and it is necessary to extend and refine it further. Therefore, this probabilistic method of determining charring rate is further included in the calculation of predicting crack distance in wood.

3. Crack distance modelling

The model given in equation (2) is used to determine the crack distance. The charring depth h_c enters the model and is calculated from the charring rate according to equation (1). This refined model follows the work of (Šejna et al., 2024a), which recommended expanding the number of samples and their diversity in terms of wood species and working with more variables, such as wood moisture content or bulk density, in the calculation of the charring rate.

To account for the larger number of samples, a statistical dataset, respectively matrix, was created that generates thousands of samples with different characteristics. After calculating 80 wood samples with different characteristics, the charring rate is solved and multiplied by the time to determine the depth of the

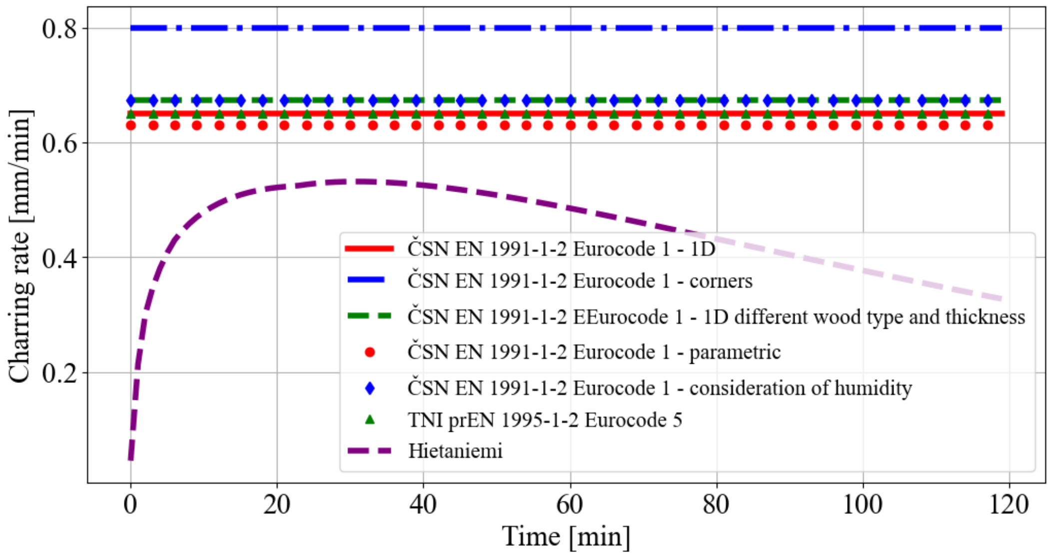

Fig. 1: Charring rates calculated by different methods

charring layer. The variability of the charring rate results is consistent with the expected variance caused by the different input parameters and the use of a ISO standard fire curve. According to (Šejna and Blesák, 2022), the charring rate can be considered in the range of 0.6 to 1.25 mm/min in the first 7 min, which is consistent with the results of this numerical model. The median is calculated as 0.64 mm/min and the MAD as 0.2 mm/min at 7 min.

The results are further used to calculate the crack distance n_i according to the equation (2). The results are compared with experimental data from the work of (Šejna et al., 2024a). Fig. 2 and Fig. 3 show the statistical evaluation of the crack distance in the investigated wooden element of two selected thicknesses over time. The orange curve shows the measured data from the experiment, the blue the calculated crack distance from the model presented in (Šejna et al., 2024a) and the green the crack distances calculated using the refined model from this research. Comparison shows that by refining the crack distance prediction model by inserting the equation (1), it is possible to achieve a greater consistency of the prediction with the data measured during the experiment.

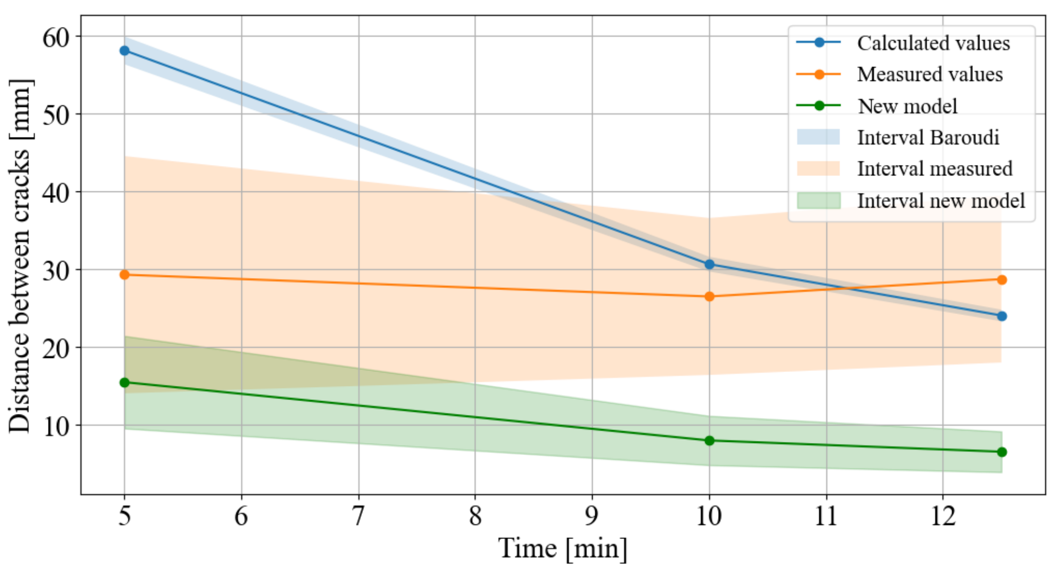

Fig. 2: Distance between cracks th. 19,5 mm

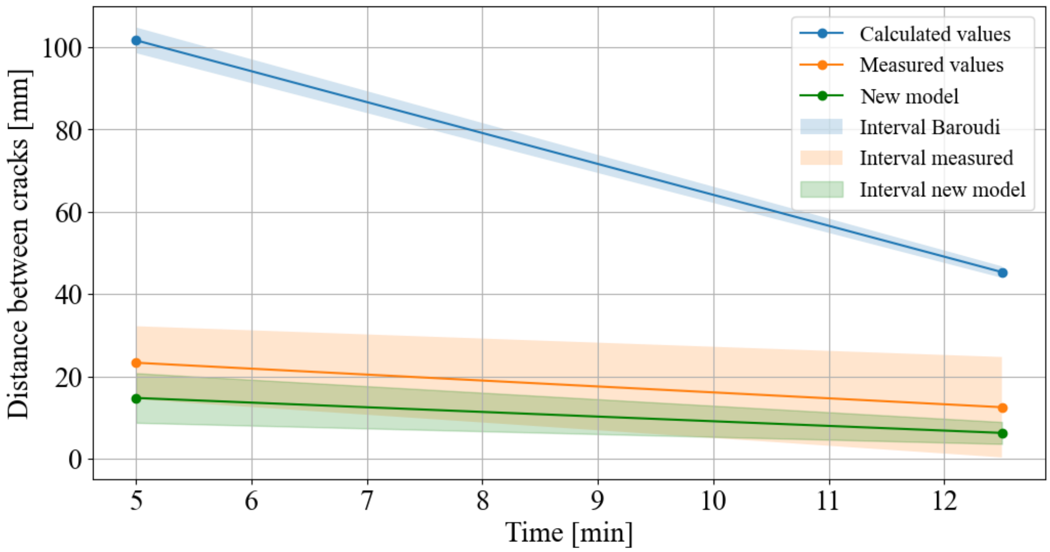

Fig. 3: Distance between cracks th. 40 mm

4. Conclusions

Cracks in the char layer negatively influence the behaviour of wooden structures exposed to fire. Advanced probabilistic methods such as (Hietaniemi, 2005) provide more accurate predictions of the charred layer than simplified models. The combination of the crack calculation (Baroudi et al., 2017) and the refined charring rate calculation (Hietaniemi, 2005) led to a greater consistency with the experimental data presented in (Šejna et al., 2024a). The results indicate that incorporating material property variables into the charring rate solution is of great significance and influence.

Acknowledgments

This research was funded by student grant SGS25/120/OHK1/3T/11 Advanced design methods of timber and steel structures exposed to fire.

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