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INTER - International Network on Timber Engineering Research

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Peer review of the abstracts before the meeting and of the papers during the meeting

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Publication of the papers and the discussion in proceedings

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All decisions including the appointment of the chairperson or the location of annual meetings are made by the participants attending a meeting.

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An Improved Design Model for Fire Exposed Cross Laminated Timber Floors

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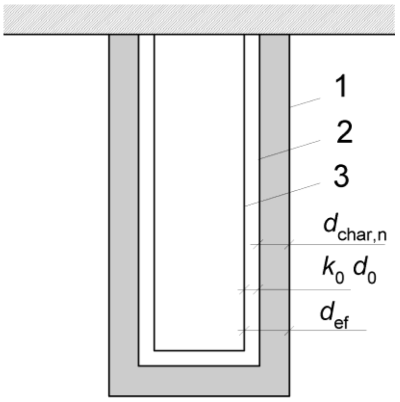
1 Introduction

The solid wood product cross-laminated timber (CLT) is a successful building product due to the attractive surface and the sustainability provided. However, the most important characteristic of a building product is the design efficiency (Jones et al., 2016) accounted by design models. Due to the complex behaviour of wood in fire in general and in particular of CLT, simplified fire design models are essential for designers to verify the fire resistance of timber structures. Currently, the fire part of Eurocode 5, EC5, (CEN, 2004) does not give design rules valid for CLT.

The popular effective cross-section method (ECSM) considers (i) the reduction of a timber section by charring and (ii) the reduction of strength and stiffness by an additional so-called zero-strength layer (ZSL), d_0. The idea of the method is that an effective cross-section (CS) with strength and stiffness properties as at normal temperature provides the same resistance as the heated, fire exposed section (Schaffer et al. 1986). In the past, some CLT producers have optimized their products in a way that the ZSL of 7 mm intended for solid timber members was located solely in the transversal layers. Thus, the reduction by the ZSL has no effect on the verification. At the World Conference on Timber Engineering 2010, WCTE 2010, a first design model for fire exposed CLT was presented (Schmid et al., 2010). This method (the 2010 method) aimed to use the terminology of EC5 where the ZSL is traditionally defined (traditional ZSL), i.e. simply as the difference between the residual and the effective CS, see Eq. 1. However, the 2010 method has some limitations and draw-backs, which are discussed in Section 3 of this paper. For this study, the current CLT product portfolio was investigated and a more flexible terminology, i.e. a new definition of the ZSL, was considered to develop design models for CLT in bending with its exposed side in tension relevant for floor elements.



Key:

1... original CS d_0 ZSL

2... residual CS $d_{char,n}$ char depth

3... effective CS d_{ef} effective char depth

Figure 1. Graphic definition of the ZSL (d_0) modified from Eurocode 5 (CEN 2004).

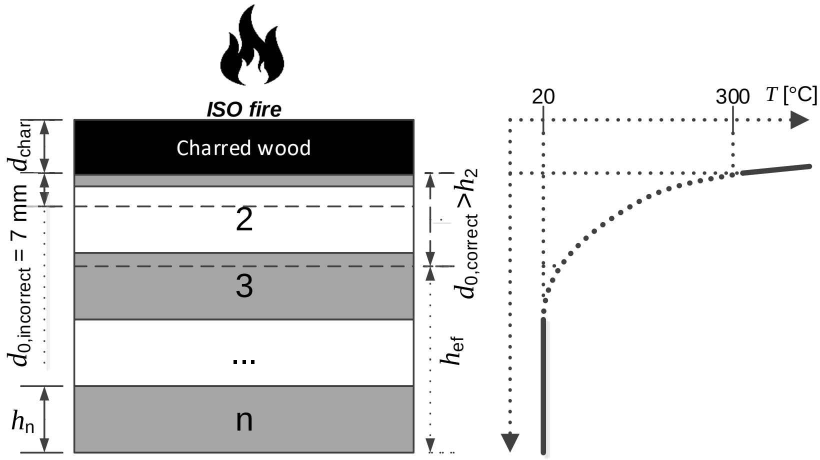


Figure 2. Overlay of a CLT layup with a typical temperature profile under ISO 834 fire.

2 The effective cross-section method for fire exposed timber members

The design model ECSM for the design of timber members exposed to fire was based on direct measurements of the strength in tension and compression and the stiffness at various temperatures using clear wood samples. The results were overlaid with temperature profiles observed in members exposed to standard fire (Schaffer et al. 1986). The relative mechanical properties were lumped together over a depth of about 40 mm. Although the proposed ZSL of 7.62 mm fits well for glued-laminated timber in bending at 30 min standard fire exposure (fire exposed on three sides), understanding the development of the ZSL suggested by Schaffer et al. (1986), it is clear that the concept is generally flawed as the stress distribution over the depth in a bending member is not constant. Further, the two-dimensional temperature distribution in members does not allow for a linear application of the "lumped strength concept" suggested by Schaffer et al. (1986). Thus, the simplified model was investigated for beams and columns by several authors and improvements were suggested by Schmid et al. (2012). It was found that many fire resistance test results cannot be used for the verification of the ECSM or that results indicate deviating ZSLs, see Schmid et al. (2014). For the revision of EC5, it is expected that an improved ECSM will be proposed for timber beams and columns based on further investigations.

3 The 2010 design model for CLT

The design model presented for CLT (Schmid et al. 2010) was determined conducting thermal simulations with SAFIR (Franssen 2007) and mechanical simulations with a self-written software code, CSTFire.

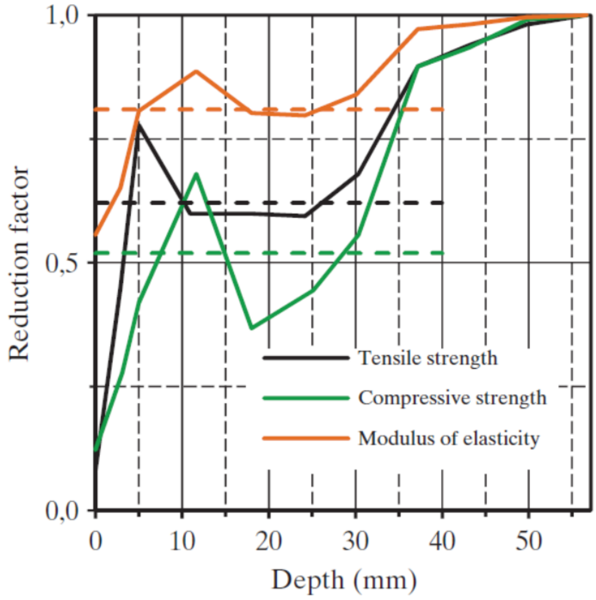


Figure 3. Relative strength and stiffness vs. distance from the char line as used in (Schaffer et al. 1986). From Schmid et al. 2015.

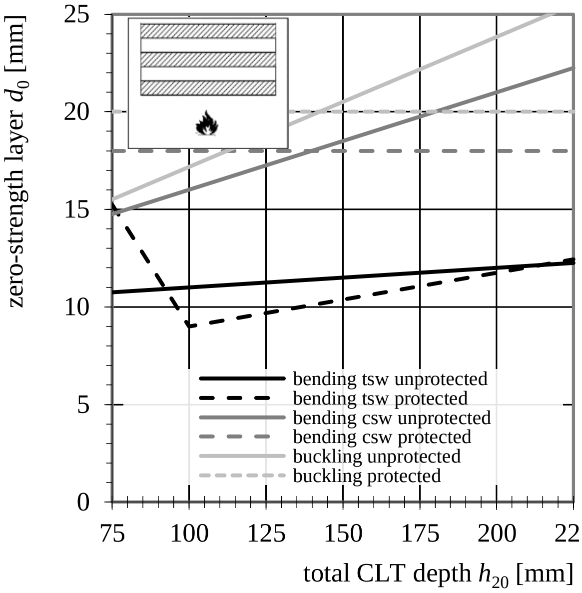


Figure 4. Zero-strength layer for five layer CLT (Schmid et al. 2010) with exposed side in tension (tsw) and compression (csw) and for buckling.

The methodology, verified by means of model scale and large scale fire tests in bending, is presented in detail in Schmid et al. (2018b). While in EC5 a general ZSL got implemented ($d_0 = 7mm$), the 2010 model for CLT gives linear functions depending on the layup, the state of stress on the fire exposed side and the depth of the product. In 2010, linear equations for three, five and seven layer CLT were given, e.g. for five layer CLT in Figure 3. The original ZSL for bending members was developed for single span beams with the exposed side in tension (tsw); the corresponding value for five layer CLT is between 11 and 12 mm, see Figure 4. In some cases, the temperature impact depth, i.e. temperatures above the normal in the temperature profile of about 40 mm beyond the char line (assumed to be at 300°C) exceeds the transversal layer as qualitatively given in Figure 2. For the extreme case when the residual section's outer lamella on the heated side is a transversal layer, the ZSL would be greater than the thickness of the transversal layers which is unable to carry loads perpendicular to the lamellae. In this case, it is obvious that the ZSL for CLT exceeds the depth of the transversal layer and is, thus, larger than 7 mm. This is due to the definition used in EC5 implicitly given in Figure 1, described using the residual depth h_{res} and the effective depth h_{ef} as follows:

$$d_0 = h_{res} - h_{ef} \quad (1)$$

Since 2010, the CLT production and the use has increased considerably and the industry pointed out the limited efficiency of the model presented in 2010, which is conservative in many cases. Thus, the authors have decided together with the industry to improve the design concept answering different needs of different end users.

4 The new design concepts

Generally, the room for improvements was defined in the CEN (European Committee for Standardization) Horizontal Group Fire, HGF, as part of the revision of the Eurocode, which should result in a new generation of codes for all materials in 2022. The HGF gave the possibilities for different design concepts on different levels of complexity. Together with the CLT industry, authors defined so-called preferred layups. Within the framework of COST FP1404 (www.costfp1404.com) an enquiry about the available product was performed involving all European CLT producers.

Table 1. Layup of preferred CLT floor elements with layup specification and total thickness of the CLT in mm.

Layup specification	Total thickness $h_{20°C}$
20+20+20	60
40+40+40	120
20+20+20+20+20	100
40+20+20+20+40	140
40+20+40+20+40	160
40+30-40-30-40	180
40+40+40+40+40	200

Twelve CLT layups were identified representing the largest share on the European marked, whereby seven layups are CLT used for floor elements. These three- and five-layer CLT define the preferred layups and are specified in Table 1. For the revision of Eurocode, it was decided for the fire parts that design models can be given on three different levels of complexity.

The intention is to fulfil needs of different groups of end users. These are (1) tabulated values, (2) simplified rules and (3) advanced models. For CLT, it is intended to give tabulated values for typical solutions, the preferred layups, and simplified rules for a more general application of CLT. Advanced models comprise Finite Element simulations. This paper provides data for (1) and (2) performing a large range of simulations using advanced models (3), which are often too complex for everyday use by engineers.

Besides the design models on different levels (1), (2) and (3), it was decided together with the European CLT industry to allow for more open definitions of the ZSL. EC5 contains an intuitive definition of the ZSL, which is the difference between the residual cross-section, see Figure 1 and Eq. (1), i.e. the original cross-section reduced by charring, and the effective cross-section. This definition is appropriate as long as a homogeneous section is available, i.e. with homogeneous strength properties. Since CLT comprises longitudinal and transversal layers cross the load-bearing direction, compare Figure 2, this definition is challenged especially when the last uncharred, outer lamellae is a transversal layer.

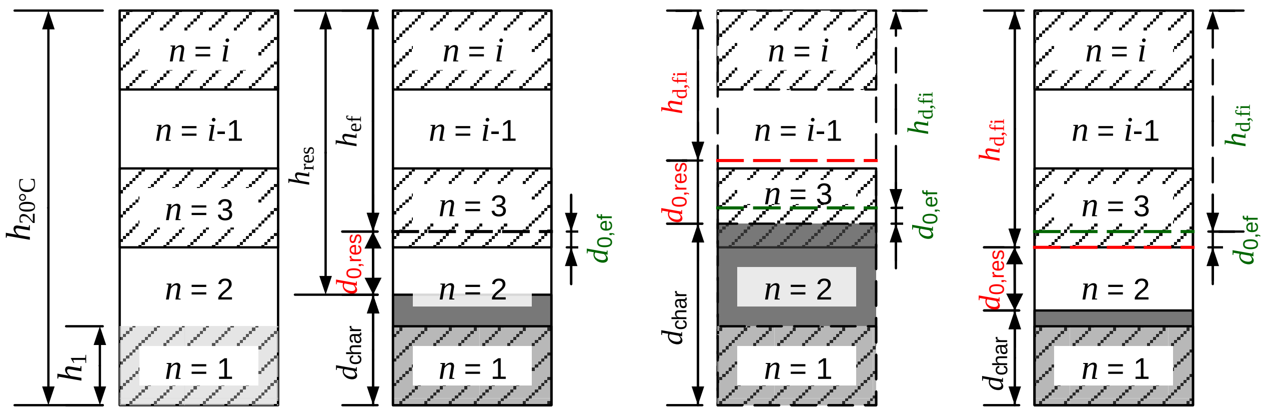


Figure 5. Determination of $d_{0,res}$ and $d_{0,ef}$ for a cross-section and two different design cases.

The improved design model makes use of a further definition, i.e. an effective ZSL, $d_{0,ef}$. This effective ZSL considers only parts of a section with its grain direction parallel to the main load-bearing direction, i.e. the longitudinal layers, parts of transversal layers are not considered. Following the introduction, the hitherto existing ZSL referring simply to the residual cross-section is indicated as $d_{0,res}$. The development and differences of both ZSL is shown in Figure 5: The development is consistent regardless the symmetrical structure with an uneven number of layers with the fire exposed layer number 1, see Figure 5 (a). Deducting the char depth in correspondence to an appropriate charring model, e.g. the stepped model or the linear charring rate of EC5, a residual cross-section h_{res} can be determined, see Figure 5 (b). The simulations deliver the corresponding cross-section with equivalent load-bearing capacity with normal temperature material properties as in the fire situation, h_{ef} . Both ZSL (indicated in red and green) are able to describe this effective depth and are intended to be applied for other design cases for this section, see (c) and (d).From (c) it becomes obvious that the determined, effective cross-sections are significantly different and more economic for the effective (green) ZSL while for (d) it is irrelevant whether to use the effective ZSL $d_{0,ef}$ or the traditional definition $d_{0,res}$.

5 Development of the improved design model

The preferred layups given in Table 1 were simulated thermally and mechanically using SAFIR and CSTFire respectively as done for the model presented in 2010, see Section 2. For the model presented here, in addition to the preferred layups further intermediate layups were included aiming for a systematic analysis. Below, the five-step procedure for the development are presented for selected examples and followed by the results of the simulations. In a final step, design models are proposed in Section 6.

5.1 Simulation and analysis procedure

(1.) Prior to any simulation of the load-bearing capacity in bending in the fire situation, the ultimate bending capacity at normal temperature M_{20} was determined. This was done using CSTFire (Schmid et al., 2018b) utilizing a compression to tension strength ratio of $f_t / f_c = 0.9$ as observed in reference tests. Perfect plasticity was assumed in compression. Using standardized strength values does not allow for correct prediction of the ultimate load-bearing capacity (Schmid et al. 2010). The possible plasticity allows for CLT elements exposed on the side in tension (tsw) for a decreased ZSL in the beginning of the fire exposure, i.e. when the first lamellae undergoes charring.

(2.) In a second step, the residual cross-section was simulated including the corresponding temperature profile within the uncharred heated section. In addition to the unprotected case (Type 2), in total ten different cases for initially protected CLT were investigated with temperature fall-off criteria between 270°C and 800°C on the unexposed face of the fire protection, i.e. gypsum plasterboards. In general, the temperature profile drops to normal temperature, i.e. 20°C within about 40 mm for unprotected members. However, this value can be up to 80 mm for initially protected CLT. The effect of the protection was simulated for typical protection applied by the industry. Protection by single and double gypsum plasterboards were simulated. Generally for initially protected CLT, charring is delayed and reduced, thus any protection is favourable. Sufficient anchorage was assumed and fall-off of the gypsum plasterboard(s) was as observed in full-scale fire resistance tests (Just et al., 2010). Gypsum plasterboards Type F (GtF) and Gypsum plasterboards Type A (GtA), typically 15 mm and 12.5 mm thick were included in the simulations which were performed with SAFIR (Franssen, 2007). Fall-off times were taken mainly from tests with timber frame assemblies. Due to the reduced heat accumulation when attached directly to CLT, the fall-off occurs usually slightly later than in case of timber frame assemblies with insulation in the cavity, which was considered in the simulations. However, it should be noted that the database for fall-off times of gypsum protecting CLT panels is rather limited and verification is needed.

(3.) In a third step, the bending capacity of the heated section was calculated; result is the relative capacity with respect to the ultimate bending capacity of Step 1, M_{fi} / M_{20} (blue line in Figure 6).

(4.) In a fourth step, a corresponding CLT section height $h_{ef,calculation}$ with a bending capacity of a cold section corresponding to the simulated heated section was calculated (broken line in Figure 6).

Graphs as presented in Figure 6 were developed for in total 15 CLT layups (preferred layups and intermediate layer thicknesses for a systematically analysis) for initially unprotected and initially protected CLT.

(5.) In a fifth step, the ZSLs were calculated with respect to the available definitions, i.e. the effective ZSL $d_{0,ef}$ and the ZSL $d_{0,res}$ with respect to the residual cross-section (the traditional understanding of the ZSL). While the latter follows a simple relationship, described in Eq. (1), for the effective ZSL the layup was considered, i.e. the location of the longitudinal layers which are represented by the grey highlighted zones in Figure 6. Thus, depending on the progression of char, i.e. the residual cross-section, a so-called relevant cross-section (neglecting uncharred transversal layers if they are the outer layer) was defined, see Figure 7.

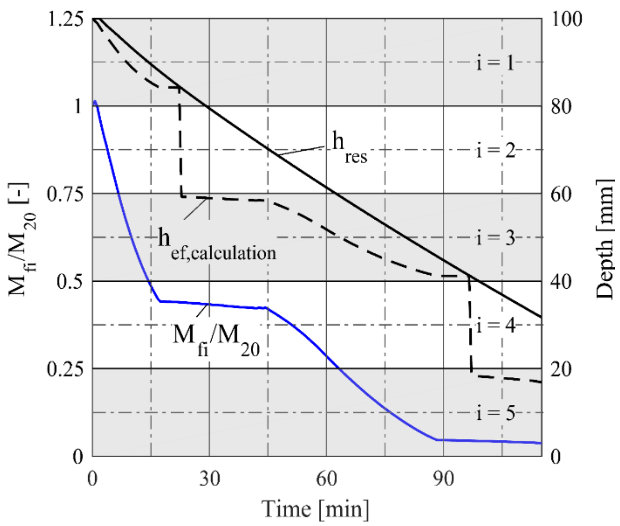


Figure 6: Residual cross-section h_{res}, simulated relative bending capacity M_{fi}/M_{20} and the corresponding section height $h_{ef,calculation}$ of a five layer CLT (5×20).

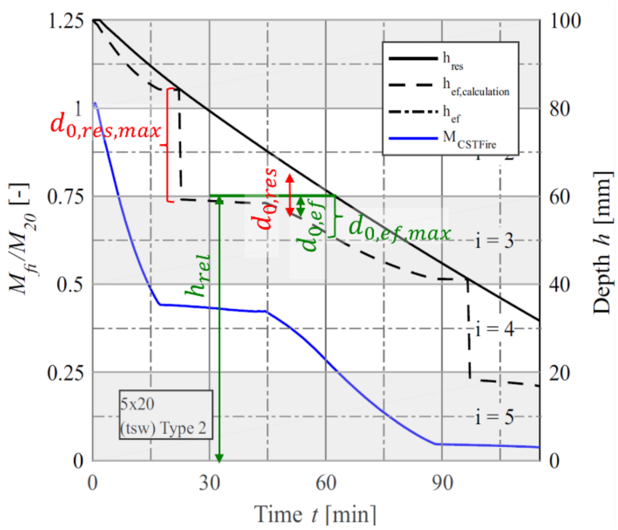


Figure 7: CLT shown in Figure 6 with the development of the effective ZSL considering a relevant depth considering layers 3 to 5 only during charring of layer 2 (transversal layer).

In Figure 7, the relevant cross-section between about $t = 30$ and $t = 62$ min is shown. Further, Figure 7 indicates both ZSL for about 50 min. Finally, Figure 7 shows maximum ZSLs over the simulated time of 120 min. In Figure 7, it is clearly visible that the traditional ZSL at about $t = 25$ min is larger than 20 mm, i.e. the thickness of the transversal layer $i = 2$.

The ZSL for this CLT (5×20), $h_{20} = 100$ mm, is smaller than in the model of 2010 where a practical range for M_{fi}/M_{20} between 40 and 20% had been used, i.e. in this case between about $t = 30$ and $t = 70$ min.

5.2 Data analysis procedure

For the analysis of results, the ZSLs were collected with respect to the definition and the design concept. The following four options were investigated based on Figure 7:

Option A: maximum ZSL over the total time, i.e. until the relative bending capacity M_{fi} / M_{20} drops under about 10%. For the example of the five layer CLT 5x20, this results in $d_{0,res,tot} = 24.8$ mm and $d_{0,ef,tot} = 9.5$ mm.

Option B: As in the model of 2010, a practical load level range for M_{fi} / M_{20} between 40 and 20% has been introduced. For the example of the five layer CLT 5×20, this is $d_{0,res,tot} = 11.1$ mm and $d_{0,ef,tot} = 9.5$ mm.

Option C: The maximum ZSL during charring of the longitudinal layers. For five layer CLT layers $i = 1$ and $i = 3$ were evaluated. For the example of the five layer CLT 5×20, this is $d_{0,ef,i=1} = d_{0,res,i=1} = 4.5$ mm $d_{0,ef,i=3} = d_{0,res,i=3} = 9.5$ mm.

Option D: especially aiming at the design concept of tabulated data, effective ZSL values at 30, 60 and 90 min were evaluated. However, to provide a measure of safety, effective ZSL within ±5 min of these times were considered. For the example of the five layer CLT 5×20, this is $d_{0,ef,R30} = 3.3$ mm, $d_{0,ef,R60} = 9.5$ mm and $d_{0,ef,R90} = 5.4$ mm. Here, it becomes obvious that the values are strongly dependent on the charring model used. Thus, individual charring rates implemented in technical approvals or falling-off of charring lamellae is not acceptable.

5.3 Limitations

The actual model aims for the description of the load-bearing capacity of the residual cross-section by an effective cross-section with material properties as at normal temperature. The ZSLs presented in the following are intended to describe the bending behaviour of CLT when exposed to standard fire which is generally connected with fire resistance classification R. Simulations covered fire exposures of up to 120 min with the exposed side in tension. The mechanical model is a single span beam as current jointing technique does not allow for consideration of two-span floors elements in fire.

Currently, the behaviour of timber members in non-standard fires are investigated, e.g. Lange et al. (2015). So far, authors of this study conclude that the standard fire should be used as reference to compare structural elements. Further, the validity of furnace tests is currently discussed, results show that they are a proper measure for fully developed fires (Schmid et al. 2018a and c).

5.4 Initially protected CLT

Exemplarily, in the following, the development of the ZSL for a five layer CLT 5×30 is shown. Figure 8 presents results for a protected CLT (indicated as configuration type 10 in Figure 8) using double layer of gypsum plasterboards with 15 mm thickness

each and a falling-off temperature criterion of 800°C. It is clearly visible that the bending resistance starts to decrease not earlier than at around $t = 30$ min. This is due to the delay of the heating of the CLT and the possibility of stress redistribution to the compression side where plastic deformations are possible. Further, it is clearly visible that the load-bearing capacity drops at $t = 30$ min before the section gets reduced by char at
$t = 82$ min. Finally, the ZSL can be determined to be slightly below 12 mm. Generally, it can be stated for the investigated initially protected CLT that the Option B could not be successfully applied as some of the elements do not reach those load levels within 120 minutes. Further, it was observed for all results that ZSL thicknesses tend to be slightly higher with protection than without but the maximum for the effective ZSL was not greater than 12 mm.

5.5 Effect of falling-off of charring layers

The value of the ZSL is linked to the temperature profile within a timber member. Generally, the steeper a temperature profile, the smaller the ZSL to compensate for the losses in load-bearing capacity due to heat. On the contrary, the smoother the temperature profile, i.e. the larger the temperature impact depth, the larger the corresponding ZSL. Consequently, fire protection by e.g. gypsum plasterboards entail larger ZSL while falling-off of charring layers would result in smaller ZSL. To simulate falling-off of charring layers, the thermal simulations considered a failure criteria of 300°C in the bond line, then all charred elements were manually deleted and the simulation was continued. Figure 11 shows exemplary the simulation of the ZSL of CLT.

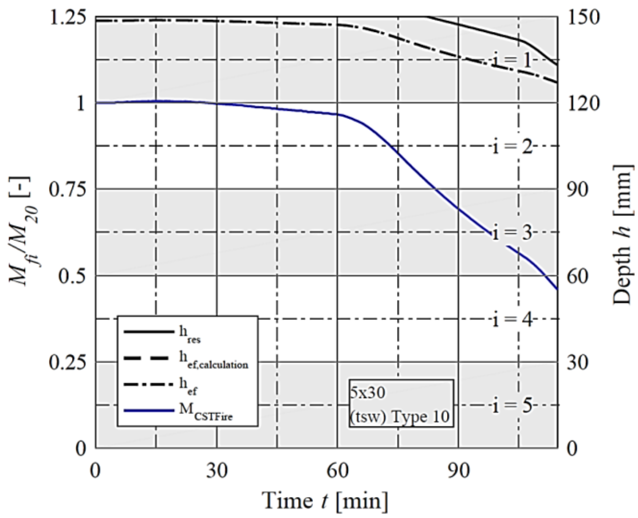


Figure 8: Residual cross-section h_{res}, simulated relative bending capacity M_{fi} / M_{20} and the corresponding section height $h_{ef,calculation}$ of a five layer CLT (5×30) initially protected by 2×GtF (Type 10).

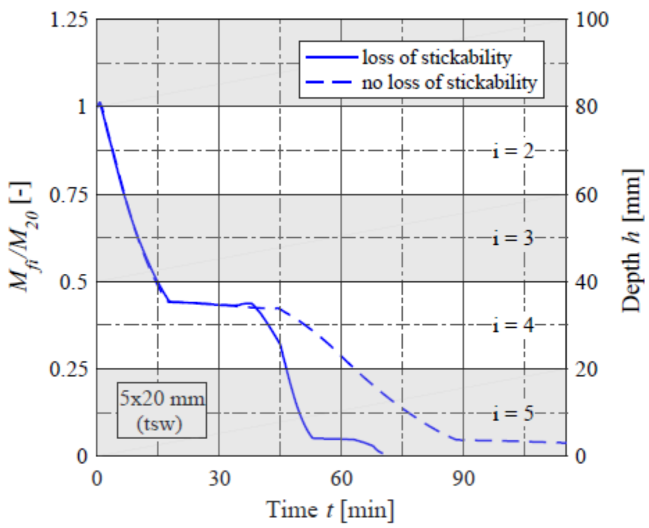


Figure 9: Relative bending moment with and without falling-off of charring layers (loss of stickability) of a five layer CLT.

5.6 Outcome

In the following, the data evaluation of some selected options and definitions of ZSLs are presented.

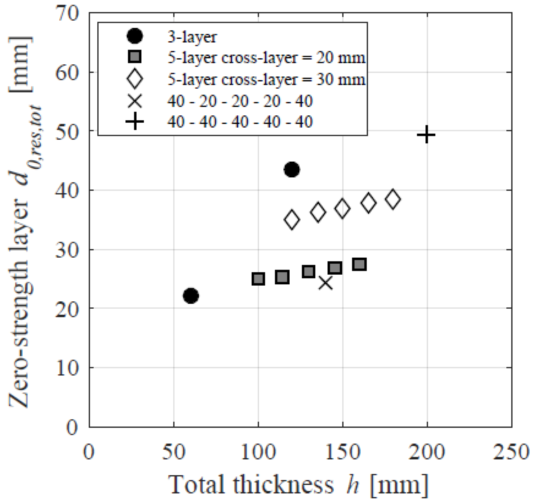


Figure 10: Option A - Traditional ZSL as function of total thickness of the CLT element.

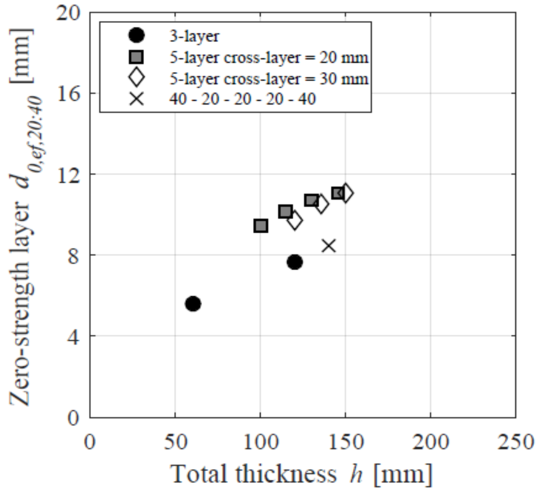


Figure 11: Option B - effective ZSL in a practical range for the relative bending capacity as function of total thickness of the CLT element.

Figure 10 shows the extreme values if a traditional definition for the ZSL, see Eq. (1), was applied. The application would result in large ZSLs and uneconomic design in many cases which was already observed presenting the 2010 model (Schmid et al., 2010). Already in the 2010 model, it was found that the introduction of the practical range between 40% and 20% M_{fi} / M_{20} would result in a higher accuracy for the traditional ZSL. The introduction of the effective ZSL exceeds the improvements implemented in 2010 and results are shown in Figure 11. The introduction of the effective ZSL would result in values between 7 and 12 mm which can be later seen as values implemented in the tabulated data, see Section 6.1.

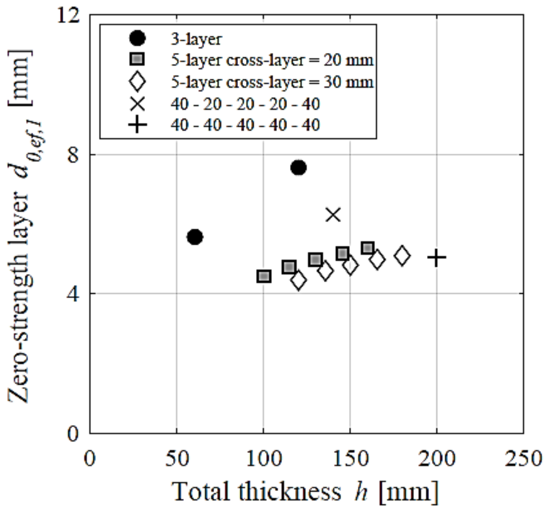


Figure 12: Option C - effective ZSL in layer $i = 1$ as function of total thickness of the CLT element.

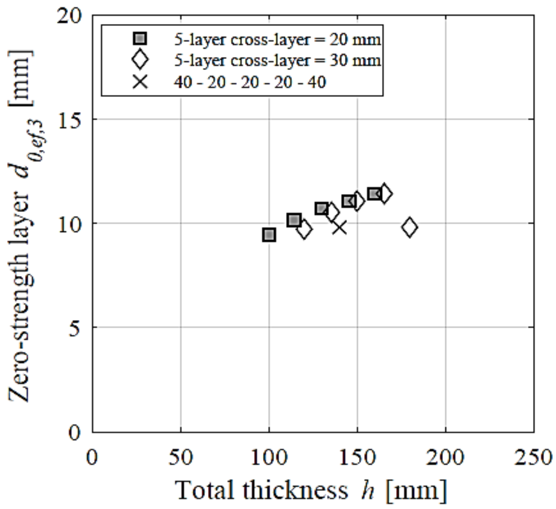


Figure 13: Option C - effective ZSL in layer $i = 3$ as function of total thickness of the CLT element.

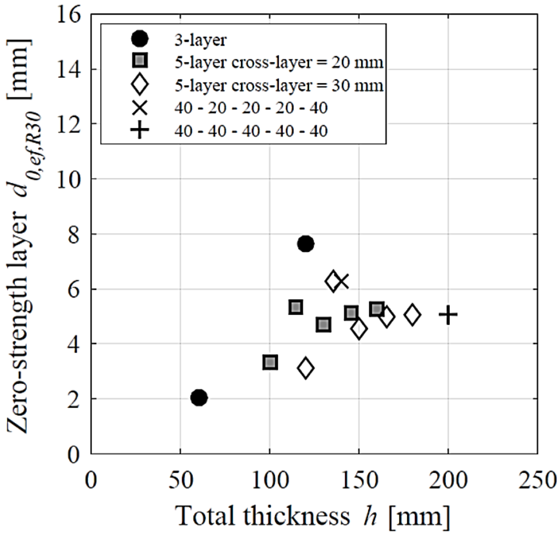


Figure 14: Option D - effective ZSL for R30 as function of total thickness of the CLT element.

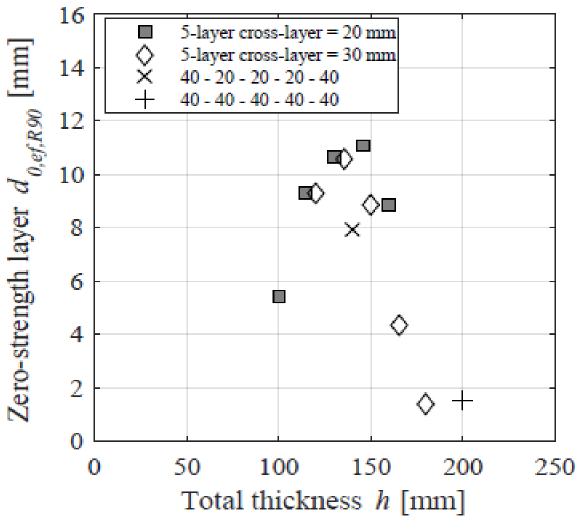


Figure 15: Option D - effective ZSL for R90 as function of total thickness of the CLT element.

An interesting finding showed the analysis of the effective ZSL for the time when charring is in the longitudinal layers $i=1$ (see Figure 12) and $i=3$ (see Figure 13). While the effective ZSL for layers $i=1$ seems to be limited to about 7.5 mm, the effective ZSL for layers $i=3$ is limited to about 12.0 mm.

Findings of Option C were later used to develop the simplified design model, presented in Section 6.2. Exemplarily, results for R30 and R90 are shown for Option D. As for R60, a large scatter of the effective ZSL can be highlighted reaching from about 2.0 mm and 7.8 mm (R30), see Figure 14, and 1.5 mm to about 12.0 mm (R90), see Figure 15.

6 Results

6.1 The tabulated data

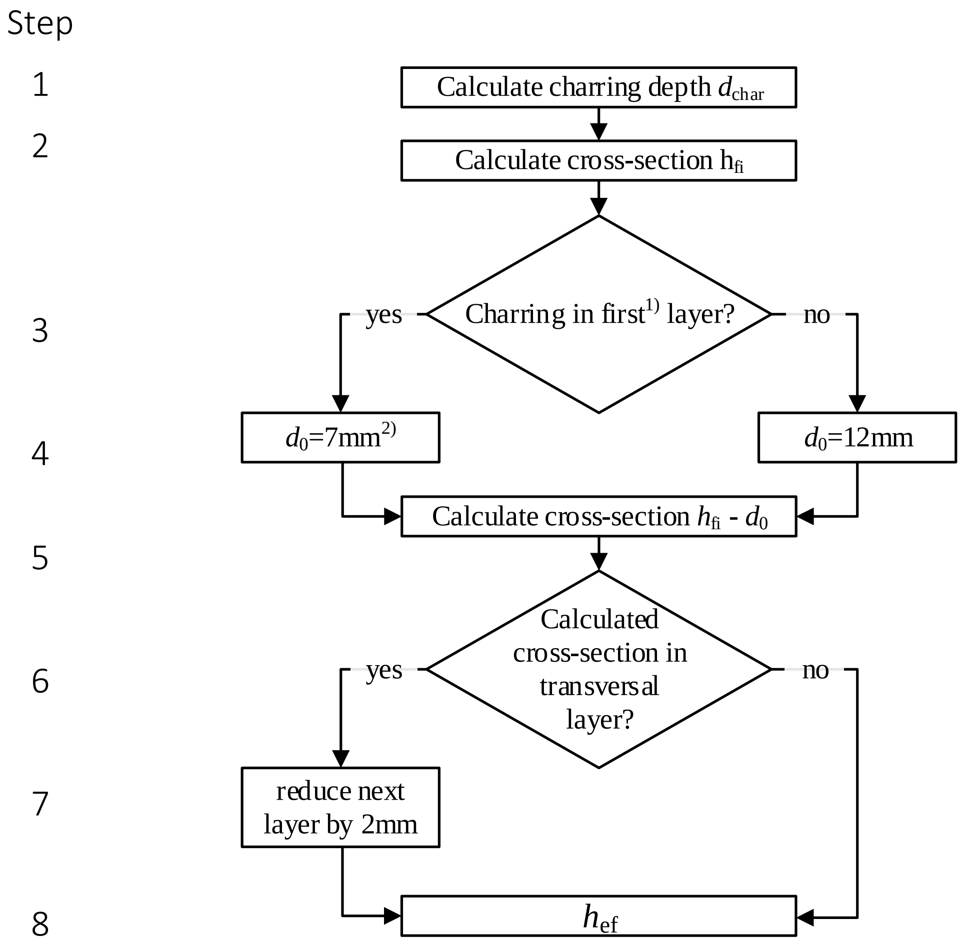
Effective ZSLs are provided as tabulated data for CLT floor elements for 30, 60 and 90 min fire exposure. It should be noted that the values are only valid for the charring model used in simulations whereby the differences to the charring model given in EC5 are limited and acceptable. Charring models defined in ETAs based on tests can not be used together with the values given for this design concept in this Section. Maximum values were found to be 7, 10, and 12 mm, respectively. The individual effective ZSL for the preferred CLT layups are given in *Table 2*.

Table 2. Layup of preferred CLT floor elements with layup specification and total thickness of the effective ZSL in mm.

Layup specification	30 min	60 min	90 min
20+20+20	2.0	7.0	n.a.
40+40+40	8.0	4.0	n.a
20+20+20+20+20	3.0	9.5	5.0
40+20+20+20+40	6.0	5.0	8.0
40+20+40+20+40	5.0	6.0	9.0
40+30-40-30-40	5.0	5.0	3.0
40+40+40+40+40	5.0	5.0	2.0

6.2 The simplified design model "twelve AND two"

The aim of the simplified rule is to increase the application range exceeding the pre-ferred layups.



1) Cover laminations with the same grain direction as the consecutive layer can be considered both as first layer.

2) 7 mm only for initially unprotected CLT; in other cases 12 mm shall be applied.

Figure 16. Determination "twelve and two" simplified design for CLT. The Eight-step procedure to determine the effective cross-section.

A large range of CLT layups was simulated and analysed systematically with respect to available products. Simulations were performed with three- and five layer CLT. The outcome is a simple design methodology which can be applied using the original definition of d_0 since the transversal layers are taken into account explicitly as shown in the flow chart in Figure 16.

To execute the resulting rule, the designer has to check whether the residual cross-section starts (i.e. the depth at the char front) in a longitudinal layer.

- d_0 of 12 mm has to be deducted from the residual cross-section unless the residual cross-section comprises parts of the first layer, then $d_0 =$ 7 mm applies. However, a reduction from 12 mm to 7 mm is only possible if the CLT is initially unprotected due to the increased temperature impact depth for initially protected CLT.
- When the calculated cross-section starts in a transversal layer, the effective depth of the following longitudinal has to be reduced by 2 mm.

6.3 Accuracy of the Simplified Model

The agreement of the model "twelve and two" was compared for the simulated CLT and is shown exemplary for a three and a five layer CLT in Figure 17.

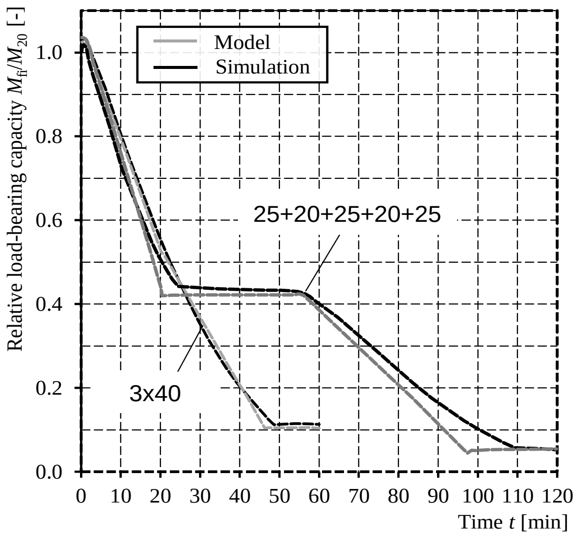


Figure 17: Comparison of the simulated relative bending moment and the result of the model "twelve and two" for two CLT layups.

Deviations are very limited; the model allows for conservative design showing a conservative solution for most of the simulated times. The economic design is granted and maximum deviations can be observed ahead of the plateau of M_{fi} / M_{20}, i.e. during the pre-heating (temperatures between 20 and 100 degrees) of the following longitudinal layer. However, neglecting the step 7 in the design process, compare Figure 16, would result in conservative design close to the end of the plateau (vertical shift of the plateau). The proposed simplified design model "twelve and two" suits also protected CLT where the thermal penetration depth tends to be increased which resulted in higher values for d_0 proposed 2010, see Section 3.

7 Conclusions

Based on the available calculation technique, thermal and mechanical simulation, new definitions for the ZSL, new design concepts and a limited product portfolio two design concepts for CLT floors exposed to fire on the side in tension were developed in this study.

All presented methods base on the ECSM, thus, methods similar to beams and columns can be introduced for CLT in the new EC5. On one hand, tabulated data were made available, on the other hand a simplified model was presented. Both methods were already tested by the industry reference group (COST FP1404/WG2/TG1), both methods seem to be practical, whereby the simplified model “twelve and two” gave more economic results. This is in line with the intention of the levels of the design concepts.

Further work will include the buckling behaviour of CLT whereby the reduction of stiffness is expected to be crucial for wall elements. The design should make it possible to use the actual buckling model implemented in EC5 for normal temperature design. Further, in correspondence to the model presented here, preferred layups and several design concepts will be considered.

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