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A stiffness-based approach to analyze the fire behavior of Cross Laminated Timber floors

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Abstract

In the present paper, the experimental deflection of Cross Laminated Timber floors exposed to fire is predicted with advanced and simplified methods. The accurate modelling is based on heat transfer prediction and reduced stiffness, while the simplified methods are based on the Reduced Cross Section Method (RCSM) of EN 1995 1-2 (CEN, 2004). Then, all methods are combined with a thick plate theory for laminates in order to compute the mid-span deflection of the floors. The more accurate modeling returned a better agreement with the experimental reference than RCSM approaches. Finally, a RCSM approach based on the time dependency of the zero stiffness layer is suggested.

Introduction

During last decades, the timber construction market has sharply increased, covering also modern residential and commercial buildings within the urban centers. This increase takes benefits from the parallel development of the new massive timber construction method based on Cross Laminated Timber (CLT) panels. These prefabricated thick panels are composed of lumber layers stacked crosswise and glued on their upper and lower faces (Figure 1). The number of layers can generally vary between 3 and 9, while the maximum span and width of a single panel can be up to approximately 15 m and 3 m respectively.

Fig. 1. Cross Laminated Timber panel (Frangi A., Fontana, Knobloch, & Bochicchio, 2009)

The orthogonal lay-up ensures more uniform mechanical and hygroscopic properties along both directions and allows the use of CLT as full-size floor, wall or roof element. The enhanced properties of CLT compared to solid wood make this product competitive with respect to traditional mineral-based construction materials (concrete, masonry) which have a higher environmental impact than wood (Piacenza, Tumer, Seyedmahmoudi, Haapala, & Hoyle, 2013).

The development of timber structures has to be followed by a progressive increase in knowledge about their fire safety. This is even more important when dealing with relatively recent products such as CLT panels. Indeed, the current version of EN 1995 1-2 (CEN, 2004) includes a fire design method for timber structures derived in the 80’s and originally developed for simply supported Glued Laminated Timber (GLT) beams. Such design method, called the Reduced Cross Section Method (RCSM), was originally derived by Schaffer in the 80’s (Schaffer, 1984) for GLT by means of simulations validated on available test results. The principle is to use normal properties of wood at
ambient conditions combined with a reduced cross section of the timber member due to the fire exposure. The reduction of the cross section is defined with two steps: (i) a first reduction due to a uniform charring rate and (ii) an additional removal of a layer considered to have null mechanical properties (also called zero strength layer - ZSTL or $d_0$, as in the EN 1995 1-2) in order to take into account the reduced properties of wood in the region close to the char front (Figure 2). The parameter $k_0$ in Figure 2 takes into account the time necessary to start the wood combustion and its values are $k_0=1$ when the exposure time is more than 20 minutes and $k_0=\text{time}/20$ when the exposure time is less than 20 minutes (see also EN 1995 1-2 (CEN, 2004)).

Fig. 2. Principle of the Reduced Cross Section Method of EN 1995 1-2 (CEN, 2004)

The main advantage of the RCSM compared to more advanced calculation methods lies in using normal properties of wood instead of reduced properties. This hypothesis can be applied to timber structures for two main reasons: (i) wood has a very low thermal conductivity and (ii) charred wood protects the intact wood after the char front, acting as an insulating material. This makes simple the approach of the RCSM, which is therefore widely used in practical applications by engineers.

The zero strength layer was originally set to 0.3 inches for bending members (Schaffer, 1984). Subsequently, in EN 1995 1-2 has been reduced to 7 mm and the use for other members than those in bending is implicitly allowed. However, the thickness of the section affected by the thermal gradient depends on the type of the thermal action (ISO or natural fire exposure), the fire duration and the kind of stresses acting on the timber member (tension, compression or shear) (Schmid, Just, Klippel, & Frangi, 2015). Recent studies (Schmid, Konig, & Just, 2012), (Schmid, Klippel, Just, & Frangi, 2014), (Schmid, Just, Klippel, & Fraggiacom, 2015), (Lineham, Thomson, Bartlett, Bisby, & Hadden, 2016) showed that the predicted behavior of timber members exposed to fire using the RCSM is not always conservative, and the “exact” value of the zero strength layer is difficult to predict since it depends on a multitude of parameters like, for instance, the boundary conditions, the panel’s geometry and the kind of acting stresses. Furthermore, falling-off of layers can occur for the presence of glued interfaces between layers. Indeed, the presence of glue at CLT layers interfaces can influence the fire behavior because of the difference of mechanical properties at high temperatures between glue and timber. When the char front is not yet at the glued interface, the temperature gradient can decrease glue mechanical properties and therefore can lead to premature falling-off of layers and an increase in the charring rate. This phenomenon has been observed in CLT floors exposed to fire in (Frangi A., Fontana, Hugi, & Jobstl, 2009), and the proposed approach of EN 1995 1-2 for initially protected surfaces seemed to well reproduce this delamination phenomenon. However, other studies found very few falling-off of layers (Craft, Desjardins, & Mehaffey, 2011), (Osborne, Dagenais, & Bénichou, 2012) or a falling-off phenomenon that has negligible influence on structural design compared to ambient design of CLT (Klippel, Leyder, Frangi, Fontana, Lam, & Ceccotti, 2014). This discrepancy between test results derives from the multitude of parameters
influencing the falling-off effect, like the type of glue, the presence of small gaps between boards of each layer, the glue thickness between layers, the panel’s lay-up and so on.

Other fire tests on loaded CLT floors can be identified in the literature: (Schmid, Koning, & Kohler, 2010), (Menis, Fragiacomo, & Clemente, 2012), (Fragiacomo, Menis, Clemente, Bochicchio, & Ceccotti, 2013). Fire tests on loaded timber elements are useful to understand the actual thermal-mechanical behavior of the specimen, but they are expensive, time-consuming and sometimes it is not straightforward to obtain reliable information on the actual load-carrying capacity the specimen. This is also due to the fact that, in most of the cases, the test is stopped before the failure of the specimen for the safety of people and equipment. Therefore, the evolution of panel’s deformation during fire exposure is the only information about the variation of mechanical properties during the fire test.

The aim of this paper is to use the measured deflections of three CLT floors exposed to ISO fire (conventional fire tests) for comparing different methods that can be applied for predicting the deflection. In this paper, two existing RCSM approaches, a more refined method and a new RCSM approach based on a zero stiffness layer (ZSSL) are compared.

Even if the existing RCSM approaches were originally derived for predicting the residual load-carrying capacity of timber members, it may be extended to the prediction of deflection, since the stiffness properties are also affected by the thermal gradient after the char front. Moreover, once the panel is designed on the basis of the exiting RCSM for the load-carrying capacity, it could be interesting to investigate about the corresponding deflection predicted using these methods.

First, the available experimental data of bending tests on fire exposed CLT floors is introduced. The subsequent section presents the advanced and simplified modeling in order to reproduce the experimental deflection. Then, the comparison between the predicted and experimental deflection of fire exposed CLT floors is presented. Finally, the results are discussed and the main conclusions are summarized.

Fire tests on CLT floors

Materials and Methods

Three CLT floors from three different producers have been tested in bending while exposed to ISO fire on their lower face in tension. Being also commercial-oriented fire tests, the out-of-plane load was set according to the producer’s demand. The rather low load levels (approximately 10-15% of the estimated load-carrying capacity at ambient conditions) ensured sufficient test durations to measure and observe the structural fire response. The load remained constant during fire exposure and the panels were simply supported on two sides. Thermocouples were placed in several sections and over the thickness in order to measure the temperature profiles. The deflection was measured with LVDTs at panel mid-span and the displacement rate was constantly monitored. The end of tests was determined when reaching the safety criterion of (i) maximal displacement rate or (ii) when rupture occurred. Moreover, the fire test could also be stopped when reaching an established time of fire exposure without satisfying any safety criterion. Table 1 shows the main properties of the fire tests on CLT floors.

All panels were made of Norway spruce (Picea abies) lamellas of strength class C24 (CEN, 2009) and glued with one-component polyurethane glue. The panel-to-panel assembling was made with screwed LVL junction and protected with fire insulating joints that ensured the integrity during fire exposure. Test-1 showed falling-off of wood pieces between 15 and 30 minutes of fire exposure, and then no other visible phenomena were observed. The same occurred for Test-2 between 50 and 60 minutes of fire exposure, while for Test-3 this phenomenon has been observed from 40 minutes of fire exposure to the end of the test. However, an accurate description of observations during tests was prevented due to the limited view inside the furnace. Suddenly after the end of fire test, the
specimen was removed to fire exposure and the fire on its exposed side extinguished with water, which took approximately 6-8 min.

Table 1. Properties of the tested specimens of CLT floors

<table>
<thead>
<tr>
<th>Test number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span [m]</td>
<td>4.2</td>
<td>4.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Width [m]</td>
<td>2.97</td>
<td>2.6</td>
<td>2.97</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>195</td>
<td>160</td>
<td>182</td>
</tr>
<tr>
<td>Total Load [kN]</td>
<td>40</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Load distribution</td>
<td>4-points</td>
<td>4-points</td>
<td>Uniform</td>
</tr>
<tr>
<td>Distance of point load from supports [m]</td>
<td>1.2</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>N° of sections with thermocouples</td>
<td>9</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>N° of thermocouples per section</td>
<td>9</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Exposure time [min]</td>
<td>150</td>
<td>86</td>
<td>90</td>
</tr>
<tr>
<td>Safety criterion reached</td>
<td>Displacement rate</td>
<td>Failure</td>
<td>None</td>
</tr>
</tbody>
</table>

Temperature profiles

The temperature evolution within the panels during fire exposure has been measured by means of thermocouples along the cross section. Figure 3 presents the position of thermocouples over the thickness for the three tested floors and the directions of each layer. The shielded thermocouples were of type K with a diameter of 1.5mm, drilled inside the specimens by means of an appropriate driller that ensured the perfect straightness and placed in a bore hole having approximately 3mm diameter.

Due to its high number of thermocouples (9 sections along the span and 9 thermocouples per section) and to the certainty of thermocouple position, Test-1 has the most certain documentation on temperature profiles over the CLT thickness. For this reason, in this paper are compared the measured and calculated temperatures only for the Test-1. Concerning the Test-2 and the Test-3 only the comparison of measured and predicted deflections are presented. In Figure 4 are plotted the registrations of Test-1 thermocouples placed at 17mm, 50mm, 67mm and 84 mm from the bottom exposed side during the test.
The solid black line is the considered mean temperature from the nine sections along the panel’s span. The significant difference between measured temperatures from different sections derives from the local delamination of timber pieces that yields a local increase of temperatures.

**Charring rates**

Starting from the temperature profiles registered by the thermocouples during the test and assuming 300 °C to be the wood charring temperature, one can simply derive the average charring rates $\beta_{\text{mean}}$ over the CLT thickness. Table 2 presents the average computed charring rates for several layers of the three tests during the fire exposure, considering mean temperatures from the available sections. The numbering of layers follows the order of layers exposed to fire.

<table>
<thead>
<tr>
<th>Test-1</th>
<th>Layer</th>
<th>Depth [mm]</th>
<th>$\beta_{\text{mean},i}$ [mm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>17</td>
<td>0.67</td>
</tr>
<tr>
<td>1/2(2)</td>
<td>16.5</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>0.68</td>
<td></td>
</tr>
</tbody>
</table>

For the three tests, the great increase in the charring rate when passing from the first to the second layer clearly shows that a delamination of layers occurred. Moreover, the charring rate within layer 2, directly exposed to fire after the delamination of layer 1, is about the double of the previous charring rate, exactly as established by the design approach of initially protected surfaces of Eurocode 5. Concerning Test-1, the charring rate across interfaces of layers 2/3 and layers 3/4 nearly
respected the charring rate of solid wood (0.65 mm/min in EN 1995 1-2) and therefore no significant delamination phenomena should have occurred.

Dealing with Test-2, it was not possible to estimate the charring rates for more than the second layer, due to the shortness of the fire test. Finally, the calculated charring rates for Test-3 highlighted possible delamination phenomena for more than the first layer, confirming the general observations during the test previously described. However, the lower certainty on temperature registration for Test-3 compared to Test-1 may somehow overestimate the estimated charring rates.

**Deflection of fire exposed CLT floors**

During the fire tests on loaded CLT floors, the mid-span deflection was constantly measured by means of Linear Variable Displacement Transducers (LVDT) placed on the upper side in compression. Figure 6 plots the evolution of mid-span deflection during fire exposure of the three tested CLT. Test-1 reached the safety criterion of maximum displacement rate at 150 minutes, highlighted by the acceleration of the increase of its mid-span displacement curve versus time. This means also that the specimen was close to the failure point at that time. The specimen of Test-2 failed on the tension side at 86 min, as the respective displacement curve shows. Finally, Test-3 was stopped after 90 minutes without reaching any safety criterion. The evolution of the mid-span deflection for Test-3 shows some acceleration at about one hour of fire exposure, with a subsequent smoother trend. The calculated charring rates and the observations during testing highlighted possible delamination phenomena at this exposure time which can explain the increase in displacement rate. The evolution of Test-1 deflection shows a slight trend variation due to the progressive charring of layers with or without load-carrying capacity. On the contrary, the floor of Test-2 presents a nearly linear trend of deflection variation until the failure, since almost only the first thick longitudinal layer has been affected by the combustion.

**Modeling**

In this section the modeling procedure to reproduce the deflection of tested CLT floors is presented, as well as the design approaches based on the RCSM which will be compared. Two types of advanced modeling are implemented: heat transfer modeling and thermo-mechanical modeling. The heat transfer modeling is based on temperature prediction with SAFIR (SAFIR, 2011) software. Then, the mid-span deflection of the floor is predicted using the Bending-Gradient plate theory for thick...
Advanced modelling of heat transfer

The temperature evolution over the panels’ thickness during fire exposure was predicted with SAFIR software. CLT panels were modeled as solid wood, with perfect connections between layers. The density of specimens was measured and values in accordance with the mean value of 420 Kg/m$^3$ specified in EN 338 (CEN, 2009) have been found. Preliminary analyses investigated on the value to use for moisture content, fitting the predicted temperature to thermocouples registrations for Test-1, leading to the value of 12%. The emissivity ($\varepsilon$) of the modeled wood was set to 0.8, while the coefficients of convection of heated ($h_h$) and unheated ($h_c$) surfaces were assumed to be respectively 25 W/m$^2$K and 4 W/m$^2$K. One dimensional uniform mesh of 1 mm was applied as a discretization over the panel thickness for the temperature prediction. Figure 7 plots the comparison between predicted and experimental temperature profiles during Test-1 across the specimen thickness. The falling-off of layer 1 of Test-1 pointed out in Table 2 and Figure 5 probably leads to the sharp increase of the measured temperatures at 20 minutes at the interface between the first and the second layer (curve for 17mm) and at half-thickness of the second layer (curve for 33.5mm). Globally, the predicted temperatures are in good agreement with the measured values during the fire test. However, for high exposure times (at deep sections), the predicted temperatures are slightly lower than measured temperatures. This can be due to the heat transfer modeled neglecting any falling off of wood during fire exposure. Indeed, even if large detachment of the whole layers were not observed, the local falling of wood pieces was visible during testing and could lead to a progressive increase of measured temperatures.

Thermo-mechanical modeling

The thermo-mechanical behavior of CLT floors has been modeled with a “multilayer” model, with each layer having the mesh thickness of 1 mm. Wood is an orthotropic material with three principal axes and therefore its elastic behavior is defined by three Young’s moduli, three shear moduli and three Poisson’s ratios. However, since within timber boards of CLT is not possible to know the local orientation of wood axes, wood can be modeled as a transversely isotropic material (Franzoni, Lebée, Lyon, & Foret, 2016a), (CEN, 2009) having only a longitudinal ($0^\circ$) and transverse ($90^\circ$)
direction. Further analyses highlighted the negligible influence of Poisson’s ratios on the deflection prediction and therefore are set to zero. Since no characterization of the raw material has been done, the elastic moduli of wood according to strength class C24 of EN 338 (CEN, 2009) and a rolling shear modulus \((G_{90})\) of 50 MPa were considered (Table 3).

<table>
<thead>
<tr>
<th>Modulus of Elasticity</th>
<th>(E_0)</th>
<th>(E_{90})</th>
<th>(G_0)</th>
<th>(G_{90})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness [MPa]</td>
<td>11000</td>
<td>370</td>
<td>690</td>
<td>50</td>
</tr>
</tbody>
</table>

Once the temperature profile is established for each considered exposure time, the elastic moduli changed as a function of temperature using the reduction coefficient \(k_{\theta,E}\) given by the EN 1995 1-2 (CEN, 2004) laws (Figure 9). Different reductions of Young’s modulus for the upper or lower part of the CLT floor, that work respectively in compression and in tension, have been taken into account. Since no reduction coefficient of the shear moduli has been given in the Eurocode, the same law as compressive Young’s modulus has been adopted for them. Finally, with the reduced properties for each 1mm mesh, the mid-span deflection is computed with the Bending-Gradient plate theory for thick layered plates (Lebée & Sab, 2011). This theory is an extension to laminated plates of the Reissner-Mindlin theory for thick homogeneous plates. Contrary to the Kirchhoff-Love theory of thin plates, this theory consider non-negligible transverse shear deformation of the cross section, taking into account the shear compliance of the panel for the deflection prediction.

Therefore transverse shear effects, which sometimes play a crucial role in CLT panels in bending, can be well predicted with this approach. The Bending-Gradient plate model has been recently applied to predict the mechanical behavior of regularly spaced CLT panels (Franzoni, Lebée, Lyon, & Foret, 2016b) and the buckling of CLT (Perret, Lebée, & Sab, 2016). According to this method, the layers are homogenized with a semi-analytical procedure in order to obtain the equivalent out-of-plane bending and shear stiffnesses of the panel. This theory can predict the linear elastic behavior of the plate and considers perfect simple support boundary conditions. The integrity of support conditions after the fire tests was checked to satisfy the modeled boundary conditions. This calculation is performed at each increment of exposure time in order to predict the evolution of mid-span deflection.

Reduced Cross Section modelling

Since recent studies pointed out that the current version of the RCSM is not always conservative, several attempts to improve the RCSM without changing its simple approach have been done. In the next paragraphs, three methods to determine the geometry of the effective cross section are
presented. Once the effective geometry is established, properties at ambient conditions of C24 timber from EN 338 are combined with the plate theory in order to predict the mid-span deflection according to the RCSM.

**Existing approaches**

- **RCSM-1.** The first existing RCSM approach has been derived by (Schmid, König, & Just, 2012) fitting results of advanced numerical simulations on timber members in bending. According to this method, the charring rate is uniform, while the ZSTL \( (d_0) \) is derived as a function of panel’s total thickness and of the exposed side. Applying this approach to the three tested panels leads to the following values of \( d_0 \): Test-1 \( = 11 \text{ mm} \); Test-2 \( = 10.7 \text{ mm} \); Test-3 \( = 10.8 \text{ mm} \).

- **RCSM-2.** The second simplified design model (Frangi A., Fontana, Hugi, & Jobstl, 2009) is based on the initially protected surfaces approach of the Eurocode, in order to take into account the delamination phenomenon already discussed. Hence, a double charring rate (1.3 mm/min) is considered after the complete charring of each layer (delamination moment), until the char depth exceeds 25 mm. Beyond these 25 mm of char depth, the charring rate returns at 0.65 mm/min. Within this method, the value of ZSTL \( (d_0) \) was not established; hence the value set by EN 1995 1-2 (7mm) is combined with RCSM-2.

**New suggested RCSM approach**

More than the two presented existing models, a new simplified approach based on the RCSM is suggested in this paper (RCSM-3). The principle is to define the reduced section of the floors taking into account the reduction factor for modulus of elasticity \( k_{0,E} \). In other words, the basic idea is to calculate the reduced thickness of each discretized mesh by the advanced modeling as a function of the temperature calculated with Safir software. Then, for each fire exposure time, the zero stiffness layer (ZSSL) of the floor is the sum of all reduced thicknesses of meshes.

The suggested derivation of the ZSSL is therefore based on the hypothesis that at established reduction of stiffness corresponds the same reduction of geometry (or “loss of material”). The studies of (Franzoni, Lebée, Lyon, & Foret, 2016b) and (Franzoni, Lebée, Lyon, & Foret, 2016c) showed that this hypothesis is valid when dealing with the bending deflection, without contribution of transverse shear. On the contrary, such hypothesis is not anymore valid concerning the transverse shear deflection. However, since the geometry and the lay-up of the considered panels yield a low contribution (in the range of 10%-12%) of transverse shear to the global deflection, this principle can be applied to the tested floors with a low margin of error. When plotting the estimated ZSSL for the three tests versus the exposure time, the plot of Figure 10 can be found. From Figure 10 it is clear that the ZSSL increases during exposure time, reaching values much higher than the constant 7 mm prescribed in EN 1995 1-2. On the basis of Figure 10, values of ZSSL as a function of time are therefore suggested, in order to take into account the increasing heat flux received by the CLT panel during fire exposure. Finally, a simplified design approach can be obtained setting four values of zero stiffness layer for four ranges of time as in Table 4. The slight differences between the estimated values of ZSSL presented in Figure 10, for the three tests, show that the four values suggested in Table 4 can be used for the new suggested RCSM.

<table>
<thead>
<tr>
<th>Time t [min]</th>
<th>0&lt;t&lt;20</th>
<th>20&lt;t&lt;40</th>
<th>40&lt;t&lt;60</th>
<th>t&gt;60</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZSSL [mm]</td>
<td>10</td>
<td>14</td>
<td>17</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 4. Suggested values of ZSSL as a function of exposure time**
Comparison

The comparison between the experimental and predicted mid-span deflection by advanced and RCSM modeling are showed from Figure 11 to Figure 13. As already introduced, the RCSM-1 method is according to (Schmid, Konig, & Just, 2012), the RCSM-2 is according to (Frangi A., Fontana, Hugi, & Jobstl, 2009) and RCSM-3 considers the ZSSL as a function of time (Table 4). For the three approaches based on reduced cross section, the $k_0$ used for the calculation of ZSTL and ZSSL are computed as in EN 1995 1-2 (Figure 2).
The advanced modeling based on reduced properties returns the mid-span deflection that less deviates from experimental results for the three tests. The evolution of the deflection predicted by all RCSM methods shows plateau corresponding to the non-contribution of cross layers to global stiffness but not highlighted by test results. By contrast, the advanced modeling based on reduced stiffness is able to follow the experimental evolution of deflection, showing that the actual phenomenon is a progressive reduction of properties and not a reduction of geometry. The RCSM-3 based on the time-dependency of the ZSSL gives a better description of the measured deflection.
compared to other RCSM approaches. The RCSM-1 approach underestimates the deflection of the three fire tests. Despite of the delamination of the first layer in Test-1 previously highlighted, the RCSM-2 (derived to take into account such phenomenon) overestimates the Test-1 deflection. The deflection of Test-2 is underestimated by both existing RCSM approaches. Dealing with Test-3, all the RCSM methods show similar slope of the deflection evolution trend, but with an offset due to the different ways of estimating the residual cross section. Indeed, the double charring rate considered by RCSM-2 compensates somehow the higher values of the additional layer to remove of RCSM-3, while RCSM-1 predicts lower deflection since it considers lower values of $d_p$.

In the final parts of Figures 11 and 12, most of the methods underestimate the deflection. This is because both of specimens were close to failure at those high exposure times and hence the increasing non-linear contributions to deflection cannot be taken into account by the plate theory.

Discussion

The stiffness-based approach presented in this paper shows that, for the three fire tests, the calculated deflections are in agreement with the measured deflections while the existing RCSM approaches globally deviate from test results. However, as is known, the existing RCSM approaches were originally derived for predicting the load-carrying capacity of timber elements, hence, the differences observed between measured and calculated deflections are understandable.

Consequently, in order to correctly model the fire behavior of CLT floors, it could be interesting to enhance the research in order to define the best method for the designs of these structural elements. Perhaps the method based on ZSSL suggested in this study could be interesting for CLT floors, but has to be further investigated for different configurations and different load levels.

Dealing with the sensitivity of predicted results, the predicted results can be affected by the variation of input material parameters. Unfortunately, the raw material of CLT has not been tested in ambient conditions and the input mechanical properties for the modeling are based on mean stiffnesses given by C24 strength class in EN 338. However, the model to predict the panel’s mechanical behavior in ambient conditions implemented in this work (the plate theory) is based on linear elasticity, like common engineering methods. Hence, a given variation of wood stiffnesses yields the same variation of mechanical response. On the contrary, physical properties of the modeled material such as conductivity, relative humidity or volume specific heat can lead to significant variation of predicted temperatures and therefore even greater variation of the predicted mechanical behavior with the advanced modeling. More accuracy in determining the physical and mechanical properties of the raw material is therefore encouraged for future researches.

The delamination phenomenon is a complex mechanism influenced by a multitude of parameters and therefore very difficult to predict. It can occur locally, with delamination of small pieces of wood, or with a complete falling-off of layer. The charring rate estimation with thermocouples registration pointed out partial delamination phenomena for the three considered tests. In particular, the calculated charring rates of Test-3 pointed out delamination of more than the first layer. The same Test-3 showed an acceleration of mid-span deflection that may be due to such delamination phenomenon. On the contrary, the less pronounced delamination of Test-1 and Test-2 had no visible influence on the global evolution of deflection. This discrepancy confirms the complexity of this phenomenon and suggests enhancing the studies about the effective influence of delamination on structural fire safety of laminated timber structures. It seems that the existing RCSM-2 model can lead to quite conservative results in the cases without delamination and to better results in cases of delamination. The suggested RCSM-3 based on the time-dependency of ZSSL is based on heat-transfer prediction of solid wood, neglecting the delamination. Taking into account this phenomenon would lead to higher predicted temperatures profiles, further increasing the already rather high values of ZSSL.
Conclusion
In the present paper, the experimental deflection of fire exposed CLT floors has been predicted with advanced modeling based on reduced properties and the simplified approach of the RCSM. The best way to correctly simulate the fire behavior of CLT floors is by means of an advanced modeling. However, the methods based on the RCSM approach are more convenient for practical applications by engineers. This is the reason why it would be interesting to find the best RCSM method for the calculation of deflection and perhaps the design of CLT in fire conditions.

The results presented in this paper show that RCSM-based on the time-dependency of the additional layer to remove could be a relevant method for simulating the fire behavior of CLT floors. The approach of the present paper is a research path which seems interesting to investigate, in order to define the relevant method for the fire design of CLT floors to be taken into account by the on-going revision process of EN 1995 1-2 (CEN, 2004). However, this method has to be further investigated for different configuration of floors and under different load conditions.

References


