Exploratory Research on the Thermal Properties of Wood in Real Fire Conditions

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Abstract. As construction material, wood represents a response to concerns over the environmental impact caused by steel and concrete. A good performance of timber structural members must be demonstrated in fire. To perform numerical simulations of timber structures under elevated temperatures, EN1995-1-2 provides effective thermal properties of wood for computing the temperature distribution. These properties have been determined considering the standard time-temperature curve. The aim of the exploratory research is to verify to what extent these properties may be considered also for natural fires, by adapting the real exposure conditions within the numerical simulations. In the tests performed at the University of Liège, timber samples were subjected on one side to heat fluxes of different intensities, including decreasing phases. Time-temperature curves inside the samples were recorded by thermo-couples inserted at different distances from the exposed side. Using SAFIR software, dedicated to the analysis of structures under elevated temperatures, the temperature distribution within the samples was calculated considering thermal properties provided by EN1995-1-2. The comparison with the experimental results emphasized that the correspondence is not satisfactory for all cases.

Keywords: wood · natural fire · thermal properties · temperature measurement · numerical modeling

1 Introduction

According to EN1995-1-2:2004 [1] and the revised version prEN 1995-1-2:2025 [2], if advanced design methods are considered for the assessment of the fire resistance of timber members, the thermal response model shall consider the temperature dependent thermal properties of the wood: thermal conductivity, specific heat, and density ratio. Both documents offer effective values of these thermal properties for softwood, as a function of temperature.

The evolution of these properties with temperature was initially determined by [3] for application to standard fire scenarios and should only be used when the conventional heat transfer is applied, that is when mass transport is not explicitly considered [4].

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These are effective values rather than physically measured values, taking into account effects which are not explicitly considered in the thermal analysis, such as increased heat transfer due to shrinkage cracks in the charcoal [1, 2].

Indeed, in a fire situation, while for construction materials as steel and concrete the heat primarily propagates through conduction, the heat propagation within wood members is also influenced by radiation and convection, considering the specific phenomena (e.g. pyrolysis gases, vapor, fissures in charcoal).

Considering that the charring rate of wood varies during a real fire, and this strongly influences the effective thermal properties, the evolution of the thermal conductivity, specific heat and density ratio specified in [1, 2] should not be applied to natural fire scenarios. The restriction to standard fire scenarios is motivated in [4], by means of six fire tests of timber slabs exposed to natural fires.

However, within a numerical thermal analysis, apart from the thermal properties of the material itself, in case of a natural fire there are some other parameters linked to the real exposure conditions, which shall be considered accordingly. The purpose of the exploratory research is to verify if the effective thermal properties of wood given by [1, 2] may be nevertheless considered for natural fire scenarios, even with certain limitations, if the real exposure conditions are properly considered within the numerical analysis.

A series of experiments using an apparatus recently developed at the "Laboratoire d'essai au feu" of the University of Liège were performed, aimed to identify the discrepancies between the real temperature evolution inside of a timber specimen subjected to different heat fluxes and the results of the numerical thermal analysis provided by SAFIR [5], using the effective thermal properties proposed in EN1995-1-2.

2 Experimental Setup

The **s**amples for the experimental work were considered from three beams (Fig. 1), of dried and planed spruce ("Picea abies"), which is classified as softwood. The beams were sectioned off in 250 × 220 × 80 mm test samples. A maximum value for the humidity of 13.4% was experimentally determined for the samples.

The device used as heat source was the experimental apparatus designed at the "Laboratoire d'essai au feu" of the University of Liège, which consists of ten ceramic heating pads divided into five heating zones, as shown in Fig. 2. A full description of the apparatus functionality and of the calibration process can be found in [6].

To produce accurate heating conditions for fire testing, two parameters can be controlled: the distance between the heating pads and the specimen, and the temperature of the heating pads.

The test set-up allows for easy adjustment of the distance between the pads and the specimen. This facilitates the achievement of well-defined heat fluxes at the exposed surface of the samples, ranging from 25–50 kW/m^2. The threshold for self-igniting and maintaining burning during the whole length of the exposure was at a heat flux of about 50 kW/m^2. At lower heat fluxes, the sample would ignite only with a pilot flame.

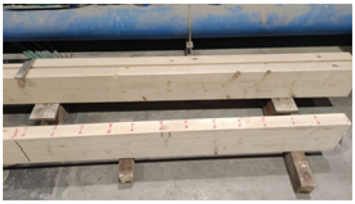


Fig. 1. Beams used for tests.

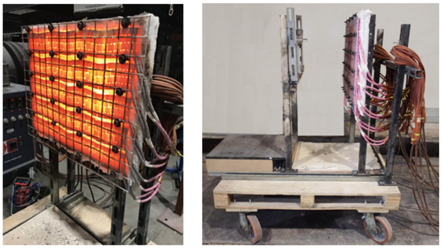


Fig. 2. Heat source.

For distances between the specimen and the heating pads no larger than 300 mm, the view factor can be considered 1. The incident radiant heat flux was determined experimentally, and for the distance of 300mm between the heating pads and timber sample, it was homogeneously distributed over the exposed surface. Therefore, this distance was considered for all tests. In these conditions, for a temperature of the heating pads of 900 °C, the flux received by the specimen was 25 kW/m^2.

To expose the test specimen to a constant heat flux from the beginning and to avoid an excessively long heating phase, a heat barrier was placed between the specimen and the heating pads (a fire-resistant gypsum board). Once the target temperature was reached and maintained, the heat barrier was removed.

The temperatures inside the timber samples were measured using thermocouples (TC), into previously drilled holes. Two directions were tested:

- holes parallel to the grain of the timber sample, parallel to the heat flux (Fig. 3a);
- holes perpendicular to the grain of the timber sample, perpendicular to the heat flux (Fig. 3b).

The holes parallel to the heat flux are more difficult to execute. Due to the geometry of the sample, these holes must go much deeper in the sample, and given that their diameter is 3 mm, the accuracy may be compromised. Before drilling holes in the test sample, some test drills were conducted to determine how accurately the holes could be executed. After drilling five holes at a spacing of 10 mm, with the timber sample properly secured in the drill machine, the timber sample was cut perpendicular to the holes, into 20 mm thick pieces. The maximum measured deviation of the holes was less than 1 mm.

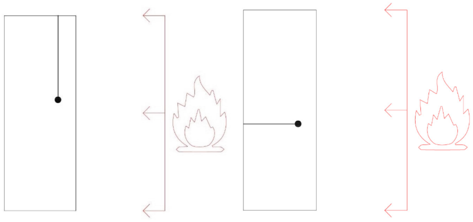


Fig. 3. Direction of thermocouple holes.

Some preliminary tests emphasized that the TC's fixed in drill holes executed parallel to the heat flux recorded higher temperatures than the ones fixed in drill holes executed perpendicular to the heat flux (Fig. 4). Therefore, for all further tests, the TC's were placed considering holes executed parallel to the heat flux. This is in agreement with literature and guidance documents [7, 8], which recommend installing thermocouples parallel to isotherms, to limit the temperature measurement errors in low conductive materials, such as wood.

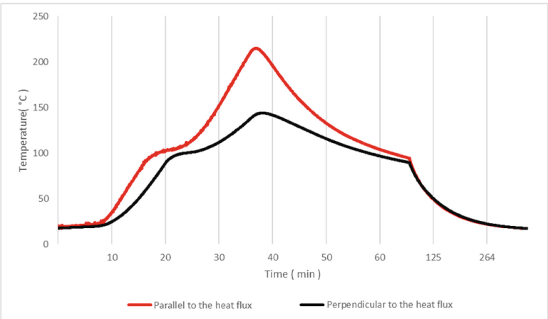


Fig. 4. Comparison between the temperatures recorded in holes parallel and perpendicular to the heat flux.

Two types of TC's were considered: type K sheathed and type K wire unsheathed. The two types demonstrated a very close thermal response, the observed difference being that sheathed wire TC's are more prone to noise during measurements. It must be mentioned that [8] also concluded that the use of sheathed TC's cannot be recommended for absolute temperature measurements within low conductive materials such as timber.

3 Numerical Simulations

A thermal analysis of the tested specimens was conducted using SAFIR software [5]. The net heat flux absorbed by the specimen at the exposed surface Q_{net}, considering the convective and radiative losses is calculated according to Eq. (1):

$$Q_{net} = \alpha \cdot Q_{int} - \alpha_c \cdot (T_S - T_G) - \sigma \cdot \varepsilon \cdot \left(T_S^4 - T_G^4\right) \tag{1}$$

in which:

- α is the absorptivity of the timber equal to 0.8;
- Q_{int} is the incident heat flux;
- α_c is the coefficient of heat transfer by convection;
- T_S is the surface temperature;
- T_G is the gas temperature;
- σ is the Stefan–Boltzmann constant equal to 5.67E−08 $W/m^2 \cdot K$;
- ε is the surface emissivity of the member equal to 0.8.

The value of the incident radiant heat flux Q_{int} was determined experimentally. In the numerical model, the surface temperature was automatically computed in the software) and the gas temperature T_G is equal to 20 °C.

In a first step, both EN 1995-1-2:2004 [1] and prEN1995-1-2:2025 [2] material thermal properties were considered in SAFIR. There are no differences between the two versions of the Eurocode for the values of thermal conductivity and specific heat. For the density ratio, the revised version [2] offers values which are no longer dependent on the moisture content until 99 °C. The values of the density ratio were calibrated with an initial moisture content for service class 2.

To illustrate the difference between the two versions of the Eurocode, Fig. 5 depicts a comparison of the evolution of density ratios, assuming a moisture content of 20%. The revised version [2] leads to a more pronounced decline in the density ratio, starting with the temperature of 121 °C, compared to the current version [1].

For the numerical thermal analysis, the following parameters were defined:

- coefficient of heat transfer by convection for the standard fire curve on the heated surface $\alpha_c = 25$ W/m^2K;
- coefficient of heat transfer by convection on the unheated surface $\alpha_c = 4$ W/m^2K;
- surface emissivity of the member $\varepsilon = 0.8$.

Figure 6 shows the comparison between the experimental and numerical results, at the level of the TC's placed at 30mm depth from the exposed side, for 30 and 60 min of exposure. It may be observed that prEN1995-1-2:2025 [2] thermal properties lead to a slightly better evolution of the temperature – time curves, with a maximum temperature discrepancy of about 20% for 30 min of exposure. For further numerical simulations, the revised thermal properties of prEN1995-1-2 were considered.

Compartment fires occur within enclosed spaces where ventilation is limited. In the present study, the experimental samples are exposed to unrestricted air supply from all sides, allowing for efficient combustion and ventilation. Therefore, the coefficients of heat transfer by convection on both exposed and unexposed sides should be modified accordingly.

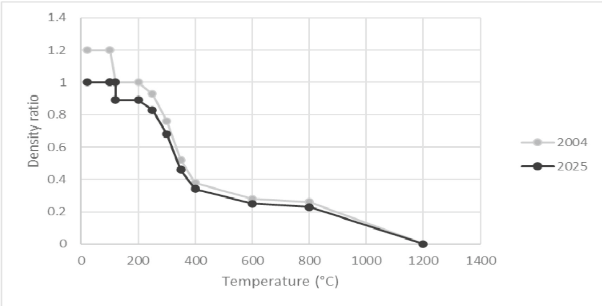
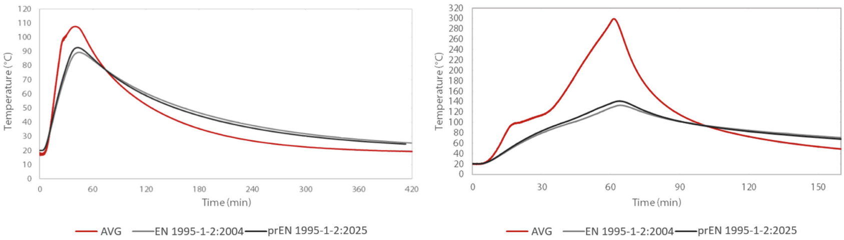


Fig. 5. Comparison of density ratio as a function of temperature for timber with an initial moisture $\omega = 20\%$.



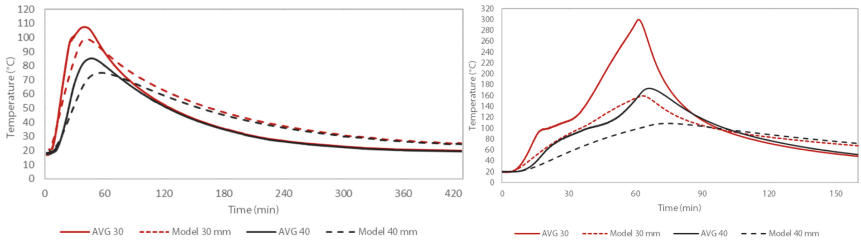
a) b)

Fig. 6. Evolution of temperature after a) 30 min and b) 60 min of exposure.

To account for exposure conditions closer to reality, the coefficient of heat transfer by convection on the exposed surface was modified to 10 W/m^2K. The coefficient of heat transfer by convection on the unheated surface, initially set at 4 W/m^2K to account for natural convection, has been adjusted to 25 W/m^2K, to simulate forced convection.

Figure 7 shows the comparison of the evolution of the temperatures between the experimental and numerical results, at the level of the thermocouples placed at 30 mm and 40 mm depth from the exposed side, for 30 and 60 min of exposure, considering the above modifications. It may be observed that the numerical models incorporating the modifications exhibit a slightly faster cooling rate after reaching the peak temperatures, which are closer to the experimental values.

Thermal camera observations (Fig. 8) revealed that the gas temperature T_G in front of the exposed surface exceeds up to a maximum of 250 °C the temperature considered for the heat exchange with the ambient air in the numerical models (20 °C). A new function representing the ambient air in the vicinity of the exposed surface was then considered in SAFIR, derived from measurements obtained through the thermal camera. On the unexposed surface, the temperature function remains at the ambient air temperature of 20 °C.



a) b)

Fig. 7. Evolution of temperature with modified coefficients of heat transfer by convection after a) 30 min and b) 60 min of exposure.

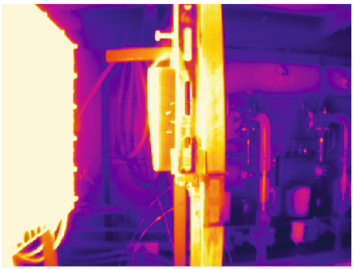
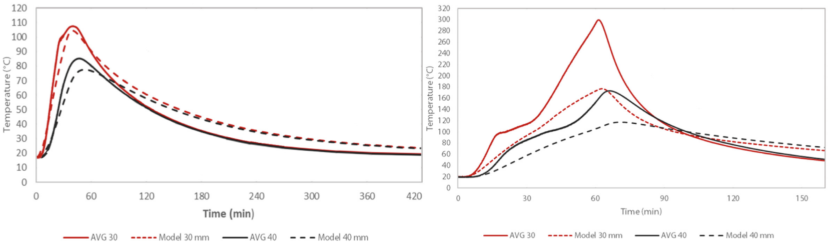


Fig. 8. Side view of the sample during captured by the thermal camera.

As Fig. 9a demonstrates, for 30 min of exposure, a better fit between the numerical and experimental peak temperatures is obtained by incorporating the new function for ambient air. A better fit is also obtained for the cooling rate, for a period of about 30 min after reaching the maximum temperature. Afterwards, the temperatures decrease at a slower rate in the numerical simulations, which means that the numerical model offers conservative temperature values for the cooling phase.

For 60 min of exposure (Fig. 9b), the temperatures obtained from the tests are still significantly higher than those of the numerical models. The numerical simulations fail to reproduce in a satisfactory manner the experimental temperature evolution for exposures longer than 30 min.



a) b)

Fig. 9. Evolution of temperature with modified coefficients of heat transfer by convection and revised gas temperature after a) 30 min and b) 60 min of exposure.

4 Conclusions

Timber is a heterogeneous material and during a fire exposure its thermal properties vary across the cross-section, being strongly affected by the charring rate. In the numerical analysis, if the initial geometry is assumed throughout the entire duration of fire exposure, the time-dependent changes in the effective thermal properties of wood, provided by EN1995-1-2, can be considered for standard fire exposure.

The exploratory research indicates that it may be possible to consider these effective thermal properties also for natural fires, with satisfactory results in case of short exposure times, up to 30 min, if the parameters linked to the real exposure conditions are properly considered.

The results are encouraging for starting an extended experimental and numerical study, to propose modified effective thermal properties for wood, adapted to different natural fire exposure conditions.

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