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EXPERIMENTAL STUDY ON THE BENDING RESISTANCE OF CROSS-LAMINATED TIMBER EXPOSED TO ISO 834-1 STANDARD FIRE

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ABSTRACT: In a fire, the load-bearing capacity of a timber structure is influenced not only by charring but also by the elevated temperatures behind the char layer. The Eurocode accounts for this increased temperature in solid timber by subtracting a compensating zero strength layer (ZSL) from the cross-section in addition to the char depth. However, this approach does not directly apply to cross-laminated timber (CLT) structures, which have transverse layers that do not carry load in the direction of the span and feature glue lines. If the glue fails to keep the lamellae in place during a fire, the charring performance and temperature distribution will differ from solid timber. This paper assesses the load-bearing capacity of CLT panels exposed to standard fire conditions, including the falling off of the charred layers. The assessment is based on fire tests conducted on two different CLT structures and the measured temperatures within the CLT panels. The structural capacity is compared to the value calculated using the ZSL method. The findings indicate that glue failure significantly increases the charring rate, impacting the equivalent ZSL differently when glue lines do not hold the layers. The fire test revealed that glue lines led to falling lamellae, increased charring rates, and affected load-bearing capacity and ZSL height.

KEYWORDS: Cross laminated timber, layered beam theory, standard fire, load bearing capacity

1 – INTRODUCTION

When building fire safety is based on prescriptive design, the fire resistance requirements are based on standard fire conditions and specific times. For example, in a P2-class 8-story building in Finland, where loadbearing structures can be timber, the required fire resistance is 60 minutes. There are also requirements for protective covering, but 20% of surfaces is allowed to be left uncovered. This area can be increased if fire resistance is increased by 30 or 60 minutes [1].

The effective cross-section method is commonly used to determine a structure's loadbearing capacity in standard fire conditions. In this method, the original cross-section is reduced by the char layer and the zero strength layer (ZSL), which accounts for the weakened layer behind the char front by assuming this layer has zero strength. For the remaining effective cross-section, strength and stiffness properties are assumed to be unchanged [2].

Cross laminated timber (CLT) fire behaviour differs from solid wood due to its layered structure and the glue lines between the layers. In a one-way spanning slab, only layers parallel to the span carry loads. If the glue cannot hold the char layer in place during a fire, the charring rate increases after the protective char layer falls off [3]. Because the structure contains loadbearing and non-loadbearing layers and because the charring rate changes during a fire, solid timber's ZSL cannot be used to calculate the effective cross-section of CLT. EN 1995-1-2 informative Annex B, "Advanced calculation methods" presents information on how charring depth, temperature development and distribution, and structural behaviour can be modelled [2].

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In this paper, the temperature profile of the structure is based on experimental data, and the behaviour of a horizontal structure with an exposed side in tension is modelled based on temperature measurements from a fire test and reduced material properties presented in EN 1995-1-2 Annex B [2]. Reduced mechanical properties are used to calculate the structure's capacity. Capacity is used to calculate the effective cross-section, where part of the exposed face is removed but material properties remain unchanged in the remaining cross-section. After this, the distance between effective heights and the char front difference during the fire is determined. Stresses in the cross-section are calculated using layered beam theory [4], and stresses are limited based on the tension to compression ratio f_t/f_c equal to 0.9 as in Schmid et al. [5] calculations. The reduction factor of strength and MOE, and the ratio between them, affects results, and this effect is discussed.

2 – BACKGROUND

Char depth is generally determined by the 300 °C isotherm, but wood properties begin to deteriorate at lower temperatures. These temperatures are exceeded behind the char layer and their effect needs to be considered when evaluating a structure's capacity. Therefore, when using the reduced cross-section method, the ZSL must be accounted for in addition to the char depth. In the current Eurocode for solid timber, the ZSL increases to 7 mm within 20 minutes and remains constant after that [2]. In the next generation Eurocode, this value is slightly increased, and it depends on whether the exposed face is in tension or in compression [6]. In national design specifications, effective char depth is calculated by multiplying the char depth by 1.2 [7].

2.1 CAPACITY OF CLT

A CLT panel, in which the glue cannot hold the char in place during a fire, has a charring rate that differs from solid timber. The char layer protects wood from fire. If the char layer falls, a higher heat flux flows through the surface and the charring rate increases, until a new protective char layer is formed. This effect can be considered by using the European charring model, which doubles the charring rate when the char front reaches the glue line and reduces it to nominal after a 25 mm char layer is formed. [3]

Eurocodes present an advanced calculation model based on cross-section temperatures in standard fire. Timber tensile and compression strength, and modulus of elasticity (MOE) decrease based on temperature with different reduction factors [2]. For timber members, it can be assumed that they exhibit ideal elastic-plastic behavior for compression and purely elastic behavior for tension [8]. There are other studies that provide different reduction factors for strength and MOE [9]. Proper material properties and the ratio between strength and MOE can have a significant effect on results.

Schmid et al. [5] simulated CLT panels under standard fire conditions and developed a method to determine the effective cross-section during a standard fire. In this method, the effective cross-section is calculated by reducing an additional 7 mm from the first layer and 12 mm from the following layers in addition to the char depth. When the calculated cross-section starts in a transverse layer, the following longitudinal layer is reduced by 2 mm when calculating the effective cross-section. The simulation is based on timber tensile and compression strength where the tensile to compression strength ratio is 90%, and plastic deformation is allowed in compression. These simulations are validated with loaded fire tests on CLT panels [10].

3 – PROJECT DESCRIPTION

Two different CLT panels were tested. The panels were made of spruce (Picea abies) with a strength class of C24. The size of the specimen was 500 mm x 1600 mm (width x length). The specimens consisted of five lamella layers. The panels were glued with one-component polyurethane (PUR) adhesive. The adhesive was applied to the faces of the lamellae in their main bond line and without edge bonding. The outer lamella layers were parallel to the longer dimension of the test specimen. In the first specimen, the odd layers were 20 mm thick, and in the second specimen, they were 40 mm thick. The even layers were 20 mm thick in both specimens. The width of each lamella was 115 mm. The panel surfaces were finished, and sanding had reduced the thickness of the outer lamellae by 1 mm. Measured gaps between the lamellae on the exposed face were less than 1 mm wide. The dry density of the reference panels was 420 kg/m3, and the moisture content on the day of testing was 9.1–9.2 dry weight-%.

The temperatures inside CLT panels were studied by exposing the panel's lower surface to the standard temperature-time curve of ISO 834-1 and measuring temperatures inside the specimen. The tests were terminated, and the burners were shut off when temperature measurements at the second bond line exceeded 300 °C. A crane located above the furnace chamber was used to lift the panels into a pool of water.

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Measured temperatures were used to calculate a structure's loadbearing capacity using reduced material properties at elevated temperatures and layered beam theory.

4 – EXPERIMENTAL SETUP

A test specimen was installed across the 1200 mm wide opening of the furnace chamber, which had internal dimensions of 3000 mm x 3000 mm x 1200 mm (height x width x depth). The long vertical side faces of the specimens were protected with mineral wool and timber boards to limit the heat flow between the specimen and the surrounding furnace roof construction and to prevent the excessive charring near the specimen corners, as shown in Figure 1. The first layer of lamella, which was to be exposed to fire, was sawn across 50 mm distance from the furnace wall to allow the lamellae to fall off freely. The saw cuts were filled with ceramic fibre paper.

During the tests, furnace temperature, specimen temperatures, oxygen content within the furnace, and the pressure differences between the furnace and test hall were monitored. The pressure difference was set to 20 Pa at the level of 100 mm below the exposed face of the specimen. The oxygen concentration 300 mm below the furnace roof was measured using a Dräger EM200-E multi-gas detector. The char fall-off of the lamellae layers was observed visually with a video camera.

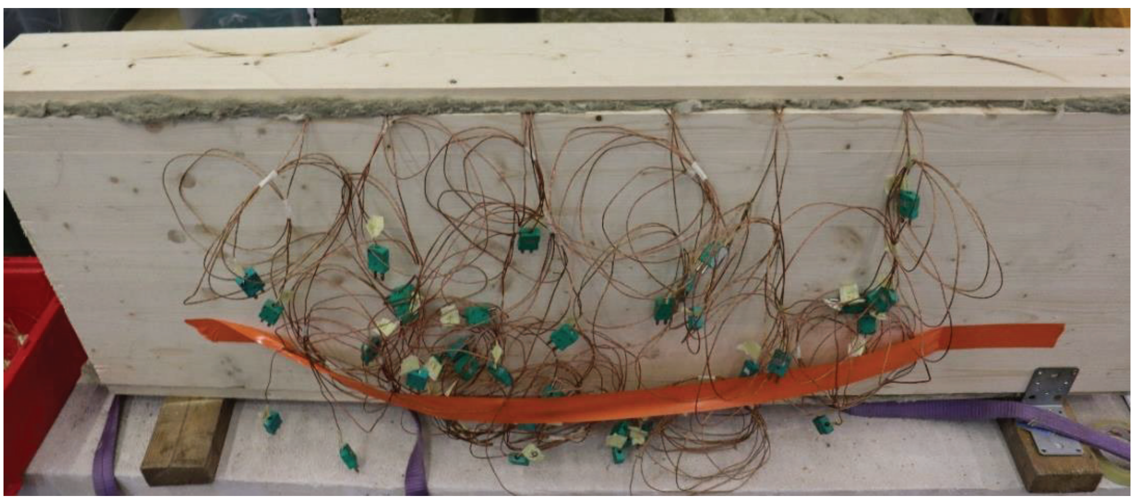

Figure 1. Overview of a test specimen showing the thermocouple wires drilled from the side face of the specimen and fire protection measures to limit heat flow and prevent excessive charring near the specimen corners.

4.1 APPLICATION OF THERMOCOUPLES

All internal thermocouple wires were placed parallel to the isotherms (horizontally), and they were installed in holes drilled into the side faces of the specimens. Holes were created using a pillar drill and a 4 mm diameter drill bit. Fibreglass-wrapped thermocouple wire (K-24-2-305) was then inserted into the hole using a 3 mm diameter wooden stick to ensure good contact between the thermocouple and the wood. The end of the stick was cut diagonally, and the welded junction of the thermocouple was mounted on the bevelled surface so that the thermocouple was wedged tightly against the CLT structure when the stick was pushed against the bottom of the hole, as shown in Figure 2. In the first lamella layer, the drilling depth was 75 mm, while in all other layers, it was 100 mm. Schematic views of the test furnace, the specimen, and the positioning of thermocouples are presented in Figure 2. The vertical spacing of the thermocouples was around 5 mm, and the consecutive thermocouples formed a measurement station. Three measurement stations were used for the first specimen and two measurement stations for the second specimen. The last temperature measurement point was at ¾ of the third lamella height. The temperatures in the last quarter of the third lamella were extrapolated, assuming the temperature follows a similar curve at subsequent depths as in previous layers (only the time when the temperature begins to increase is delayed).

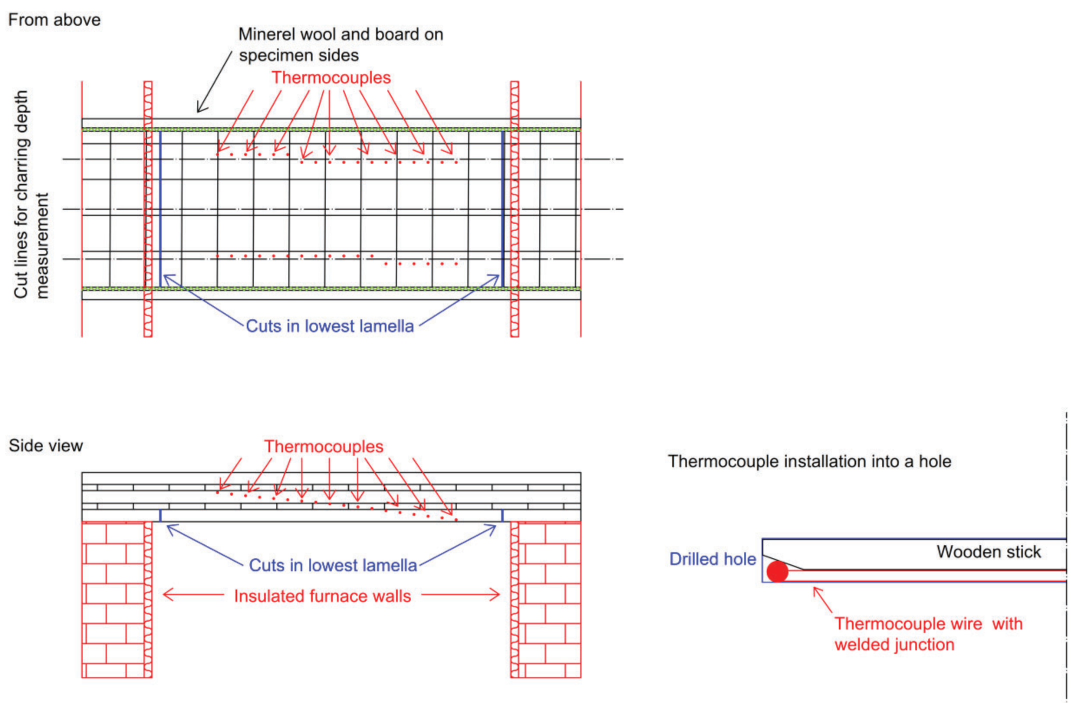

Figure 2. Schematic views of the test furnace, the specimen and the positioning of thermocouples: (a) plan and (b) vertical side views of the specimen, and (c) a thermocouple installation into a hole.

4.2 DETERMINING REDUCTION FACTORS IN CROSS-SECTION

The cross-section is divided into 1 mm layers. The temperature of each layer at mid-height is determined by interpolating (or extrapolating) the temperature between measurement point depths, separately in each station. Measured values and interpolated and extrapolated temperatures from one station of the 20-20-20-20-20 specimen are presented in Figure 3. These temperatures are used in accordance with EN 1995-1-2 to determine the reduction factor for strength and MOE in that layer. Temperatures on the compression side are assumed to remain close to ambient levels and material properties remain unchanged.

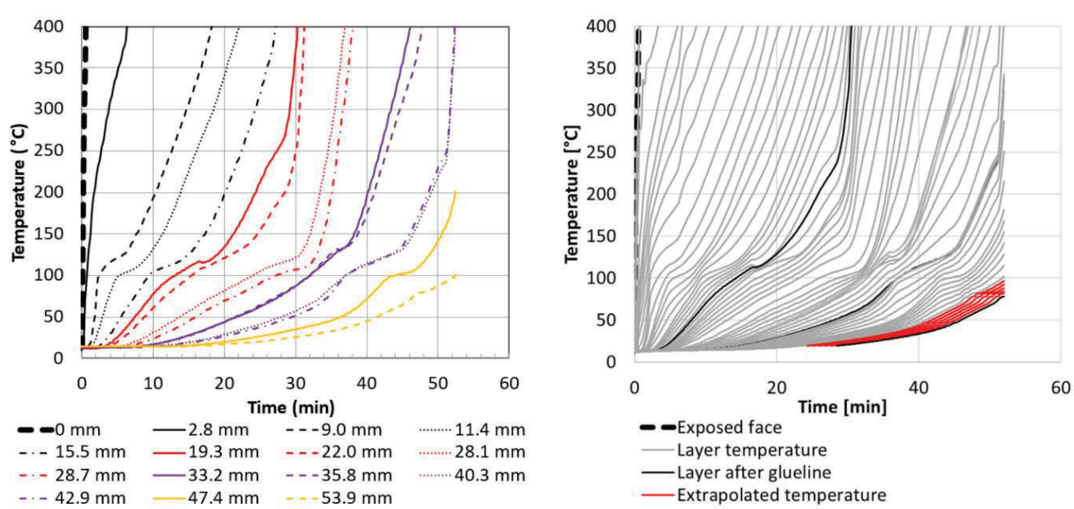

Figure 3: Left side is temperatures measured from one 20-20-20-20-20 station. The right side is interpolated temperatures middle of 1 mm layers.

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4.3 CALCULATING CROSS-SECTION CAPACITY

Stresses in the cross-section are calculated using layered beam theory [4] and reduced MOE. The calculated stress is compared to the reduced tensile strength, and the specimen is assumed to fail when the reduced tensile strength is exceeded. Additionally, compression side stress is limited according to the tension-to-compression ratio. The material model permits plastic deformation under compression. However, the compressive stresses did not exceed the proportional limit in the calculations. In the calculations, slab length and width were 3800 mm and 500 mm, respectively. The loading was uniform, and stresses were calculated at the slab's midpoint. Even layers that are orthogonal to the span are not assumed to bear any axial stresses.

In the calculations, the shear factor k is calculated using the normal temperature value for shear modulus (G90 = 69 MPa). Therefore, the increased temperature effect on shear modulus is not taken into account. Additionally, because the cross-section is not symmetric after the beginning of a fire, the layered beam theory is valid only approximately [4]. As the lowest lamella area and properties decrease, this causes different shear deformations in the second and fourth lamella layers. The presented results are based on calculations where the same k-factor is applied to the entire cross-section, which causes some error in the results.

Cross-section capacity using deteriorated material properties is calculated to determine the effective cross-section that has the same capacity. In effective cross-section calculations, material properties are kept unchanged from the initial condition, and cross-section height is reduced by removing material from the lower surface. Results are compared to the initial loadbearing capacity and between the reduced material properties method and the reduced cross-section method. Therefore, initial wood strength does not affect the results.

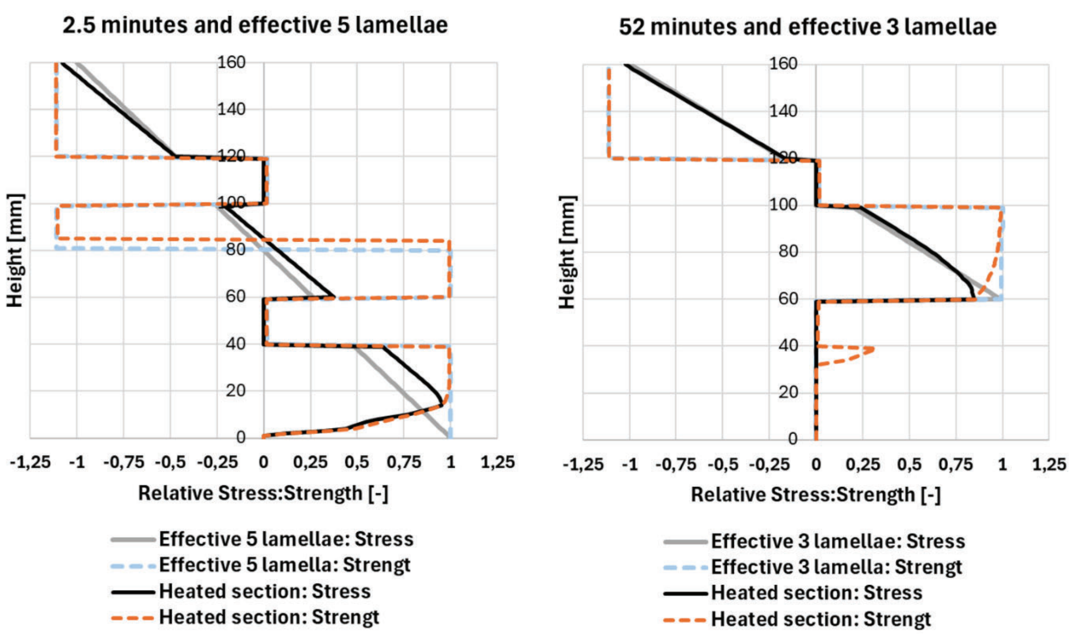

Figure 4. Stresses and timber strength in 40-20-40-20-40 panel cross section. The compression strength and tensile strength ratio is f_t/f_c = 0.9.

CLT panel 40-20-40-20-40 stresses and reduced strength in the initial condition, after 2.5 minutes, and after 52 minutes, are presented in Figure 4. Because the material is weak close to the char front and deformations are highest, stresses exceed material strength first. When the lowest layers, or lowest lamella, are removed from calculations, the highest capacity for the remaining cross-section can be calculated. Because the MOE decreases faster than material strength as temperature increases at the beginning of a fire or when the next loadbearing layer begins to heat up, this reduces stresses in layers further from the elastic centroid and causes stress to spread evenly in the lowest layers. The slight increase in temperature does not diminish the loadbearing capacity. In fact, when the temperature in the third lamella layer with the 40-20-40-20-40 panel begins to increase, calculations demonstrate a slightly higher capacity that of the specimen at ambient temperature, as stresses are distributed more evenly on the lower surface and compression stresses in the top layers increase, as can be seen on the right side of Figure 4. Stresses and strength in the figures are divided by timber tensile strength, and values are related to that. On the right side of Figure 4, the lowest lamella still has an uncharred layer that has remaining strength, but the highest capacity is reached when stresses in it exceed its strength, and it would break. Because of this, it is removed from calculations, and there is no stress on it.

Gray lines in the figures represent stresses in the panel where the effective cross-section comprises the top three or five lamellas, and dark lines represent stresses in the heated cross-section. Moment resistance with three lamellas is equivalent to the heated cross-section shown in right side of Figure 4.

5 – RESULTS

Temperature based char front (300 °C isotherm) and calculated charring depth using the stepped model [3] are presented in Figure 5. An increase in charring rate in test results can be seen after charring reaches the glue line at a 20 mm or 40 mm depth.

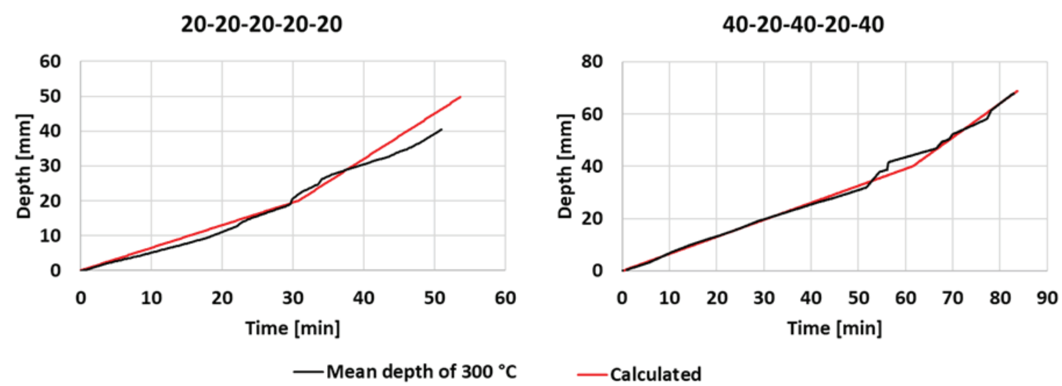

Figure 5. Measured mean depth of 300 °C isotherm (char depth), and calculated charring depth using the stepped charring model.

Cross-section loadbearing capacity compared to the initial value is presented in Figure 6. The lowest layers of lamella are removed from the calculation until the highest capacity is reached. The diamond mark in the curve represents the point where the bottom lamella is removed from calculations and the load is carried by only three lamellas. After the first layer is lost, charring proceeds in the second layer that does not contribute to loadbearing capacity. In this part, capacity remains quite steady until temperatures in the third layer begin to increase.

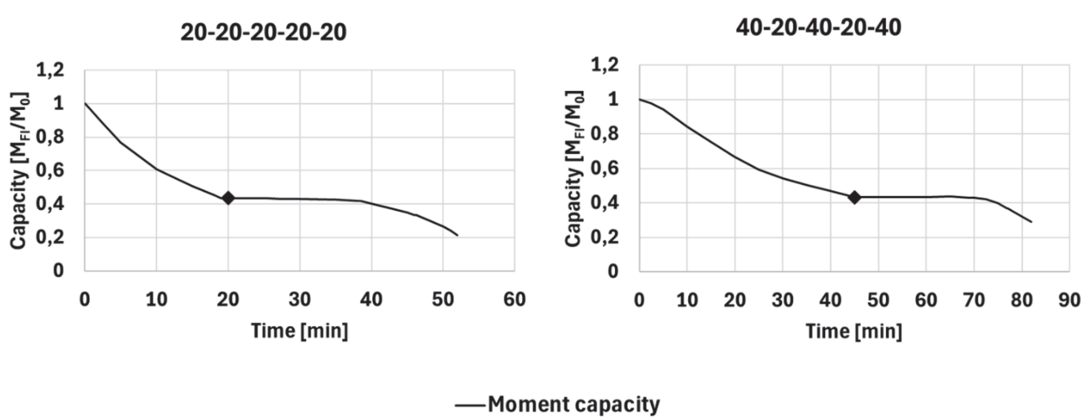

Figure 6. Tested panels' loadbearing capacity. The diamond represents the point where stresses in the lowest lamella exceed its strength before the cross-section reaches its highest capacity.

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Reduced effective cross-section distance to the char front is presented in Figure 7. The presented value is effective ZSL, $d_{0,ef}$ [5]. This effective ZSL considers only parts of a section with grain direction parallel to the span. Effective ZSL determined by using Schmid et al. [5] method and stepped charring rate [3] is presented as the green line in Figure 7. The gap in figures indicates the point where the first lamella layer breaks, and capacity is calculated based on three lamellas. The red line and black line represent effective ZSL calculated from temperatures to the char front from the stepped charring model [3] and the measured 300 °C isotherm, respectively. These calculated results follow values achieved by using the Smith et al. [5] method where ZSL height after the first layer is 12 mm, and an additional 2 mm reduction from the next layer is applied if the effective height is in an orthogonal layer. An additional 2 mm reduction is needed with the 20-20-20-20-20 panel after 35 minutes, but with the 40-20-40-20-40 panel 12 mm ZSL after the first layer is sufficient. The temperature increases to an even larger depth, with over 50 °C measured in the third lamella layer before the first lamella layer is fully charred, as seen in Figure 3. This doesn't affect the panel's capacity because the MOE reduction is higher than the strength reduction, allowing high stresses to spread over a wider area in the heated zone.

When charring reaches the third lamella, effective ZSL is thicker than in the first layer. In the 20-20-20-20-20 panel effective ZSL appears to decrease, but this is because measured charring was slower than the stepped model predicted, as seen in Figure 5. Effective ZSL is negative in the 40-20-40-20-40 panel at the beginning of the fire because when a small layer is charred, stresses behind the char layer are spread over a wider area due to reduced MOE, as seen in Figure 4.

In the current Eurocode EN 1995-1-2 [2] the ZSL increases to its maximum value of 7 mm after 20 minutes, this fits well with the 40-20-40-20-40 panel, but with the thinner 20-20-20-20-20 panel, this increase occurred faster and the steady state for effective ZSL was reached in 10 minutes.

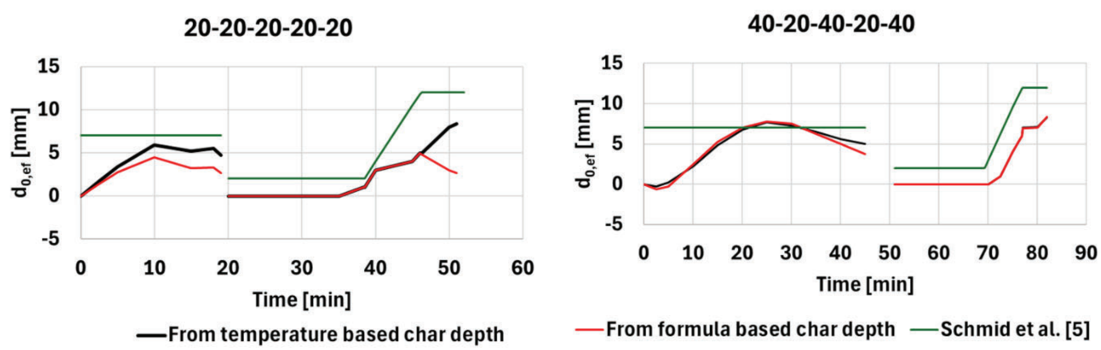

Figure 7. Effective ZSL in panels during standard fire.

The used material properties and their ratio affect the results. Qian et al. [9] reported a study in which the MOE reduction at elevated temperatures is smaller below 200 °C compared to Eurocode values. This would affect the result because the presented results are based on a higher MOE reduction than strength reduction, which allows for a more even stress distribution behind the char layer. A higher MOE would cause higher stresses in heated timber behind the char layer, leading to breakage at a lower load. One reason for the higher MOE might be moisture content, but above 100 °C, this should not have much effect. Specimens were heat-treated for a relatively long time compared to fire exposure, and this could be one reason for the differences.

6 – CONCLUSION

During a fire, the lowest surface properties deteriorate to almost zero and barely withstand any stress. When calculating cross-section capacity, these layers need to be removed, and calculations should be based on the remaining reduced cross-section.

Because the MOE reduction factor is higher than the tension strength reduction factor and timber compression strength is higher than tensile strength, the slight temperature increase behind the orthogonal layer doesn't affect effective ZSL until charring gets close to the loadbearing layer. With these panels, a simplified method [5] with a 12 mm ZSL and an additional 2 mm reduction from the next layer is the effective depth is in an orthogonal layer, is sufficient behind the first layer.

The relation between the reduction factor for MOE and strength affects how the structure behaves. If the MOE reduction increases faster than the strength reduction, it is beneficial for capacity because high stresses in heated zone spread over a wider area. Some studies [9] demonstrate that the MOE reduction is smaller than the strength reduction. In this case, stresses close to the char layer are higher and more layers should be removed when calculating the structure's capacity. Material properties at elevated temperatures in EN 1995-1-2 [2] are meant to be used in a standard fire. If these values are derived from tests with solid wood, the use of these values causes errors due to the effect of falling layers on temperature and moisture distribution in the structure. When using an advanced calculation method, material properties need to be well known.

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