

CHARRING LAYER ON A CROSS-LAMINATED TIMBER PANEL CONSTRUCTION

Katarína Dúbravská–Dominik Špilák - Ľudmila Tereňová – Jaroslava Štefková

ABSTRACT

When the wood is thermally loaded, the microscopic changes of wood structure and macroscopic changes appear and are examined. The macroscopic changes include formation of char layer on the surface of the wood-based material. The main aim of the medium-scale test is to assess the char layer formation on the surface of the sample under thermal loading. The test sample was made of CLT (cross-laminated timber) panel with no surface treatment with the dimensions of $1000 \times 1500 \times 80$ mm. It was a 3-layer panel made of spruce lamellas. The test sample underwent a medium-scale test during which it was exposed to a radiation panel for 40 minutes. Intensity of the radiation panel was $43.1 \text{ kW} \cdot \text{m}^{-2}$. During the test, the temperature on the exposed side of the test sample was recorded by a thermocouple. The test sample immediately began to degrade and char. After complete charring of the CLT panel layer on the exposed side, its rupture and consequent falling off appeared. The middle layer of the CLT panel was minimal, only in the area where the outer layer fell off. The results of the medium-scale test were compared to the results of the simulation which were achieved from the Ansys 18.1 program. When the medium-scale test and simulation results were compared, some differences were found. The main difference was found when the char layer fell off from the CLT panel and further charring into the depth of the sample followed in the medium-scale test.

Keywords: cross-laminated timber panel, char layer, medium-scale test, Ansys 18.1 program simulation.

INTRODUCTION

Cross-laminated timber panel (CLT panel) is considered a large-area material. As stated by ÖSTMAN *et al.* (2018), this material is classified into D-s2,d0 or D_{fl}-s1 reaction to fire class depending on thickness and density. It is then a combustible material which burns on the surface, releases heat and as so it develops fire and forms smoke according to FRANGI *et al.* (2009). They also state that CLT panel performance under a thermal load is characterized by fire performance of the individual layers. The significant changes can be observed on its surface by KUČEROVÁ *et al.* (2009). By OSVALD (2015), a significant macroscopic change, which can be observed, is formation of a char layer which is formed on the surface during a thermal load of the wood by OSVALD (2011), LEŠKO and LOPUŠNIAK (2015), KUKLÍK (2005). This process (KAČÍKOVÁ *et al.* 2006) starts temperatures higher than 250°C. The char layer form cracked black layer, which has worse thermal conductivity and

slows down the transfer of heat into deeper layers (PAULDURO and KAČÍKOVÁ 2014). The fact that the char layer functions as an insulation layer and slows down degradation of the remaining cross-section material is also stated by FONSECA and BARREIRA (2009).

As stated by ÖSTMAN *et al.* (2018), charring of the CLT panel can be different from the charring of the homogenous wood panel due to the method of gluing the individual layers together and due to bonding between the wood layers (local increased charring). The charring of the CLT panel is not influenced by orientation of the layers, in particular parallelly or perpendicularly to the whole panel orientation (FRAGIACOMO *et al.* 2013).

When a CLT panel is thermally loaded, two situations can appear (FRANGI *et al.* 2008):

- Char layer does not disaffiliate. If the exposed layer of the CLT panel is charred in the whole depth and remains at the place, it works as heat insulation of the remaining layers of the CLT panel.
- Char layer disaffiliates. If the char layer of the exposed side of the CLT panel disaffiliates, it does not protect the remaining layers against the effects of the fire and charring of the internal layers takes place. The process of charring progresses faster as a result of a higher temperature of the flame. This process is similar to increased charring which can be observed at the protected wood surfaces after disaffiliation of fire cladding.

The effect of the kind of adhesive bonding the individual layers of a CLT panel was dealt by MENIS (2012), FRIQUIN *et al.* (2010), KLIPPEL *et al.* (2014). If the individual layers of CLT panel are bonded by PUR adhesive, the falling off of the char layer occurs rather often. This was also observed by KLIPPEL *et al.* (2014) and MENIS (2012).

Disaffiliation of the char layer (FRANGI *et al.* 2009) is influenced by the position of the panel (vertical or horizontal), thickness of individual layers, and adhesive performance at elevated temperatures.

The aim of the paper is evaluation of the CLT panel under thermal load and evaluation of the char layer formed at the construction made of CLT panel. At the same time, the results achieved by the medium-scale test shall be compared to the results of the Ansys 18.1 program simulation.

EXPERIMENTAL

Methodology of a medium-scale test

The test sample was made of cross-laminated timber with no surface finish. It was a three-layer panel whose individual layers were made of spruce wood with the moisture content up to 12% ($\pm 2\%$). The panel's dimensions were $1000 \times 1500 \times 80$ mm. The thickness of outer layers was 20 mm and the middle layer was 40 mm thick. The weight was defined as $5,0 \text{ kN}\cdot\text{m}^{-3}$ according to DIN 1055-1:2002 for static calculations. The density of the sample was approximately $470 \text{ kg}\cdot\text{m}^{-3}$. The manufacturer states the material is classified as D-s2,d0 class of Reaction to fire by the Decision of the European Commission 2003/43/ES.

The sample was loaded by a radiation panel for 40 minutes. The sample was placed in distance of 200 mm from the radiation panel. This distance equals the radiation intensity of $43,11 \text{ kW}\cdot\text{m}^{-2}$ for the radiation panel in the size of 480×280 mm. The energy supply for the ceramic radiation panel was propane -butane gas of a constant flow.

The macroscopic change, particularly, formation of the char layer on the surface, was observed during the medium-scale test.

Methodology of the simulation

To observe the CLT panel behaviour under thermal load, the finite element computational

method of Ansys 18.1 was used. The simulation was set for the change of material properties according to STN EN 1995-1-5 (2008), while different properties of wood along the fibre and across the fibre were taken into the consideration. The mechanical loading consisted of only the own weight of the panel. Thermal loading consisted of two sources – the radiation heat whose source was the radiation panel and a flame which appeared after the ignition temperature was reached of the spruce wood. The output of the radiation panel was set for $43.1 \text{ kW}\cdot\text{m}^{-2}$. Due to the fact the room was closed, only the natural air flow caused by the different temperature of heated gases and the surroundings appeared. The heat transfer between the wooden beam and the air changed depending on the temperature. The aim of the computer simulation was to simulate the conditions of medium-scale test and compare the results gained from test with the results of the computational simulation.

Geometry and discretization

The simulation consisted of the dynamic thermal analysis using Ansys 18:1 program. During the simulation, the following element types available in the program – SOLID90, SURF152, TARGET170, CONTA174 were used. SOLID90 and SURF152 are thermal elements serving for simulation of heat transfer, where SOLID90 is a 10-node thermal element simulating heat transfer into the depth of the material, while SURF152 is a four-node thermal element simulating conduction, convection and radiation on the surface (ANSYS Inc 2013). The nodes of SURF152 must share the nodes of the underlying solid element i.e SOLID90. TARGET170 and CONTA174 are elements simulating heat transfer between individual layers of CLT panel (between wood and PUR adhesive) (ANSYS Inc 2013).

The beam model was projected by Ansys 18.1 program via the tetrahedron pattern network enabling higher number of elements maintaining the same number of nodes. To save computational efforts and bigger refinement of the final network of finite elements, the function of symmetry split in the program and the symmetrical shape of the panel was used to divide the CLT panel vertically in half as well as the radiation panel force in half. The total number of nodes was 555,839 and the total number of elements was 618,482 (Fig. 1). The given number of nodes and elements provides a very fine network and higher accuracy of the simulation results.

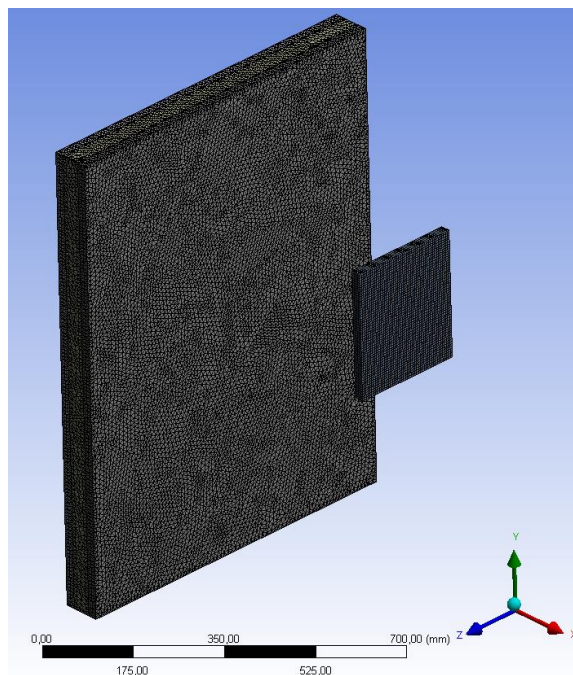


Fig. 1 The network of finite elements.

RESULTS AND DISCUSSION

CLT panel behavior in medium-scale tests

The test sample surface started to thermally degrade right from the start of the test. By ZACHAR *et al.* (2017), the combustion process and typical behavior of materials during thermal degradation is determined by initiation energy which is necessary for the material to ignite. The thermal degradation was accompanied by the color change of the surface and by production of the smoke. The surface area gradually grew (Fig. 2) and its color changed from brown to black. The flames on the surface appeared approximately in the 7th minute (Fig. 3). As stated by VAVRUŠKOVÁ and LOKAJ (2009), the wooden objects exposed to fire and temperature of about 300°C flame up on the surface and burn quite intensely at the beginning. The vigorous flame combustion lasted for about three minutes, then its intensity decreased gradually. In the 12th minute, it showed as a non-flaming combustion. As stated by OSVALD and GAFF (2017), combustion is typical in two phases for most combustible materials - the first stage typical by flaming combustion of gaseous products and the second stage represented by non-flaming combustion of the residues of the materials rich in carbon.



Fig. 2 The test sample at the beginning of the medium-scale test.



Fig. 3 The test sample in the seventh minute.

When observing the macroscopic changes at progressing stages of thermal degradation of wood under elevated temperatures in longer time it is possible to observe only the formation of the char layer (OSVALD 2015).

As mentioned earlier (FRANGI *et al.* 2008), behavior of CLT panel in conditions of fire is characterized by the behavior of individual layers of the CLT panel. The process of

charring of the first layer of the CLT panel and the rate of charring is similar to the behavior of massive timber sample, taking in account the local increased charring at bonding of the layers. This fact is also confirmed by FRANGI *et al.* (2008), the depth of charring of the CLT panel is identical as for the homogenous timber until the first layer is completely charred. As MARTINKA *et al.* (2016) state, charred layer on the test sample surface slows down heating of non-degraded surface which results in decreasing the thermal degradation rate, gaseous products release rate, and heat release rate. The char layer works as an insulation layer. VAVRUŠKOVÁ and LOKAJ (2009), BLASS (1995) mention that thermal conductivity is approximately one sixth of the thermal conductivity of non-degraded wood. It also slows down the further thermal degradation of remaining wood.

As mentioned earlier, in case of charring of a complete layer on the loaded side, two situations can occur: the char layer protects the residual cross-section against heat or the char layer can fall off. During thermal loading of the sample, the second situation appeared. The charred layer fell off in 37th minute. In this time the outer layer of the CLT sample was completely charred in the whole thickness at some places. We suppose the fall-off of this layer was caused by two effects – the pressure between the layers of the CLT panel and structure of the char layer. Approximately after 23rd minute, the temperature between the inner layer of the CLT panel and the outer layer on the exposed side ranged over 100°C. In the temperature span between 20°C and 150°C dehydration of wood starts, according to KAČÍKOVEJ *et al.* (2011), when wood loses water starting with free water and ending with bound water. A part of this water is cumulated between the individual layers of a CLT panel, therefore the pressure is formed at the mentioned contact. At the same time, heating of the PUR adhesive film releases and cumulates volatile products.

Charring of the inner layer started after fall-off of the outer layer of the panel. Fig. 5 shows charring of the inner layer especially at the places where outer layer has fallen off. The authors KLIPPEL *et al.* (2014) state that charring rate of the next layer of a CLT panel is twice as fast.

ZOUFAL *et al.* (2009) define the depth of charring as the distance between the outer surface of the intact timber and the position of the charring line. At the place where the fall-off of the first layer appeared, the depth of charring was 28 mm (maximal value). At the places where the char insulation did not protect the remaining wood, the thermal degradation of the inner layer occurred.

Simulation results

Simulation result is illustration of charring ratio of CLT panel in 40 minute time span. Figure 6 shows a detail of the left half of the simulated panel without the char layer which has been removed. The color fields divide the CLT panel into the following layers: green color shows the char layer and border of charring, dark blue and dark green color depict the pyrolysis layer and light blue shows intact wood.

Maximal depth of the char layer in direction of the *x* axis in the area of radiation panel achieved 15 mm, on the upper edge of CLT panel it achieved 19 mm. The program determined the average depth only on the bases of the thermally loaded area of the CLT panel after 40 minutes of thermal loading. The value of the average depth of charring was 9 mm. Based on the data on charring depth, the conclusion that charring of wood appeared only on the exposed layer of the CLT panel was reached, i.e. the first layer of the CLT panel exposed to thermal loading charred. The maximal depth of the pyrolysis in the direction of the *x* axis achieved 35 mm, on the upper edge it achieved 41mm (Fig.7).

According to the computer simulation, the flames appeared in 9th minute (Fig.8), having achieved the ignition temperature of spruce wood. The flame spread by linear velocity across the surface until it reached the upper edge of the panel. Maximal measured

temperature on the surface on the exposed panel was 648°C. On the non-exposed side of the panel, the temperature did not increase.



Fig. 2 Char layer fall-off during the medium-scale test.



Fig. 3 Cross-section of the sample after the medium-scale test.

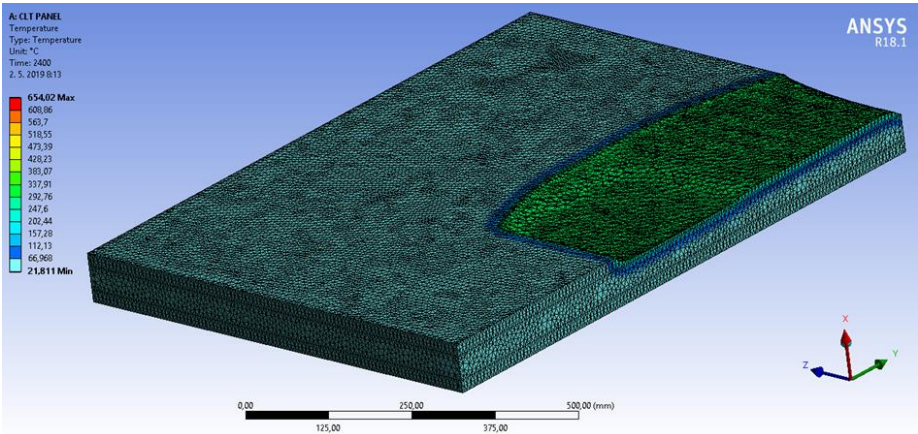


Fig. 4 Charring after 40 minutes.

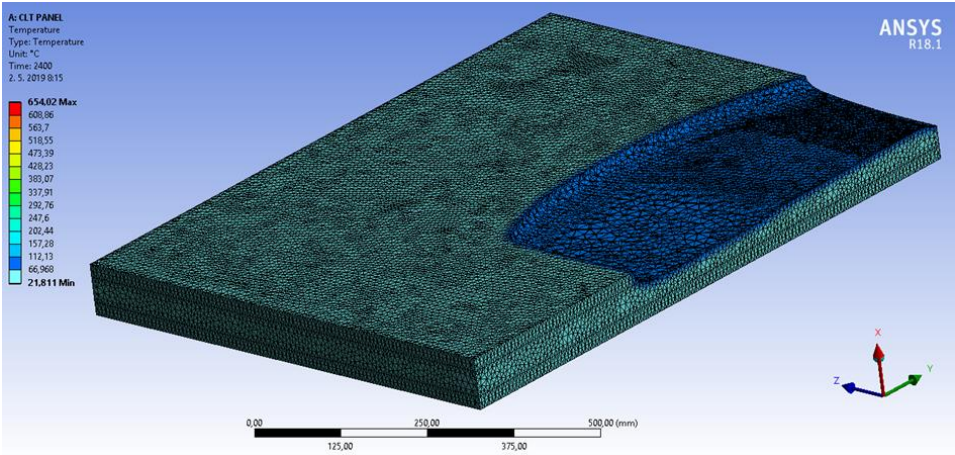


Fig. 5 Pyrolysis layer.

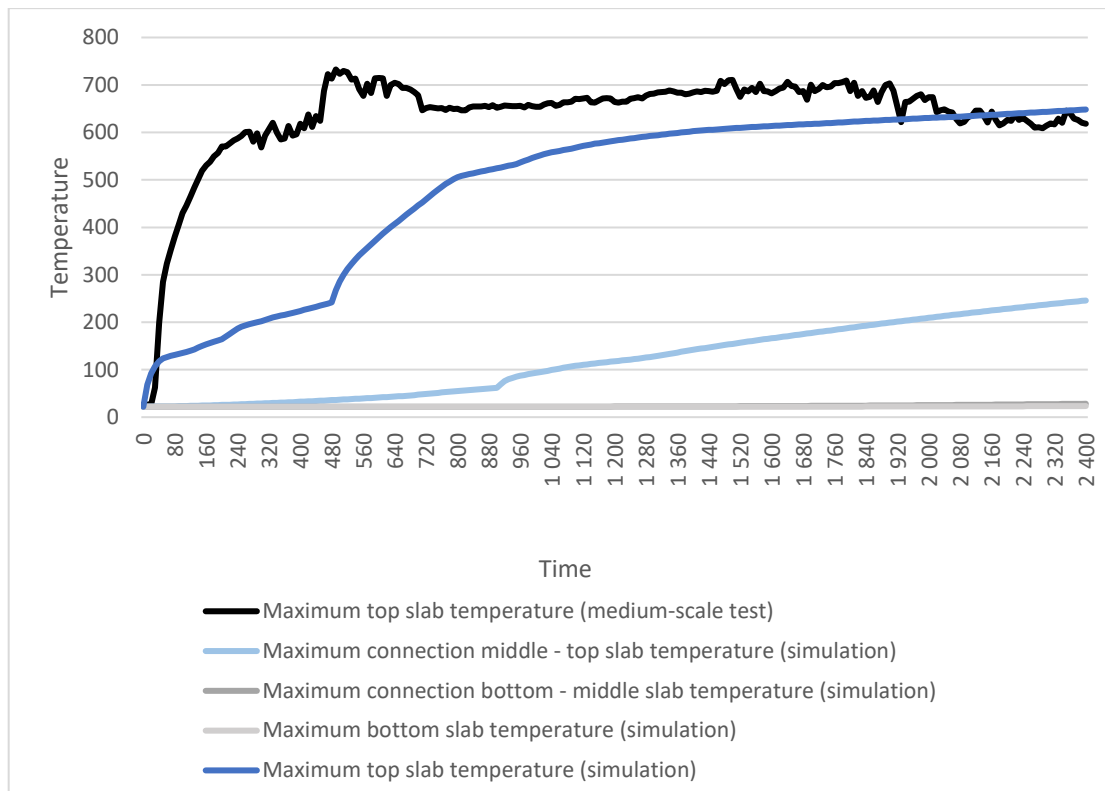


Fig. 6 Thermal load.

The area of non-degraded wood in the cross-section has a significant impact on the value of its fire resistance since the wood under thermal degradation loses its mechanical and thermal insulation properties.

Evaluation of the char layer and the charring rate was also dealt by MENIS (2012). This author points out the fact that if the individual layers of the CLT panel are glued by PUR adhesive when exposed to fire effects the fall-off the char layer does occur. This phenomenon was observed on the samples when there was used five different PUR adhesives. MENIS (2012) also explains that fall-off the char layer did not appear when the bond between two layers was provided by MUF adhesive.

CLT panel performance in fire was also investigated by FRANGI *et al.* (2009). A small horizontal furnace was used to perform a fire test. The test was conducted the samples where different adhesives were used. The charring rate for the sample with MUF adhesive was constant. After charring of the first layer of the CLT panel, it did not fall off and protected the remaining wood against elevated temperatures.

During the test samples with PUR adhesive, the charring rate was not constant. Once the first layer has charred, it fell off. This fact led towards an increase in charring rate compared with charring of a homogenous wooden panel. Three other test samples in thicknesses of 60 mm which had a 20 mm thick layer on the exposed side were evaluated. The 28 mm thick charring occurred at 41st minute, 42nd minute and 44th minute.

FRIQUIN *et al.* (2010) dealt with the charring rate and charring depth of a CLT panel. They investigated the dependence on the fire scenario which affected the samples. The CLT panel was exposed to thermal loading equaling to Standard curve, Parametric curve and a Swedish curve of fire. At the same time, the changes in charring depending on the fire stage were observed. The char depth and charring rate were interpreted graphically. The results regarding charring are as follows FRIQUIN *et al.* (2010):

- When the test samples were exposed to thermal loading corresponding to the parametric fire curve, 20 mm char depth in case of 120 mm thick test sample (the first layer thickness 19.5 mm) appeared in the 22nd minute. 20 mm charring depth in case of 240 mm thick test sample appeared in 29th minute.

- When the test samples were exposed to thermal loading corresponding to the standard fire curve, 20 mm char depth in case of 180 mm thick test sample (32 mm thickness of the first layer) appeared in approximately in 43rd minute. 20 mm charring depth in case of 240 mm thick test sample (31.5 mm thickness of the first layer) appeared in 45th minute.

- When the test samples were exposed to thermal loading corresponding to Swedish curve, 10 mm char depth in case of 240 mm thick test sample (29.5 mm thickness of the first layer) appeared in approximately in 20th minute.

The test samples exposed to thermal loading by a standard fire curve were tested for 150 minutes and longer. In that case, the charring depth of 28 mm appeared approximately in 48th minute on the 240 mm thick sample. In case of a parametric fire, charring was recorded approximately before 30th minute FRIQUIN *et al.* (2010): In case of Swedish fire curve, the recorded char depth appeared approximately before 20th minute FRIQUIN *et al.* (2010).

The fire performance of CLT panel was also dealt by KLIPPEL and FRANGI (2016). They summarised the other authors' results which focused on the influence of the adhesive on falling off the charred layer. There, CLT panel behavior in a fire was compared subjected to the use of PUR, MUF and PRF adhesive to glue individual layers. Based on the conducted research they came to the conclusion that in case of PUR adhesive use falling off the charred layer occurs in most tests. While, when MUF or PRF adhesive is used, the charred layer does not fall off.

CONSLUSIONS

On a CLT panel surface, a char layer is formed when it is thermally loaded in the same manner as on all wood-based materials. The process of charring depends on the fire behavior of individual layers of the CLT panel.

The results of the medium-scale test and the simulation by Ansys 18.1 program can be resumed into the following points:

- Maximal temperature on the exposed side of the panel in the medium-scale test was 711°C, maximal temperature on the exposed side of the panel in the simulation was 648°C.
- The flame on the surface of the sample appeared in 7th minute in the medium-scale test, the flame on the surface of the panel appeared in the 9th minute,
- In simulation, the formation of a char layer on the edge of the test sample was predicted. Due to the thermal degradation at this place, rounding appeared. In case of medium-sale test, there was no charring on the edge, so there was no rounding on the edge.
- In simulation, the charring of the first layer of the CLT panel was incomplete, therefore, it did not fall off. Even if the complete charring did appear, it is uncertain if the program would consider its falling off. The reason is that the kind of adhesive does not have such a significant impact in the simulation.
- In the medium-scale test, a complete charring of the first layer appeared. In the place where the charred mass fell off, the charring of the inner layer appeared.

As can be noticed, the simulation results and the medium-scale results are partially different. In case of the medium-scale test, the char layer was formed especially in the place radiation panel exposure. In simulation, the char layer was formed in the center (the place of radiation panel exposure) up to the edge of the test sample.

Ansys 18.1 program does not allow us to imitate the wood structure in detail including its defects. This fact might be the reason of different temperature development recorded on the exposed side. Meanwhile, in this type of simulation, it is not possible to imitate the fall-off of the char layer, which appeared in the medium-scale test. This phenomenon bears a significant impact. If the char layer does not fall off, it protects by insulation the remaining wood mass and thermal degradation progresses more slowly. If the char layer falls off, the charring of the inner layer occurs. The charring rate proceeds twice as fast at the beginning. The increased charring rate was also mentioned by FRANGI *et al.* 2008 as the consequence of pre-heating of the timber in the layer.

The differences in the results are caused by the temperature of charring. It is necessary to put in the temperature of charring in Ansys 18.1 program. The temperature of charring was determined as 300°C according to STN 1995-1-2 (2008). However, KAČÍKOVÁ *et al.* (2001) state that charring of wood can appear at as low as 250°C. In the medium-scale test, the temperature of charring lower than 300°C imposed the differences in the depth of charring. The simulation program generates the simulation according to the input temperature of charring. The standard states the temperature of charring as 300°C for wood, in general; however, the individual species might have different temperatures of charring, which was not considered by the program. The charring temperature by the wood species has been specified only if in particular studies and as so it is not included in the standard. The amendment of the standard for the temperature of charring by wood species would need to be considered as it would produce the more accurate results in further investigation.

The main contribution of the research is the finding that the results of medium-scale tests of wooden construction members and the results achieved by the computational simulation are different, yet only to a certain extent. Medium-scale testing is, therefore, more suitable to state real fire behavior parameters for construction members and computational simulation is suitable for designing and dimensioning construction members and for predicting the behavior under thermal loading.

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AUTHORS’ ADDRESSES

Ing. Katarína Dúbravská, PhD.
Ing. Dominik Špilák
Ing. Ľudmila Tereňová, PhD.
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Fire Protection
T. G. Masaryka 24
960 01 Zvolen
Slovakia
katarina.dubravska@tuzvo.sk
xspilakd@is.tuzvo.sk
ludmila.terenova@tuzvo.sk

Mgr. Jaroslava Štefková, PhD.
Technical University in Zvolen
Institute of Foreign Languages
960 01 Zvolen
Slovakia
jaroslava.stefkova@tuzvo.sk

