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INVESTIGATION OF CLT PANEL DEGRADATION DURING HEATING AND COOLING PHASES OF FIRE

VLADIMÍR MÓZER, LUKÁŠ VELEBIL, ANDREA SMETANOVÁ
CZECH TECHNICAL UNIVERSITY IN PRAGUE
CZECH REPUBLIC

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ABSTRACT

The research presented in this paper investigates the behavior of Cross-laminated timber (CLT) under fire exposure during the heating and cooling phases. A sample CLT panel was exposed to a 60 min heating phase as per the ISO 834 standard time-temperature curve, following which it was removed from the furnace and left to cool at ambient temperature. Due to char formation and availability of oxygen during the intended cooling phase, the intensity glowing combustion was growing and resulted in increasing temperatures and even flaming combustion in its latter stages. The char layer thickness doubled during the intended cooling phase under the experimental conditions. Temperature profiles measured parallel and perpendicular to isotherms indicated significant underestimations associated with the perpendicular orientation. The study highlights the need for consideration and further investigation of the cooling phase and its impact on structural design and fire investigation.

KEYWORDS: CLT, heating phase, cooling phase, temperature, charring.

INTRODUCTION

Cross-laminated (CLT) panels are widely used in construction and are most often found in mid-rise buildings (Jeong 2024). Apart from increased speed of construction, the use of CLT affords 40% reduction in greenhouse gas emissions, when compared to conventional construction materials, such as steel or concrete (Younis & Dodoo 2022). Despite these clear environmental advantages, CLT as a combustible material poses several challenges from the fire safety perspective, similar to other timber- and wood-based construction materials and elements. Specific fire dynamics are observed in compartment with exposed CLT surfaces, stemming from differences in boundary heat exchange, production of combustible gases and vapors by compartment boundaries etc., affecting temperature distribution, fire severity, duration, reignition etc. (Buchanan & Östman 2022; Gorska et al. 2021; Hopkin et al. 2024). A significant body of research is focused on fire behavior of CLT both on full (Brandon et al. 2021; Emberley et al. 2017; Hopkin et al. 2024; Kotsovinos et al. 2023) and reduced-scale (Dúbravská et al. 2019, 2020; Miyamoto et al. 2021; Wachter et al. 2018).

One of differences between mass timber and CLT is the behavior of the char layer. CLT is made of layers of lamellae glued together. As a number of studies indicate, these glue lines are more susceptible to high temperatures and char layer fall-off or delamination occur (Čolić et al. 2024; Johansson & Svenningssson 2018). The char fall-off or delamination causes loss of the protection (insulation) to the virgin or partially pyrolyzed timber. When this timber suddenly becomes exposed to fire and increases fire severity and the charring rate. This may lead to second flashover as Hopkin et al. (2024) found.

Given this behavior a specific approach is required for fire resistance design calculations. In Europe, Eurocodes provide design rules for different types of construction. Eurocode 5 (EC5) contains design rules for wood and timber construction elements. The first edition of EC5 (EN 1995-1-2, 2004) did not contain CLT design rules for fire conditions (Östman et al. 2018). The current (prEN) version of EC5 (prEN 1995-1-2, 2023) now contains the design rules for CLT, specifically accounting for the delamination of char layers, as well as other changes (Frangi et al. 2023). Nonetheless the standard design procedure focuses mainly on the heating phase of a fire, yet research indicates that the cooling phase also contributes to the reduction of the effective cross section, primarily through the zero-strength layer development and also by charring, however, to a lesser extent. In total the cooling phase may account up to 1/3 of the overall effective char depth (Lucherini et al. 2025).

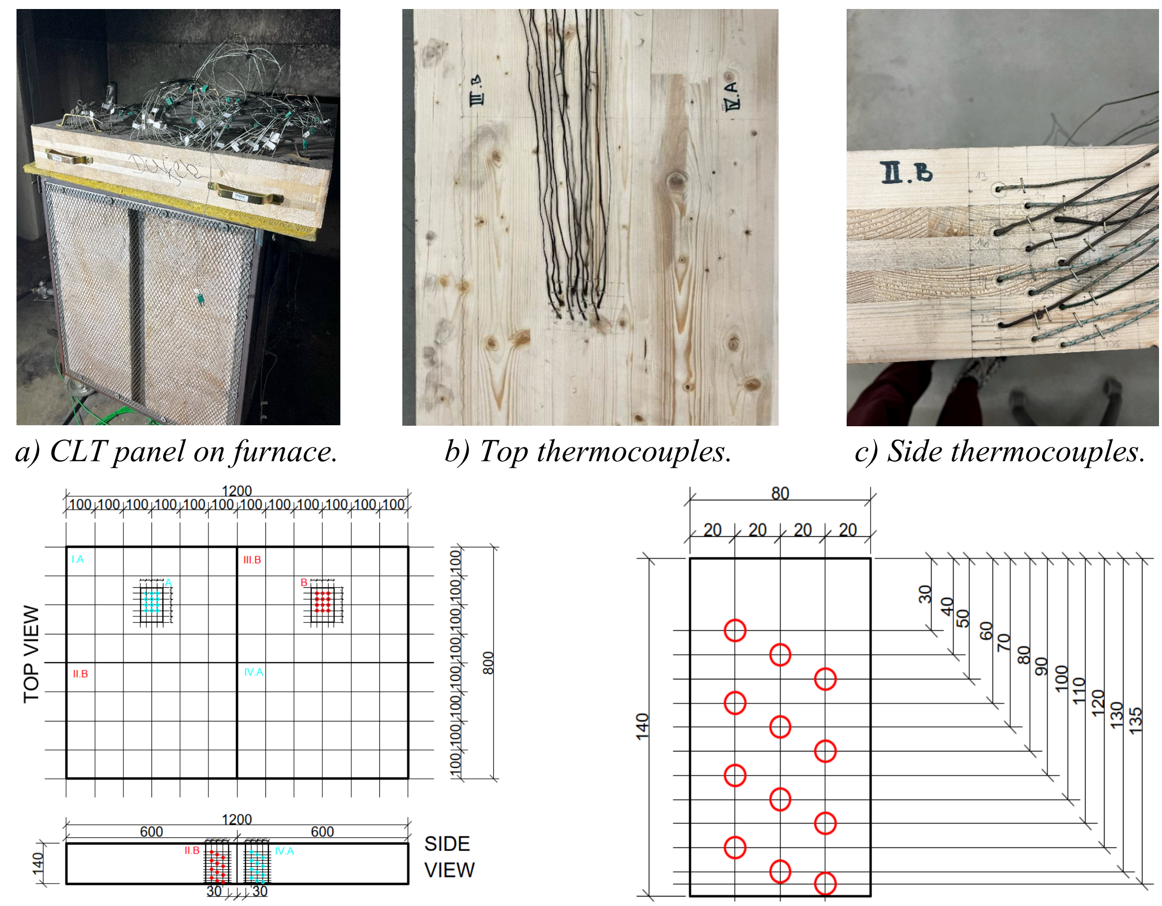
One of the challenges for describing fire behavior and performance of CLT panels and timber construction products in general is accurate temperature measurement. Research (Pope 2023; Pope et al. 2021, 2022) shows, that there are differences in recorded temperatures, depending on the placement of the thermocouples relative to the direction of heat transfer. Thermocouples installed from the unexposed side are perpendicular to the isotherms and this orientation results in temperature underestimation and delays. A detailed comparison of these parameters is provided in (Fahrni et al. 2018a, 2018b). These studies also pay attention to the differences caused by thermocouples installed parallel and perpendicular to the isotherm.

In addition to design considerations charring is relevant for fire investigation. (NFPA 921, 2024) lists a number of recommendations and limitations regarding the measurement and interpretation of char at the fire scene. Still, it considers the relative char depth a useful tool for evaluating fire spread. Babrauskas (2004, 2005) discusses the possibility of estimating the potential duration. Gorbet (2015) lists charring as both visible and measurable effect of a fire. The intention is to provide insights on the implications of the charring process and cooling phase on fire investigation.

MATERIAL AND METHODS

A 140 mm CLT panel sample produced by Stora Enso was used for the experiment. The panel was made of spruce, with an approximate bulk density of 470 $kg.m^{-3}$.

Formaldehyde-free PUR adhesive was used as the main adhesive (Stora Enso 2024). The panel had 5-layers with the following thicknesses of lamellae 40-20-20-20-40 mm. The overall dimensions of the CLT samples were 1 300 mm × 958 mm. The sample was stored indoors at approximately 20°C for more than 30 days at approx. 37% relative air humidity and the resulting moisture content before the tests was measured through electric resistance at 9.2%.



a) CLT panel on furnace. *b) Top thermocouples.* *c) Side thermocouples.*

d) Temperature measurement locations. *e) Side thermocouples location details – exposed side on the bottom.*

Fig. 1: CLT test specimens and their instrumentation.

The experiment was carried out on a small fire resistance test furnace allowing for the fire exposed ceiling surface of 1 100 mm × 700 mm. 20mm-thick MW strips were placed along the furnace frame perimeter (top side) to provide seal between the frame and the CLT sample, as shown in Fig. 1a). The MW strips extended towards the outer edges of the CLT sample to provide protection against hot gases and flames escaping from the furnace ventilation openings.

Standard wire K-type thermocouples were used with an approximate bead diameter of 1 mm and overall outer diameter of 2 mm. The thermocouples were installed into pre-drilled holes with a diameter of 4 mm. The top thermocouples (indicated by ↓, Fig. 1b) measured temperature perpendicular to the progressing isotherm and the side thermocouples (indicated by →, Fig. 1c) parallel to the isotherm. There were four measurement locations in the CLT sample (Fig. 1d), each containing 12 thermocouples. The measurement depths are indicated in Fig. 1e) ranged from 135 mm (5 mm from the exposed side) to 30 mm (110 mm) and were identical for all four measurement locations. The side measurement locations were drilled 185 mm deep and sealed with a high-temperature sealant.

The test comprised two phases – heating and cooling. During the heating phase the intention was to follow the ISO 834 standard time-temperature curve. Subsequently the cooling phase followed. The temperature profile of the heating phase is shown in Fig. 2. After 60-minutes the sample was removed from the furnace and placed on its edge to cool down freely under the extraction hood at 1.5 $m^3.s^{-1}$. The intended cooling period was supposed to last until the sample reaches approximately 50°C, however, after approximately 15 min of cooling under the hood and cessation of flaming combustion, glowing combustion intensified, as evidenced by the temperature profiles in Fig. 3. Due to the reignition, the test was terminated at 135 min and the panel extinguished with water.

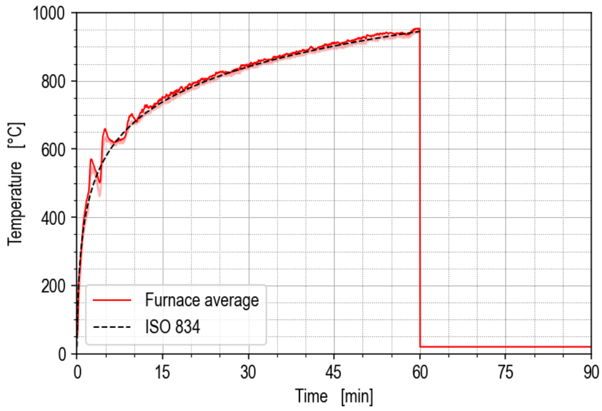


Fig. 2: Heating and cooling phase temperature profiles for furnace test(left), free cooling of the CLT sample (right) – note the presence of charred first layer of CLT sample.

RESULTS AND DISCUSSION

Fig. 3 shows the temperature profiles measured by the thermocouples installed from the side of the CLT panel. Apart from thermocouple →A50 mm the two side measurement locations show relatively good agreement for the heating phase, indicating that the intended measurement depths were achieved. The 300°C isotherm representing char layer boundary (char line in Fig. 3) reaches the →5* mm thermocouple at approximately 10 min (*the → or ↓ marking without the letter A or B, e.g. →5 mm, indicates that very similar temperatures were measured at both of the thermocouples in the A and B locations at the indicated depth and it is not necessary to distinguish them). After 60 min, the side measurement location indicates, that the 300°C isotherm is located between the →30 mm and →40 mm thermocouples. Minor temperature growth is present at the →70 mm between the 30 and 60 min of the heating phase. Beyond this depth only very limited temperature increases, below 5°C, were recorded.

What is also noticeable is the increasing effect of the 100°C plateau due to water evaporation. The plateau becomes longer with increasing depth and peaks at the end of the heating phase as indicated by thermocouples →60 mm. It should be noted that this is also due to the temporary decrease of the surface temperature after the CLT sample was removed from the furnace until reignition occurred, which is evidenced by various thermocouples →5 mm to →50 mm shown in Fig. 3.

The cooling phase is strongly affected by the presence of glowing combustion. Fig. 3. indicates that there is a limited decrease present in the already charred portion of the CLT sample (thermocouples →5 mm to →30 mm). The side thermocouples at greater depth (→40 and more mm) indicate continuous growth at a reduced rate.

It should be noted that the temperature increase is relatively large, and the charred layer increased beyond 60 mm by the end of the test, as measured by the →60 mm thermocouples. A similar trend is evident with the 120°C isotherm indicating the lower boundary of the zero-strength layer (ZSL).

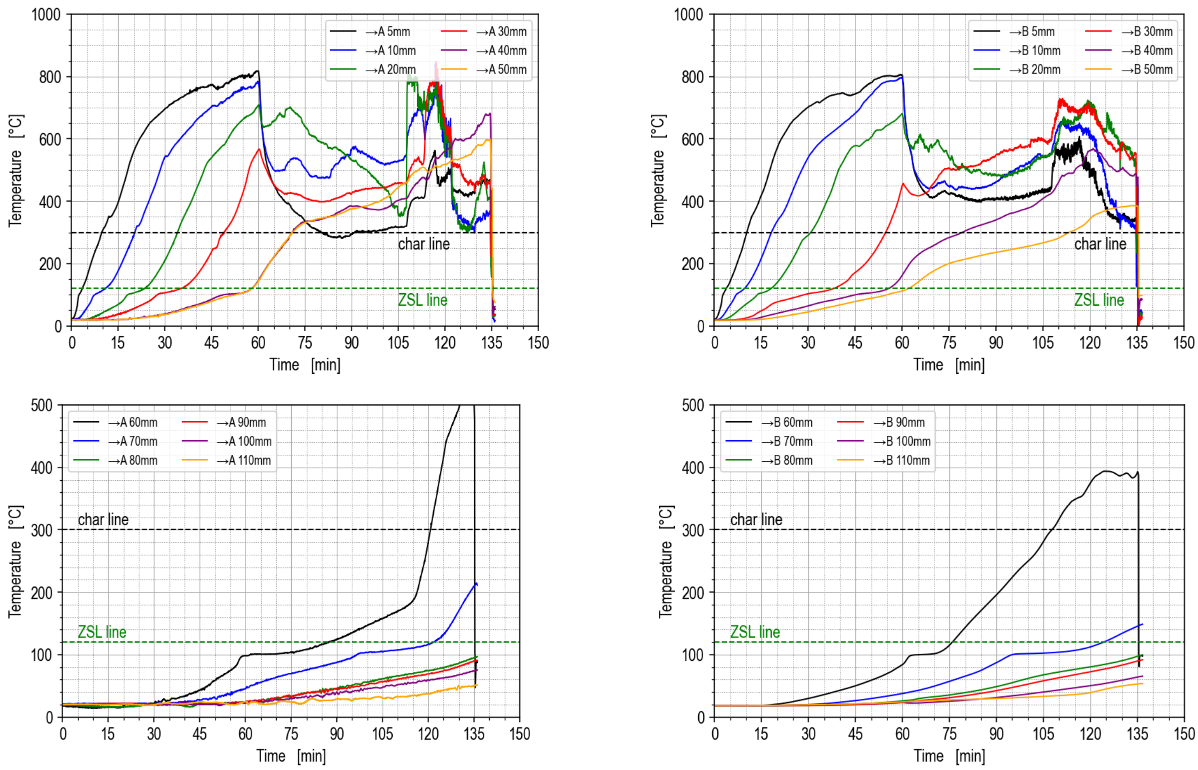


Fig. 3: Heating and cooling phase temperature profiles for SIDE measuring locations A(left) and B (right) – depths indicated from the fire exposed surface. Char line = 300°C isotherm; zero-strength layer (ZSL) line = 120°C isotherm.

One of the intentions of the presented research was to compare temperature measurement by thermocouples installed parallel and perpendicular to the isotherms. Therefore Fig. 4 presents the same measurements depths as those shown in Fig. 3 with the thermocouples installed perpendicular to the progressing isotherm, i.e. the thermocouples were installed from the top (unexposed) side of the CLT sample. The top measurement locations A and B show relatively good agreement in the measured temperature profiles.

When the side measurement locations (Fig. 3) are compared to the top measurement locations (Fig. 4), it is evident that the recorded temperatures are lower and there appears to be a delay in the temperature profiles measured in top locations. An overview of thermocouples located at depths of 5 mm to 30 mm is provided in Tab. 1. The table shows that delay between the side (→) and top (↓) thermocouples ranges mostly between 5 to 12 min for the 300°C isotherm and 3 to 5 min for the 120°C isotherm. Tab. 1 also lists the calculated charring rates for comparison with the EC5 one-dimensional β_0=0,65 mm.min^{-1} and notional β_n=0,65 mm.min^{-1} design charring rates for glue-laminated timber (EN 1995-1-2, 2004).

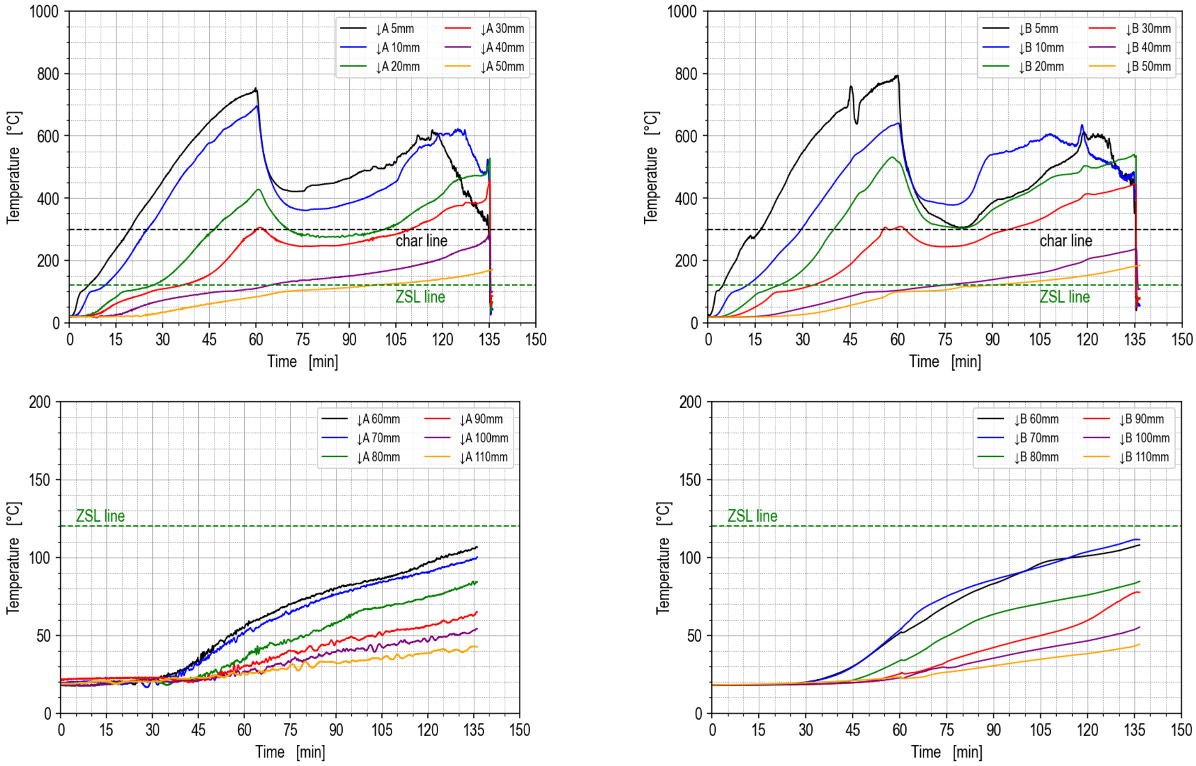


Fig. 4: Heating and cooling phase temperature profiles for TOP measuring locations A(left) and B (right) – depths indicated from the fire exposed surface. Char line = 300°C isotherm; zero-strength layer (ZSL) line = 120°C isotherm.

Tab. 1: Comparison of times to reach char and ZSL lines temperatures at various depths for side and top measurement locations.

Temperature	Time to reach temperature in measurement location (A/B)							
	→5 mm	↓5 mm	→10 mm	↓10 mm	→20 mm	↓20 mm	→30 mm	↓30 mm
300 °C	9.7/10.4	19.5/16.8	20.4/18.2	25.1/29.6	34.1/30.8	46.6/39.9	49/54.7	60.2/55.5
120 °C	3.5/3.8	6.1/4.7	10.9/9.6	11.4/13.2	23.4/18.2	26.8/22.5	35.1/38.2	36.2/33.1
Charring rate	0.52/0.48	0.25/0.29	0.46/0.64	0.89/0.39	0.73/0.79	0.47/0.97	0.67/0.42	0.73/0.64

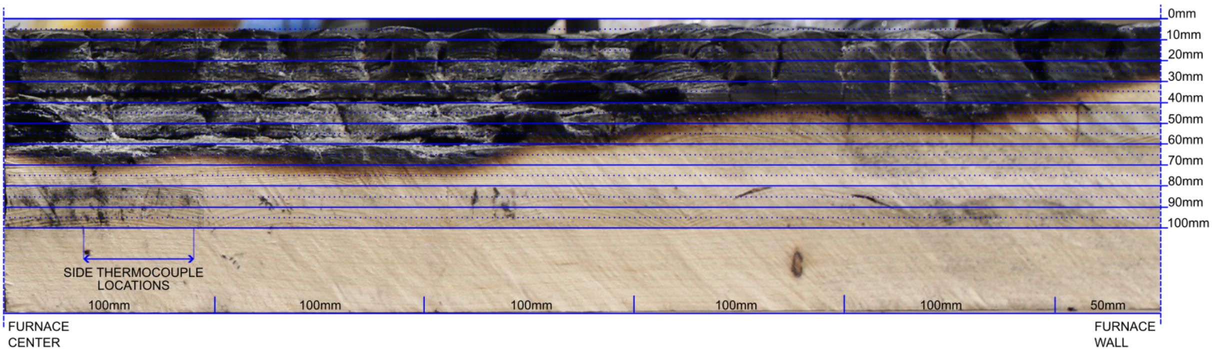
Note: Charring rates [mm.min^{-1}] were calculated from the time between reaching 300°C in two consecutive thermocouples in the given measurement location.

It should be noted that the differences in temperature profiles increase with temperature. As an example, the side thermocouples located at 5 mm measured a maximum of approx. 820 °C, whereas the top thermocouples measured a maximum of 750°C. Significant differences are also present at 30 mm, where the side thermocouples indicate 560°C (→A) and 450°C (→B) and the top thermocouples barely reach 300°C at this depth.

The final stage of development of the charred layer is shown in Fig. 5a. It can be seen that with the exception of the outer edge, the charred layer is at least 40 mm thick. This indicates that even some time after the end of the heating phase, when the charred layer reached approx.

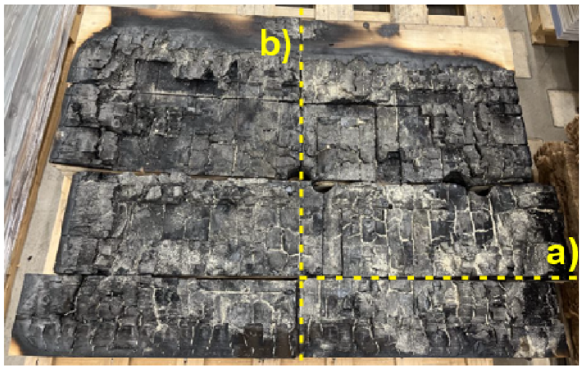
35 mm, charring continued relatively uniformly in the entire area of the CLT panel. A gap indicating partial delamination of the first CLT layer (40 mm) is present in the left half of the cross cut. The extent of char layer delamination is also clear from Fig. 5b and c, from which it is evident, that the first layer of CLT fell off almost entirely.

An additional 25 to 35 mm of charring is evident in the left half of the cross cut, which is central part of the panel (lengthwise). The maximum charring depth is nearing 70 mm, which corresponds well with the temperatures recorded at this depth with in the side A location; refer to temperature profiles →A 60 mm and →A 70 mm. The varying depth may be attributed to the placement of the CLT sample on the furnace frame. Near the furnace walls, the heat losses through the unexposed edges of the CLT sample resulted in reduced char depth.



a) Longitudinal cut at 185 mm from panel edge.

b) Cut in the middle of the CLT panel.



c) Locations of cuts.

Fig. 5: Charring of CLT panel – cuts and planar view.

The experiment was run under an open calorimeter and the furnace burners were regulated by the calorimeter controllers. As Fig. 6 shows, the burners' output remained relatively stable at around 30 kW for the entire duration of the heating phase. The short peaks reaching up to 50 kW were due to the PID controller operation and lasted only for a couple of seconds.

It can therefore be seen, that the temperature growth which followed the intended ISO 834 curve, was due to the increasing heat release from the CLT sample itself. After the first 10 min, the heat release rate of the CLT panel started increasing almost linearly to about 28 kW at the end of the heating phase. Afterwards, it was removed from the furnace immediately with the intention of switching to the cooling phase. After a peak in heat release rate due to the exposure of the entire burning surface of the CLT panel to fresh air, a sharp decrease followed. This decrease lasted only for about 5 min, after which the glowing combustion caused a slowly increasing heat release rate. The second sharp decrease recorded at 96 min was due to the restart of the RCT hood analyzer.

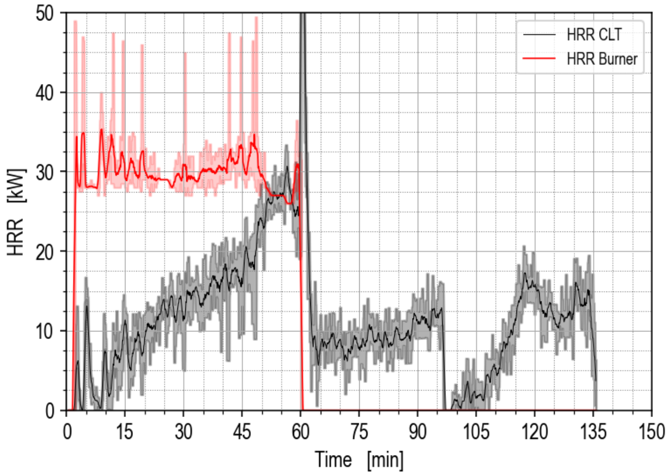


Fig. 6: Heat release rate during the experiment.

The above is indicative of quite significant contribution of the CLT sample to the overall heat production during the test. When considered from an enclosure fire perspective, two aspects are of importance. Firstly, the fire is affected significantly by the presence of combustible construction and linings. Secondly, reignition and continuous combustion and heat release can occur even in situations where a planar element is exposed to continuous flow of cold air and no significant heat retention or reradiation (e.g. in corners) is present. It is most likely the continuous supply of fresh air which sustained and promoted the glowing combustion. Another test, in which the CLT panel was in a horizontal position after the end of heating period did not exhibit any reignition.

CONCLUSIONS

The main findings and conclusions of this study on the CLT behavior during the heating and cooling phase of fire of may be summarized as follows: *(1)* Significant differences were found between the side and top measurement locations. The top measurement locations (perpendicular to isotherms) were delayed and recorded unrealistically low temperatures when compared to the side measurement locations and expected progression of the char line. *(2)* Continuous charring, reignition and increasing temperatures were observed after the removal of the CLT sample from the furnace at the end of the heating phase. Despite room temperature and no external or reflected radiation. *(3)* The heat released by the CLT sample had an increasing tendency and grew with temperature during the experiment. This indicates that even after the burnout of movable fire load, there is a potential for continuous and significant heat release. *(4)* It appears that the vertical orientation of the panel and sufficient oxygen supply combined with forced airflow due to extraction, were the contributing factors to sustaining and promoting glowing combustion. As the delamination of the first charred layer progressed, the exposed glowing pockets exhibited flaming combustion.

Given the above findings, the implications and recommendations are as follows: *(1)* Temperature measurements in CLT and timber should be made in parallel to the isotherms due to measurement errors present with perpendicular orientation. *(2)* From the design perspective, the contribution of the cooling phase should not be neglected, as significant charring and thermal degradation may occur. *(3)* From the fire investigation perspective, the depth of char layer may not be indicative of the duration of fully developed fire. The CLT panel was able to sustain glowing combustion under the outer char layer and this may allow for irregular char depth patterns. It appears that the partially delaminated and cracked char layer creates pockets with good heat retention and access of air which intensifies the glowing combustion process.

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VLADIMÍR MÓZER*, LUKÁŠ VELEBIL, ANDREA SMETANOVÁ
CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF CIVIL ENGINEERING
THAKUROVA 7, PRAGUE
CZECH REPUBLIC
*Corresponding author: vladimir.mozer@cvut.cz