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METHODS FOR DETERMINING THE CHARRING RATE OF TIMBER AND THEIR MUTUAL COMPARISON

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ABSTRACT

There are simplified and advanced design methods for the determination of the mechanical resistance of timber structures in fire. The simplified methods have some limitations and in case it is not possible to use the simplified methods, it is necessary to use the advanced ones. These advanced design methods can be analytical or numerical. This contribution deals with the determination of the one-dimensional charring rate depending on time by advanced calculations, focusing on the influence of different input parameters, with the results of an experiment being presented for comparison. The aim of this paper is to show that despite the suitability and conservativeness of the method according to Eurocode 5, there are various cases (different moisture, wood species etc.) when it is necessary to perform numerical or analytical analyses without the possibility to apply standard input parameters. Therefore, this contribution compares individual methods for finding of the most appropriate one.

KEYWORDS: Fire, timber, advanced modelling, charring rate.

INTRODUCTION

In the structural fire design of timber structures, it is crucial to correctly identify the residual cross-section capable of carrying the load after a period of fire exposure. It is relevant to calculate the charring depth to determine this cross-section (Werther 2016) and it is related to the charring rate. The standard contains the simplified and advanced calculation methods. In the simplified methods, a constant value for the charring rate is assumed. However, the simplified methods have some limitations. The reduced properties method can be used for rectangular cross-sections of softwood exposed to fire on three or four sides and for round cross-sections exposed along their whole perimeter (STN EN 1995-1-2, 2008). Although the reduced cross-section method does not have these limitations, it is not possible to use it for every case in building practice. The advanced methods can be used for various cases which are not included in the standard, e.g. for consideration of various wood defects or moisture, for connections, CLT members, and so on. A software based on FEM is used for the advanced calculation methods, where the thermal properties are specified depending on the temperature. The charring rate is slightly slowing down after a certain time in these calculations. It is caused by a formation of charring layer and pyrolysis which act like a thermal insulation. This is then considered through the change of thermal properties in higher temperatures. In addition to the numerical calculations, there are various analytical calculation methods which are described in works such as (Mikkola 1991) or (Hietaniemi 2005). The determination of charring rate with consideration of various factors (various emissivity, density, moisture, heat flux, etc.) is mentioned in these publications. The results obtained from the calculations according to the above mentioned publications vary considerably. Alternatively, experiments can be conducted to obtain the most accurate data.

MATERIAL AND METHODS

The charring rate can be calculated by different methods. It is possible to determine the charring rate based on the charring depth for models in FEM-based software or for experiments. The char-line is defined as the position of isotherm of a specific temperature and can reach different values according to various publications – from 260 to 350°C (Erchinger 2009). The most commonly considered is the 300-degree isotherm which is also in accordance with the standard (STN EN 1995-1-2, 2008).

Experiment

The experiment on a timber-concrete beam was conducted in the testing premises of PAVUS in cooperation with the Czech Technical University in Prague, the Czech Academy of Sciences and Designtec ltd. (Caldová et al. 2014). The beam was made of the timber with strength class GL24h and steel fibre reinforced concrete of the concrete class C45/55. The density of the timber was determined at the value of 512 kg·m^{-3}. The moisture was measured in six locations in the beam with a resistive moisture meter in accordance with (STN EN 13183-1, 2003) and it was determined at the value of 12 %. The concrete was reinforced with steel fibres HE 75/50 Arcelor, its content amounting to 70 kg·m^{-3}. Screws Eurotec with diameter 7.3 mm and length 150 mm were used. They were placed in two rows, inclined by 45 degrees with spacing of 100 mm in the longitudinal direction and 40 mm in the transverse direction. The total length of the beam was 4.7 m. The horizontal furnace has an internal floor plan of 4 m (length) x 3 m (width). The furnace is heated by eight diesel burners, 4 on each of the longer sides of the furnace. The temperature inside the furnace is controlled by plate thermocouples. The aim is to follow the standard temperature curve (ISO 834) (STN EN 1991-1-2, 2007). Thermocouples of type K were used inside of the tested beam. The position of the thermocouples in transverse direction is illustrated in the Fig. 1 (with numbers 23, 24, 43, 44, 45). They were placed on the edge of beam in longitudinal direction. The composite beam was exposed to standard fire ISO 834 on three sides. The beam was exerted on a four-point bending test (Caldová et al. 2014). The experiment was terminated in the 22nd minute of the standard fire due to the failure of the beam.

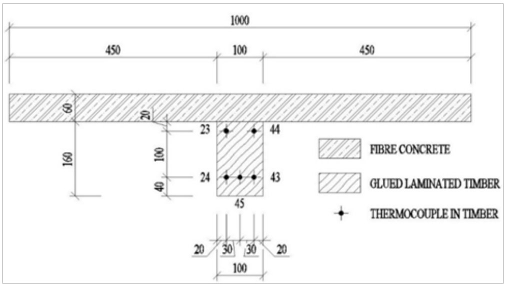

Fig. 1: The position of the thermocouples in the cross-section of the timber-concrete beam.

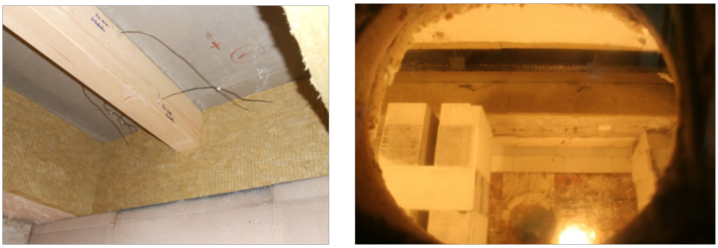

Fig. 2a, 2b: Photos of the tested beam before the experiment (left) and during the experiment (right).

Thermal properties of timber

The influence of moisture is taken into account only in case of the density in the standard (STN EN 1995-1-2, 2008), but the influence can be taken into account in case of the specific heat capacity according to several authors, e.g. in (Cachim and Franssen 2010, Hietaniemi and Mikkola 2010) and the thermal conductivity according to some authors, e.g. in (Hietaniemi and Mikkola 2010). These authors claim that the lower value of the moisture causes lower values of the specific heat capacity and the thermal conductivity until the time of the vaporisation of water (Fig. 3).

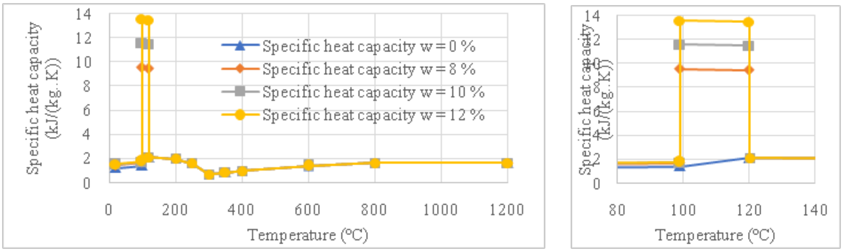

Fig. 3: The influence of the moisture on the specific heat capacity (Hietaniemi and Mikkola 2010).

Modelling of the timber-concrete beam in FE-program

The software Ansys Workbench was used for this study. The numerical model was created based on the above mentioned experiment on the timber-concrete composite beam. The thermal properties of the timber were taken according to (STN EN 1995-1-2, 2008) and those of concrete according to (STN EN 1992-1-2, 2007). The densities and moistures were specified according to (Caldová et al. 2014). The thermal conductivity was consistent with the values from the standard, and the specific heat capacity was modified (what is in accordance with the standard STN EN 1995-1-2, 2008, annex B). The temperatures in the 20th minute were compared in specified points where the thermocouples were placed in the experiment. The criterion to stop the optimization process was reaching the deviation of less than 20°C (less than 15 %). The maximum deviation of the results reached ±13 % (Fig. 4).

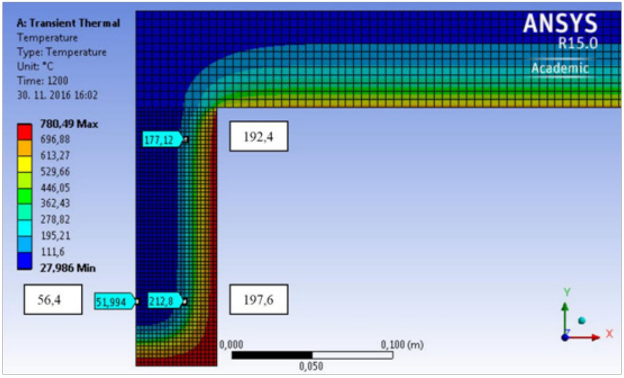

Fig. 4: The distribution of temperatures within the examined half of the cross-section in the software Ansys Workbench in comparison with the experiment.

Analytical models

Charring rate calculation according to (Mikkola 1991)

It is stated in the publications Mikkola (1991) that more than 50 experiments were conducted to establish the influence of the moisture and density on the charring rate of timber. The equations and boundary conditions for the calculation of the charring rate were derived from the results.

The charring rate is calculated according to (Mikkola 1991) as:

$$\beta = (q_e - q_L)/(\rho \cdot \{c_O \cdot (T_p - T_0) + L_v + [(c_w - c_{O.1}) \cdot (T_v - T_0) + L_{v.w}] \cdot w\}) \tag{1}$$

where: q_e - the net heat flux to unit surface (it is referred to ashnet according to (STN EN 1991-1-2, 2007)) and it is composed of the radiation and the convection component (W·m^{-2}),
q_L - the heat losses on the char surface (W·m^{-2}),
ρ - the wood density (512 kg·m^{-3}),
c_O - the specific heat capacity of wood for temperature between T_0 and T_p (J/(kg.K)),
c_w - the specific heat capacity of water vaporisation (J/(kg.K)),
$c_{O.1}$ - the specific heat capacity expressed as the average of specific heat capacities for the temperature of 20°C and 99°C (J/(kg.K)),
T_p - the average pyrolysis layer temperature (360°C),
T_0 - the initial temperature (20°C),
T_v - the temperature of water vaporisation (100°C),
L_v - the heat of vaporisationof dry wood (2250 J·kg^{-1}),
$L_{v,w}$ - the heat of vaporisationof water (2260 J·kg^{-1}),
w - the wood moisture content (12%).

Charring rate calculation according to (Hietaniemi 2005)

The following equation was created to calculate the charring rate depending on the time of fire exposure according to (Hietaniemi 2005):

$$\beta = f(\chi_{O2}, t) \cdot (C.q_{std}(t)^{p}) \,/\, ((\rho + \rho_0) \,.\, (A + B \,.\, w)).\exp(-t/\tau) \qquad (2)$$

where: $f(\chi_{O2},t)$ – the factor depending on the oxygen concentration (-),
C – the parameter obtained from the constant heat flux (3.93 $kW \cdot m^{-2}$),
$q_{std}(t)$ – the heat flux ($kW \cdot m^{-2}$),
p – the parameter (0.5),
ρ – the wood density(512 $kg \cdot m^{-3}$),
ρ_0 – the density of dry wood (457 $kg \cdot m^{-3}$),
A – the parameter (800 $kJ \cdot kg^{-1}$),
B – the parameter (2490 $kJ \cdot kg^{-1}$),
w – the wood moisture content (12%),
t – the time of fire exposure (min),
τ – the time constant (100 min).

The input parameters to calculate the particular charring rate in time are in brackets. Individual parameters entering the calculation of (2) are described in detail in the publication (Hietaniemi 2005).

RESULTS AND DISCUSSION

The resulting values of the charring rate at the time of fire exposure (Fig. 5) were obtained from the above-mentioned calculation methods and the experiment.

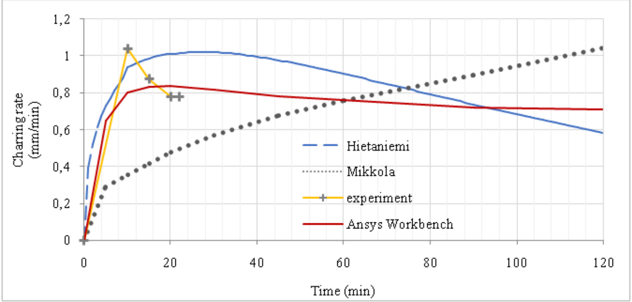

Fig. 5: Charring rates depending on the time of fire exposure according to various calculation methods.

The slope of curve of the charring rate in the first five minutes is comparable for every method, later the course of this curve differs significantly. The charring rate should increase only until a specific time according to Erchinger (2009), and then start to decrease, followed by the formation of the pyrolysis layer which acts as a thermal insulation. The charring rates according to the experiment, model from the software Ansys Workbench and the calculation according to (Hietaniemi 2005) correspond with that. The calculation according to Hietaniemi (2005) is affected mainly by the heat flux and the oxygen concentration which change in the first 10 to 20 minutes. For that reason, the charring rate increases until the 30th minute in this analysed case, and the charring rate subsequently starts to slow down. This calculation has the highest formation of the charring rate in initial minutes, but it has lower values compared to the other methods after the 90th minute. The calculation according to Mikkola (1991) does not take into account the formation of the char layer in time, because this calculation is most influenced by the increasing gas temperature during fire. This calculation is also influenced by various parameters. However, there are not any implemented parameters which would change depending whether the fire develops in the first minutes, or later. Therefore, such parameters should be implemented in the analytical calculations, otherwise this calculation is not usable in the first minutes of fire. This method according to Mikkola (1991) is not suitable for the calculation of the charring rate in any time of fire exposure. It is usable approximately in time from 45th to 90th minute. It is necessary to implement certain parameters to capture the real distribution of the charring rate in time, i.e. when the charring rate is increased by these parameters in the first minutes and decreased in later. The charring rate in the experiment reached the highest value in the 10th minute, but it subsequently decreased significantly.

It was not possible to gain results for longer duration of fire due to the failure of the beam in the 22nd minute. However, this experiment was used as a pattern of real case of timber-concrete composite beam with real values of moisture and density which were used as input data for other analyses. The model of timber-concrete composite beam was created in the Ansys Workbench software on the base of this experiment, where the half of the cross-section was analysed. It was not possible to use only this model for the purpose of comparison with other methods due to dimensions of the timber cross-section. Therefore, the second model of the timber cross-section was created with the same thermal properties and with the same thermal load, but with bigger dimensions to monitor the charring rate until the 120th minute. The charring rate was the same for both models in the first 45 minutes, but then it became influenced by the temperature from the bottom of the beam, in addition to the considerable influence of the corner rounding, and the temperatures then reached values which imply the destruction of the char layer. The charring rate in the second model continuously decreased until the 120th minute. For that reason, the Fig. 5 shows only the results only from this model. The comparison of the resulting charring rates of individual methods is in Tab. 1.

Tab. 1: Comparison of results for individual methods in 10th, 15th a 20th minute, where the percentage differences compared to results according to Experiment are in brackets (β / β (Experiment)).

		Hietaniemi	Mikkola	Experiment	Ansys Workbench
Charring rate β ($mm \cdot min^{-1}$)	10 min	0.940 (89 %)	0.355 (34 %)	1.04 (100 %)	0.800 (77 %)
	15 min	0.986 (112 %)	0.419 (47 %)	0.873 (100 %)	0.833 (95 %)
	20 min	1.008 (128 %)	0.476 (60 %)	0.779 (100 %)	0.838 (108 %)

The results of the numerical analysis indicate that until the 20th minute, the charring rate can be considered as increasing, whilst after this time it starts to decrease. This correspond with the statement that the formation of the pyrolysis layer acts as a thermal insulation. It is possible to solve many cases in a real timber structure by selecting the correct parameters into the numerical analysis. However, the modelling of the mechanical and thermo-mechanical behaviour of timber structures cannot be solved lightly, because there are many uncertain variables. It is usually possible to change only the thermal properties, such as the specific heat capacity, the thermal conductivity, the density depending on the temperature, or the surface emissivity in the numerical methods, but the other parameters (the heat of vaporisation of dry wood, the surface temperature, the moisture etc.) which can decisively influence the charring rate can only be determined by the analytical calculations. For the analytical methods, it is significant to use time depending parameters, with which the charring rate will be increased in the first minutes and decreased later on.

CONCLUSIONS

It is possible to use various calculation methods to determine the charring rate and subsequently the residual cross-section. The charring rate according to the simplified calculation procedures is determined as a constant value during the whole time of fire exposure and, consequently, the use of this method is relatively fast and easy, but it has some limitations. The reduced properties method can be used for rectangular cross-sections of softwood exposed to fire on three or four sides and for round cross-sections exposed along their whole perimeter (STN EN 1995-1-2, 2008). Although the reduced cross-section method does not have these limitations, it is not possible to use it for every case in building practice. These simplified methods are usable only for timber with 12% moisture, considering the normalised fire scenario with curve ISO 834 and it is possible to use only some fire protection materials for protected surfaces. The advanced calculations have an advantage of less limitations. Therefore, it is possible to solve, for example, the issues of CLT members, various connections, various moisture content, various fire scenarios, fissures, or other wood defects. The disadvantages of the advanced calculations are the demands on the computing program and the uncertain input parameters, since various authors present different attitudes to this issue. It is possible to change the temperature load in time for both the numerical and analytical calculations. The experimental measurements also have certain advantages and disadvantages. It is possible to use them to simulate any case in the structure with various thermal conditions, but the results can be influenced by several factors (for example the measurement of temperatures can be influenced by heat transfer by thermocouple, by space between the thermocouple and timber etc.). The simplified methods according to (STN EN 1995-1-2, 2008) are the best methods to use in common civil practice in common cases. It is suitable to use e.g. modelling in FE-programme for other (above mentioned) cases, where it is possible to consider the influence of moisture by the changing of thermal properties. In case of analytical methods (e.g. according to (Hietaniemi 2005, Mikkola 1990), or some other publications), it is necessary to implement time depending parameters.

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