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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.

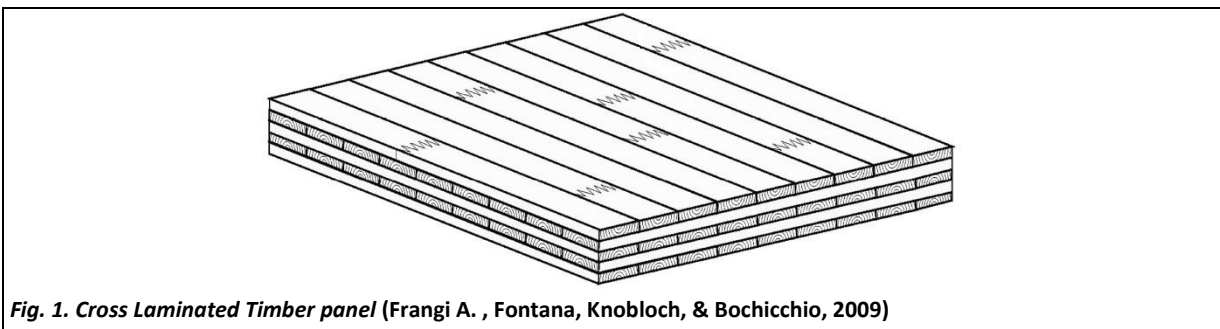


Fig. 1. Cross Laminated Timber panel (Frangi A. , Fontana, Knobloch, & Boichichio, 2009)

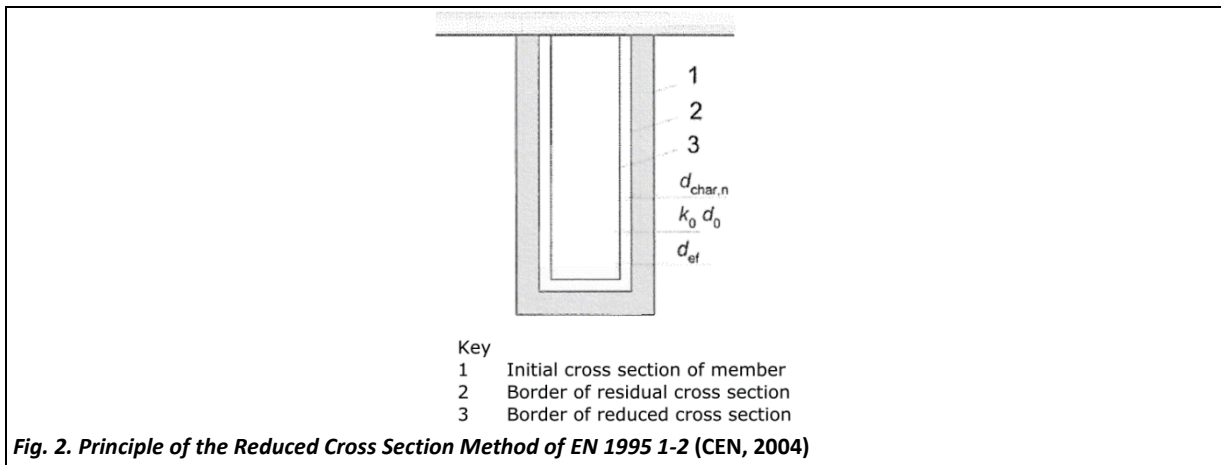
The orthogonal lay-up ensures more uniform mechanical and hygroscopic properties along both directions and allows the use of CLT as full-size floor, wall or roof element. The enhanced properties of CLT compared to solid wood make this product competitive with respect to traditional mineral-based construction 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



36 ambient conditions combined with a reduced cross section of the timber member due to the fire
37 exposure. The reduction of the cross section is defined with two steps: (i) a first reduction due to a
38 uniform charring rate and (ii) an additional removal of a layer considered to have null mechanical
39 properties (also called zero strength layer - ZSTL or d_0 , as in the EN 1995 1-2) in order to take into
40 account the reduced properties of wood in the region close to the char front (Figure 2). The
41 parameter k_0 in Figure 2 takes into account the time necessary to start the wood combustion and its
42 values are $k_0=1$ when the exposure time is more than 20 minutes and $k_0=\text{time}/20$ when the exposure
43 time is less than 20 minutes (see also EN 1995 1-2 (CEN, 2004)).

44



45

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

51 The zero strength layer was originally set to 0.3 inches for bending members (Schaffer, 1984).
52 Subsequently, in EN 1995 1-2 has been reduced to 7 mm and the use for other members than those
53 in bending is implicitly allowed. However, the thickness of the section affected by the thermal
54 gradient depends on the type of the thermal action (ISO or natural fire exposure), the fire duration
55 and the kind of stresses acting on the timber member (tension, compression or shear) (Schmid, Just,
56 Klippel, & Fragiaco, 2015). Recent studies (Schmid, Konig, & Just, 2012), (Schmid, Klippel, Just, &
57 Frangi, 2014), (Schmid, Just, Klippel, & Fragiaco, 2015), (Lineham, Thomson, Bartlett, Bisby, &
58 Hadden, 2016) showed that the predicted behavior of timber members exposed to fire using the
59 RCSM is not always conservative, and the “exact” value of the zero strength layer is difficult to
60 predict since it depends on a multitude of parameters like, for instance, the boundary conditions,
61 the panel’s geometry and the kind of acting stresses. Furthermore, falling-off of layers can occur for
62 the presence of glued interfaces between layers. Indeed, the presence of glue at CLT layers
63 interfaces can influence the fire behavior because of the difference of mechanical properties at high
64 temperatures between glue and timber. When the char front is not yet at the glued interface, the
65 temperature gradient can decrease glue mechanical properties and therefore can lead to premature
66 falling-off of layers and an increase in the charring rate. This phenomenon has been observed in CLT
67 floors exposed to fire in (Frangi A. , Fontana, Hugi, & Jobstl, 2009), and the proposed approach of EN
68 1995 1-2 for initially protected surfaces seemed to well reproduce this delamination phenomenon.
69 However, other studies found very few falling-off of layers (Craft, Desjardins, & Mehaffey, 2011),
70 (Osborne, Dagenais, & Bénichou, 2012) or a falling-off phenomenon that has negligible influence on
71 structural design compared to ambient design of CLT (Klippel, Leyder, Frangi, Fontana, Lam, &
72 Ceccotti, 2014). This discrepancy between test results derives from the multitude of parameters



73 influencing the falling-off effect, like the type of glue, the presence of small gaps between boards of
74 each layer, the glue thickness between layers, the panel's lay-up and so on.

75 Other fire tests on loaded CLT floors can be identified in the literature: (Schmid, Koning, & Kohler,
76 2010), (Menis, Fragiaco, & Clemente, 2012), (Fragiacomo, Menis, Clemente, Bochicchio, &
77 Ceccotti, 2013). Fire tests on loaded timber elements are useful to understand the actual thermal-
78 mechanical behavior of the specimen, but they are expensive, time-consuming and sometimes it is
79 not straightforward to obtain reliable information on the actual load-carrying capacity the specimen.
80 This is also due to the fact that, in most of the cases, the test is stopped before the failure of the
81 specimen for the safety of people and equipment. Therefore, the evolution of panel's deformation
82 during fire exposure is the only information about the variation of mechanical properties during the
83 fire test.

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

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

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

98 Fire tests on CLT floors

99 Materials and Methods

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

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



120 specimen was removed to fire exposure and the fire on its exposed side extinguished with water,
 121 which took approximately 6-8 min.
 122

Table 1. Properties of the tested specimens of CLT floors

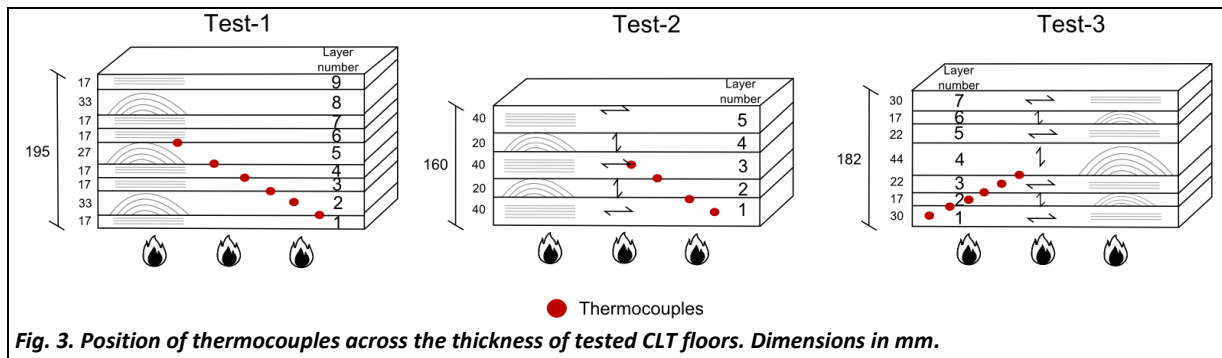
Test number	1	2	3
Span [m]	4.2	4.5	4.6
Width [m]	2.97	2.6	2.97
Thickness [mm]	195	160	182
Total Load [kN]	40	40	60
Load distribution	4-points	4-points	Uniform
Distance of point load from supports [m]	1.2	1.2	-
N° of sections with thermocouples	9	1	4
N° of thermocouples per section	9	4	6
Exposure time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

123

124 Temperature profiles

125 The temperature evolution within the panels during fire exposure has been measured by means of
 126 thermocouples along the cross section. Figure 3 presents the position of thermocouples over the
 127 thickness for the three tested floors and the directions of each layer. The shielded thermocouples
 128 were of type K with a diameter of 1.5mm, drilled inside the specimens by means of an appropriate
 129 driller that ensured the perfect straightness and placed in a bore hole having approximately 3mm
 130 diameter.
 131

131



132

133 Due to its high number of thermocouples (9 sections along the span and 9 thermocouples per
 134 section) and to the certainty of thermocouple position, Test-1 has the most certain documentation
 135 on temperature profiles over the CLT thickness. For this reason, in this paper are compared the
 136 measured and calculated temperatures only for the Test-1. Concerning the Test-2 and the Test-3
 137 only the comparison of measured and predicted deflections are presented. In Figure 4 are plotted
 138 the registrations of Test-1 thermocouples placed at 17mm, 50mm, 67mm and 84 mm from the
 139 bottom exposed side during the test.

140

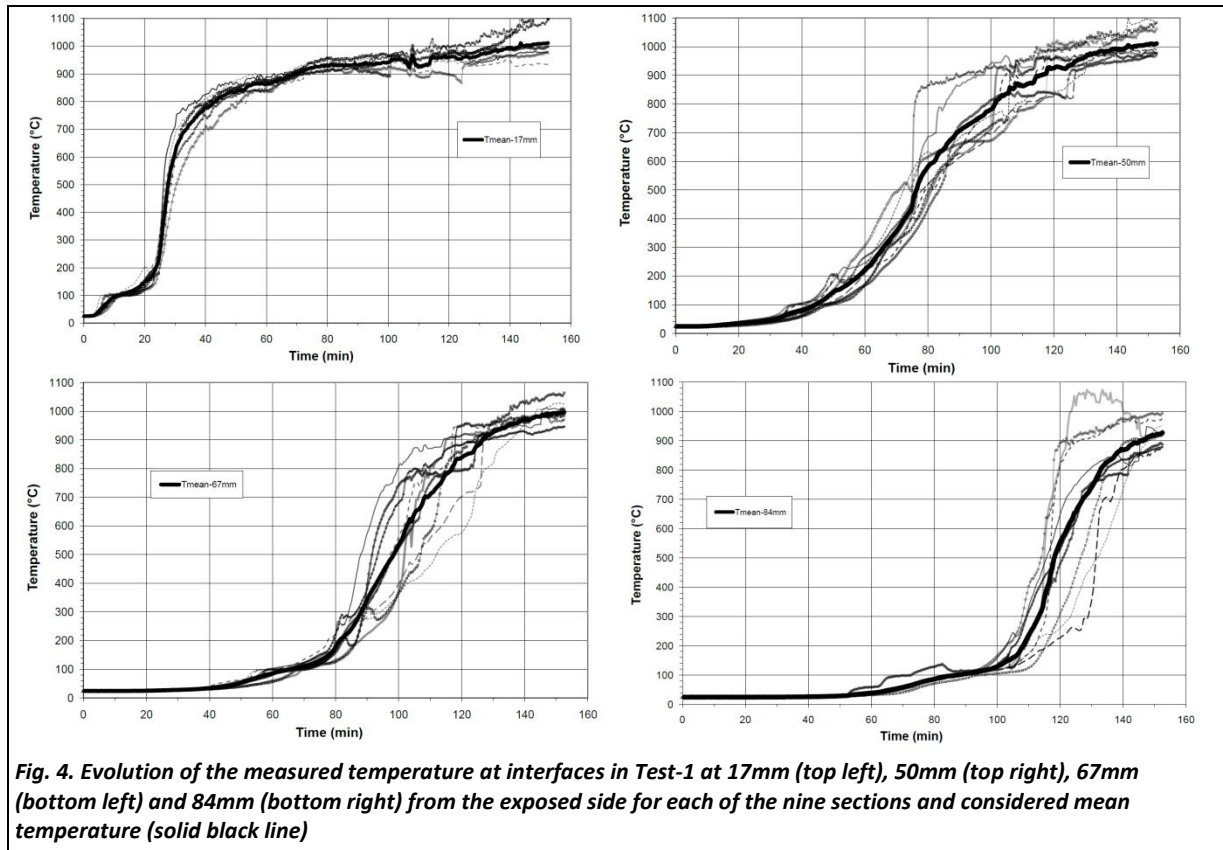


Fig. 4. Evolution of the measured temperature at interfaces in Test-1 at 17mm (top left), 50mm (top right), 67mm (bottom left) and 84mm (bottom right) from the exposed side for each of the nine sections and considered mean temperature (solid black line)

141

142 The solid black line is the considered mean temperature from the nine sections along the panel's
 143 span. The significant difference between measured temperatures from different sections derives
 144 from the local delamination of timber pieces that yields a local increase of temperatures.

145 **Charring rates**

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

151

Table 2. Calculated charring rates for the three fire tests from mean measured temperatures. In green the nearly respected charring rate of solid wood according to EN 1995 1-2 (0.65mm/min) while the red gradient shows higher charring rates.

Test-1			Test-2			Test-3		
Layer	Depth [mm]	$\beta_{mean,i}$ [mm/min]	Layer	Depth [mm]	$\beta_{mean,i}$ [mm/min]	Layer	Depth [mm]	$\beta_{mean,i}$ [mm/min]
1	17	0.67	1	40	0.70	1	30	0.61
1/2(2)	16.5	1.38	2	20	1.34	1/2(2)	8.5	1.70
2	33	0.81				2	17	1.15
3	17	0.77				1/2(3)	11	1.35
4	17	0.68				3	22	1.60

152

153 For the three tests, the great increase in the charring rate when passing from the first to the second
 154 layer clearly shows that a delamination of layers occurred. Moreover, the charring rate within layer
 155 2, directly exposed to fire after the delamination of layer 1, is about the double of the previous
 156 charring rate, exactly as established by the design approach of initially protected surfaces of
 157 Eurocode 5. Concerning Test-1, the charring rate across interfaces of layers 2/3 and layers 3/4 nearly



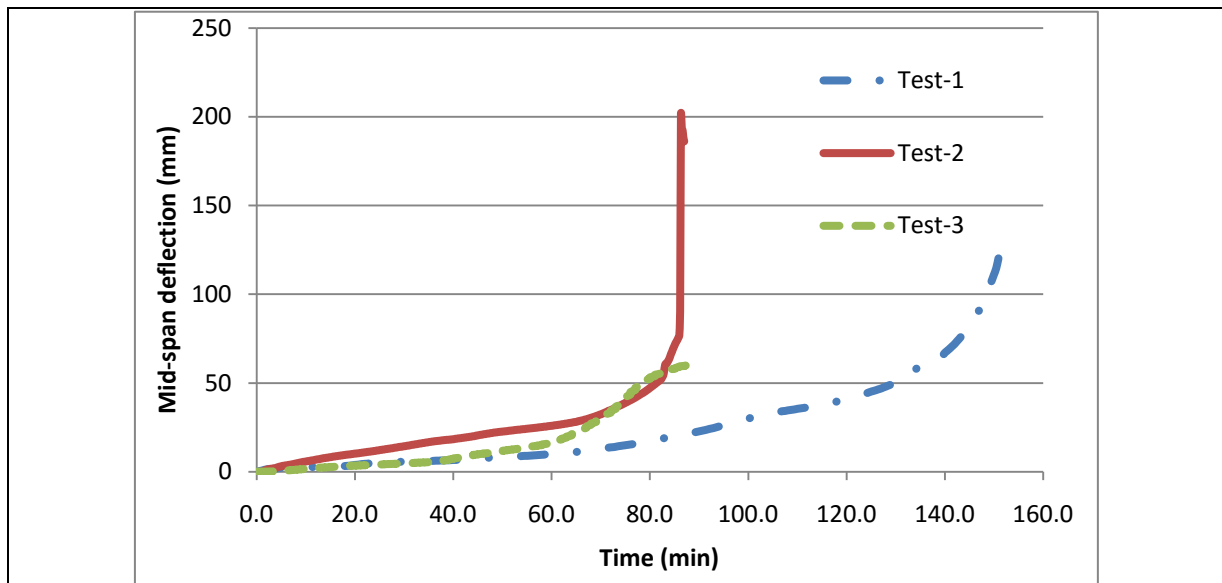
158 respected the charring rate of solid wood (0.65 mm/min in EN 1995 1-2) and therefore no significant
159 delamination phenomena should have occurred.

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

165 Deflection of fire exposed CLT floors

166 During the fire tests on loaded CLT floors, the mid-span, deflection was constantly measured by
167 means of Linear Variable Displacement Transducers (LVDT) placed on the upper side in compression.
168 Figure 6 plots the evolution of mid-span deflection during fire exposure of the three tested CLT. Test-
169 1 reached the safety criterion of maximum displacement rate at 150 minutes, highlighted by the
170 acceleration of the increase of its mid-span displacement curve versus time. This means also that the
171 specimen was close to the failure point at that time. The specimen of Test-2 failed on the tension
172 side at 86 min, as the respective displacement curve shows. Finally, Test-3 was stopped after 90
173 minutes without reaching any safety criterion. The evolution of the mid-span deflection for Test-3
174 shows some acceleration at about one hour of fire exposure, with a subsequent smoother trend. The
175 calculated charring rates and the observations during testing highlighted possible delamination
176 phenomena at this exposure time which can explain the increase in displacement rate. The evolution
177 of Test-1 deflection shows a slight trend variation due to the progressive charring of layers with or
178 without load-carrying capacity. On the contrary, the floor of Test-2 presents a nearly linear trend of
179 deflection variation until the failure, since almost only the first thick longitudinal layer has been
180 affected by the combustion.

181



182 **Fig. 5. Evolution of the mid-span deflection during the three fire tests on CLT floors**

182

183 Modeling

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



189 plates (Lebéé & Sab, 2011), combined with wood's reduced properties by the Eurocode's law (CEN,
190 2004).

191 Advanced modelling of heat transfer

192 The temperature evolution over the panels' thickness during fire exposure was predicted with SAFIR
193 software. CLT panels were modeled as solid wood, with perfect connections between layers. The
194 density of specimens was measured and values in accordance with the mean value of 420 Kg/m^3
195 specified in EN 338 (CEN, 2009) have been found. Preliminary analyses investigated on the value to
196 use for moisture content, fitting the predicted temperature to thermocouples registrations for Test-
197 1, leading to the value of 12%. The emissivity (ϵ) of the modeled wood was set to 0.8, while the
198 coefficients of convection of heated (h_h) and unheated (h_c) surfaces were assumed to be respectively
199 $25 \text{ W/m}^2\text{K}$ and $4 \text{ W/m}^2\text{K}$. One dimensional uniform mesh of 1 mm was applied as a discretization
200 over the panel thickness for the temperature prediction. Figure 7 plots the comparison between
201 predicted and experimental temperature profiles during Test-1 across the specimen thickness. The
202 falling-off of layer 1 of Test-1 pointed out in Table 2 and Figure 5 probably leads to the sharp
203 increase of the measured temperatures at 20 minutes at the interface between the first and the
204 second layer (curve for 17mm) and at half-thickness of the second layer (curve for 33.5mm).
205 Globally, the predicted temperatures are in good agreement with the measured values during the
206 fire test. However, for high exposure times (at deep sections), the predicted temperatures are
207 slightly lower than measured temperatures. This can be due to the heat transfer modeled neglecting
208 any falling off of wood during fire exposure. Indeed, even if large detachment of the whole layers
209 were not observed, the local falling of wood pieces was visible during testing and could lead to a
210 progressive increase of measured temperatures.

211

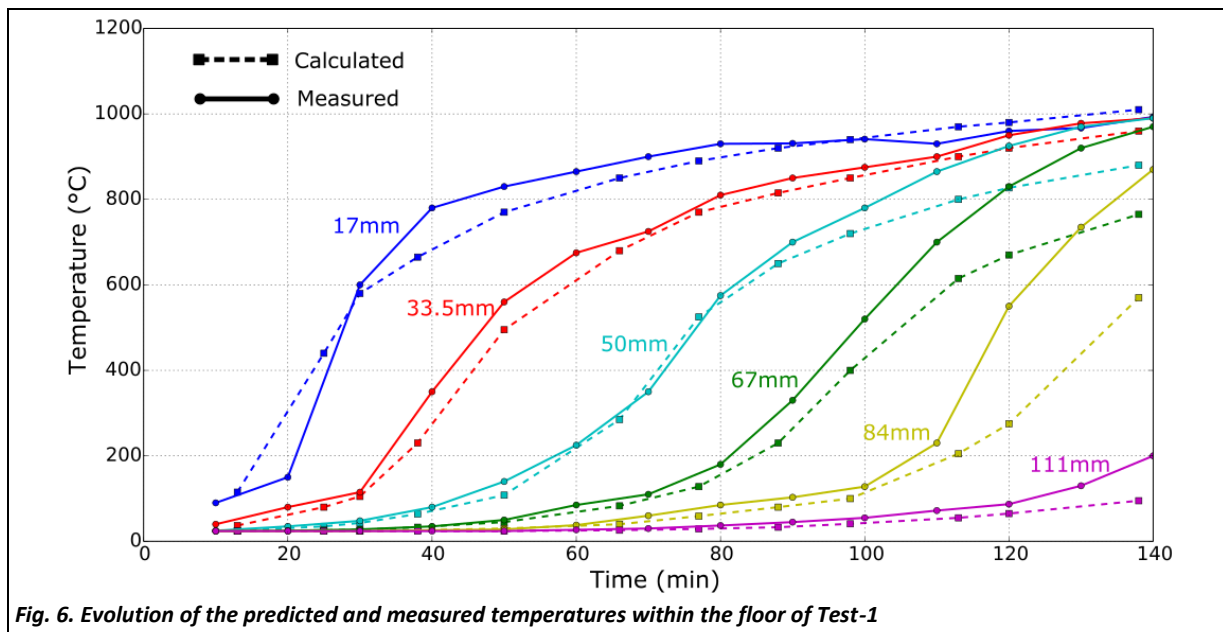


Fig. 6. Evolution of the predicted and measured temperatures within the floor of Test-1

212

213 Thermo-mechanical modeling

214 The thermo-mechanical behavior of CLT floors has been modeled with a "multilayer" model, with
215 each layer having the mesh thickness of 1 mm. Wood is an orthotropic material with three principal
216 axes and therefore its elastic behavior is defined by three Young's moduli, three shear moduli and
217 three Poisson's ratios. However, since within timber boards of CLT is not possible to know the local
218 orientation of wood axes, wood can be modeled as a transversely isotropic material (Franzoni,
219 Lebéé, Lyon, & Foret, 2016a), (CEN, 2009) having only a longitudinal (0) and transverse (90)



220 direction. Further analyses highlighted the negligible influence of Poisson's ratios on the deflection
221 prediction and therefore are set to zero. Since no characterization of the raw material has been
222 done, the elastic moduli of wood according to strength class C24 of EN 338 (CEN, 2009) and a *rolling*
223 shear modulus (G_{90}) of 50 MPa were considered (Table 3).

224

Table 3. Stiffness properties of C24 strength class timber according to EN 338 (2009)

Modulus of Elasticity	E_0	E_{90}	G_0	G_{90}
Stiffness [MPa]	11000	370	690	50

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

236

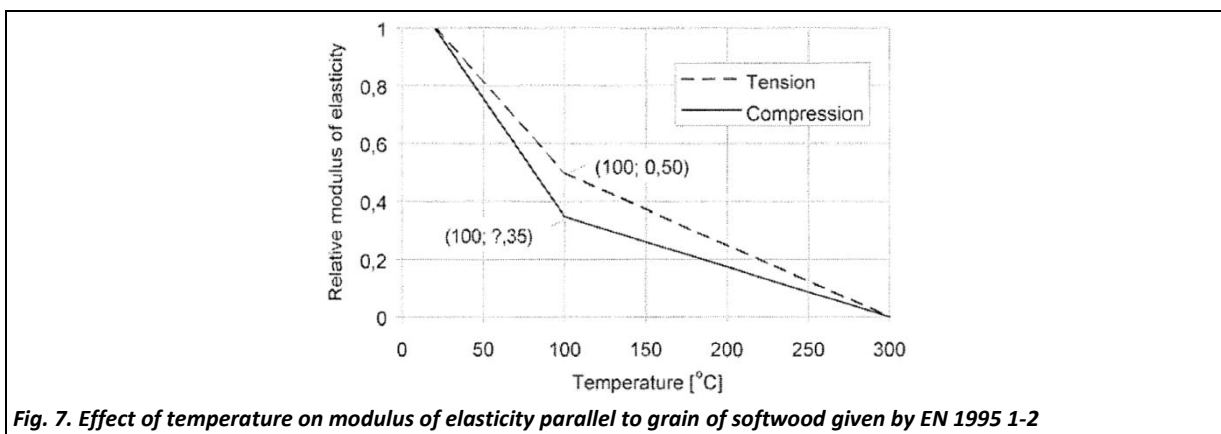


Fig. 7. Effect of temperature on modulus of elasticity parallel to grain of softwood given by EN 1995 1-2

237

238 Therefore transverse shear effects, which sometimes play a crucial role in CLT panels in bending, can
239 be well predicted with this approach. The Bending-Gradient plate model has been recently applied
240 to predict the mechanical behavior of regularly spaced CLT panels (Franzoni, Lebée, Lyon, & Foret,
241 2016b) and the buckling of CLT (Perret, Lebée, & Sab, 2016). According to this method, the layers are
242 homogenized with a semi-analytical procedure in order to obtain the equivalent out-of-plane
243 bending and shear stiffnesses of the panel. This theory can predict the linear elastic behavior of the
244 plate and considers perfect simple support boundary conditions. The integrity of support conditions
245 after the fire tests was checked to satisfy the modeled boundary conditions. This calculation is
246 performed at each increment of exposure time in order to predict the evolution of mid-span
247 deflection.

248 Reduced Cross Section modelling

249 Since recent studies pointed out that the current version of the RCSM is not always conservative,
250 several attempts to improve the RCSM without changing its simple approach have been done. In the
251 next paragraphs, three methods to determine the geometry of the effective cross section are



252 presented. Once the effective geometry is established, properties at ambient conditions of C24
253 timber from EN 338 are combined with the plate theory in order to predict the mid-span deflection
254 according to the RCSM.

255 Existing approaches

256 ❖ **RCSM-1.** The first existing RCSM approach has been derived by (Schmid, König, & Just, 2012)
257 fitting results of advanced numerical simulations on timber members in bending. According
258 to this method, the charring rate is uniform as prescribed in EN 1995 1-2 (0.65 mm/min),
259 while the ZSTL (d_0) is derived as a function of panel's total thickness and of the exposed side.
260 Applying this approach to the three tested panels leads to the following values of d_0 : Test-1
261 = 11 mm; Test-2 = 10.7 mm; Test-3 = 10.8 mm.

262 ❖ **RCSM-2.** The second simplified design model (Frangi A. , Fontana, Hugi, & Jobstl, 2009) is
263 based on the initially protected surfaces approach of the Eurocode, in order to take into
264 account the delamination phenomenon already discussed. Hence, a double charring rate
265 (1.3 mm/min) is considered after the complete charring of each layer (delamination
266 moment), until the char depth exceeds 25 mm. Beyond these 25 mm of char depth, the
267 charring rate returns at 0.65 mm/min. Within this method, the value of ZSTL (d_0) was not
268 established; hence the value set by EN 1995 1-2 (7mm) is combined with RCSM-2.

269 New suggested RCSM approach

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

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

292

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

Time t [min]	0<t<20	20<t<40	40<t<60	t>60
ZSSL [mm]	10	14	17	20

293

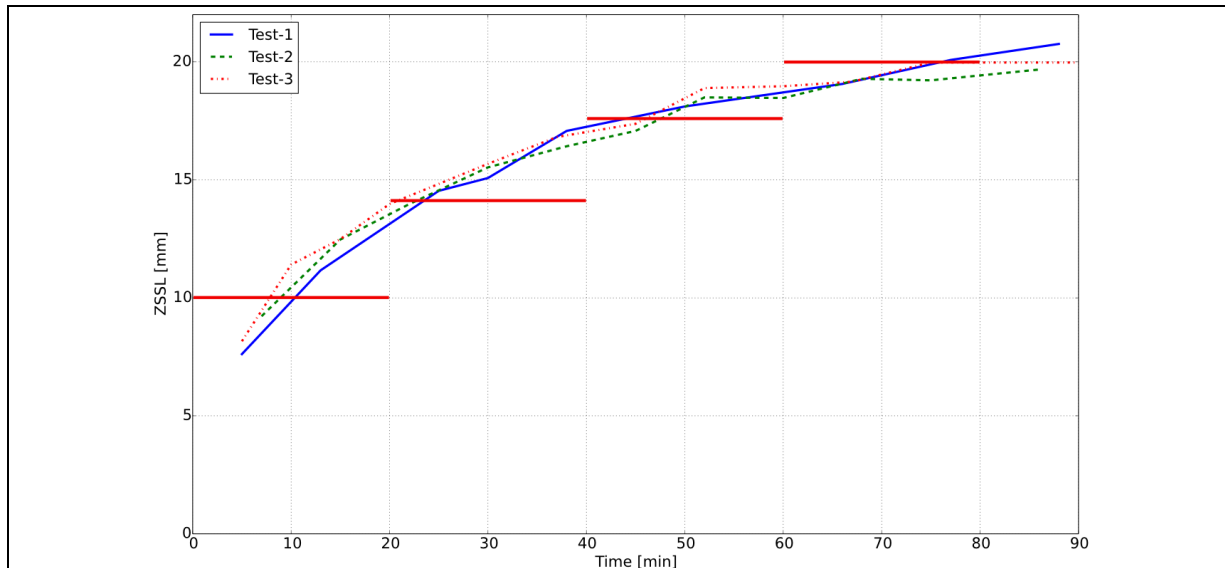


Fig. 8. Evolution of the estimated zero stiffness layer (ZSSL) for the three tests as a function of exposure time. The red lines shows the considered values for four ranges of time (Table 4)

294

295 Comparison

296 The comparison between the experimental and predicted mid-span deflection by advanced and
297 RCSM modeling are showed from Figure 11 to Figure 13. As already introduced, the RCSM-1 method
298 is according to (Schmid, König, & Just, 2012), the RCSM-2 is according to (Frangi A., Fontana, Hugi, &
299 Jobstl, 2009) and RCSM-3 considers the ZSSL as a function of time (Table 4). For the three
300 approaches based on reduced cross section, the k_0 used for the calculation of ZSTL and ZSSL are
301 computed as in EN 1995 1-2 (Figure 2).

302

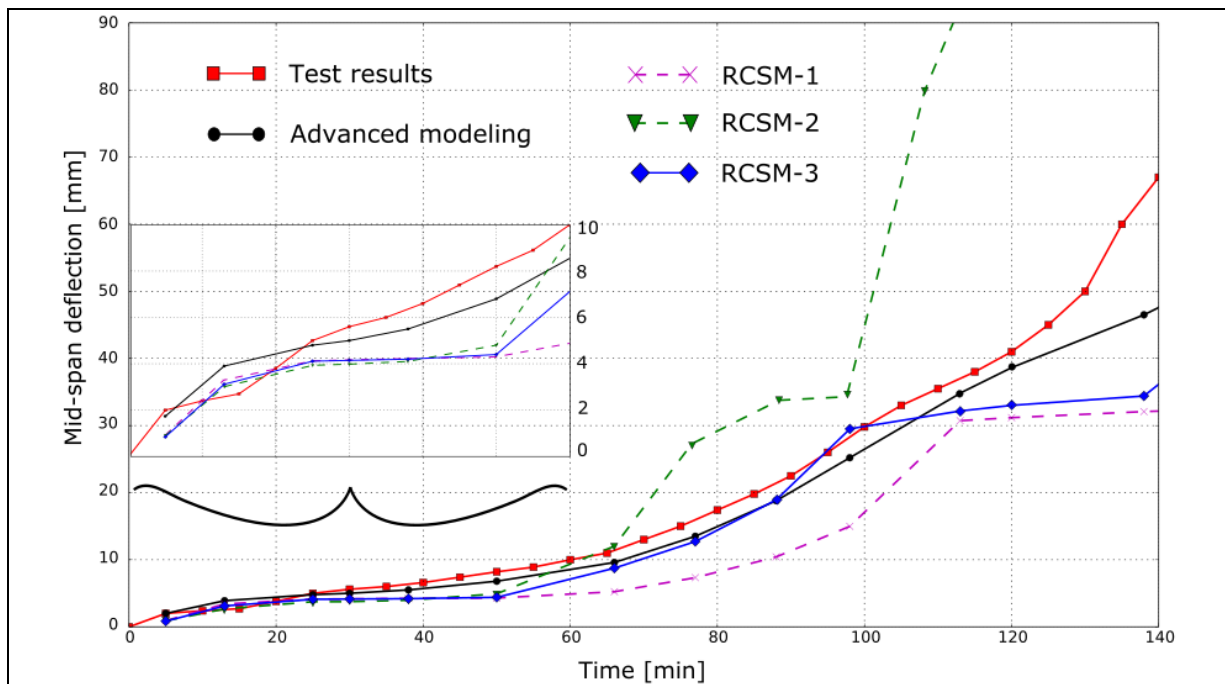


Fig. 9. Comparison between predicted and experimental deflection of Test-1

303

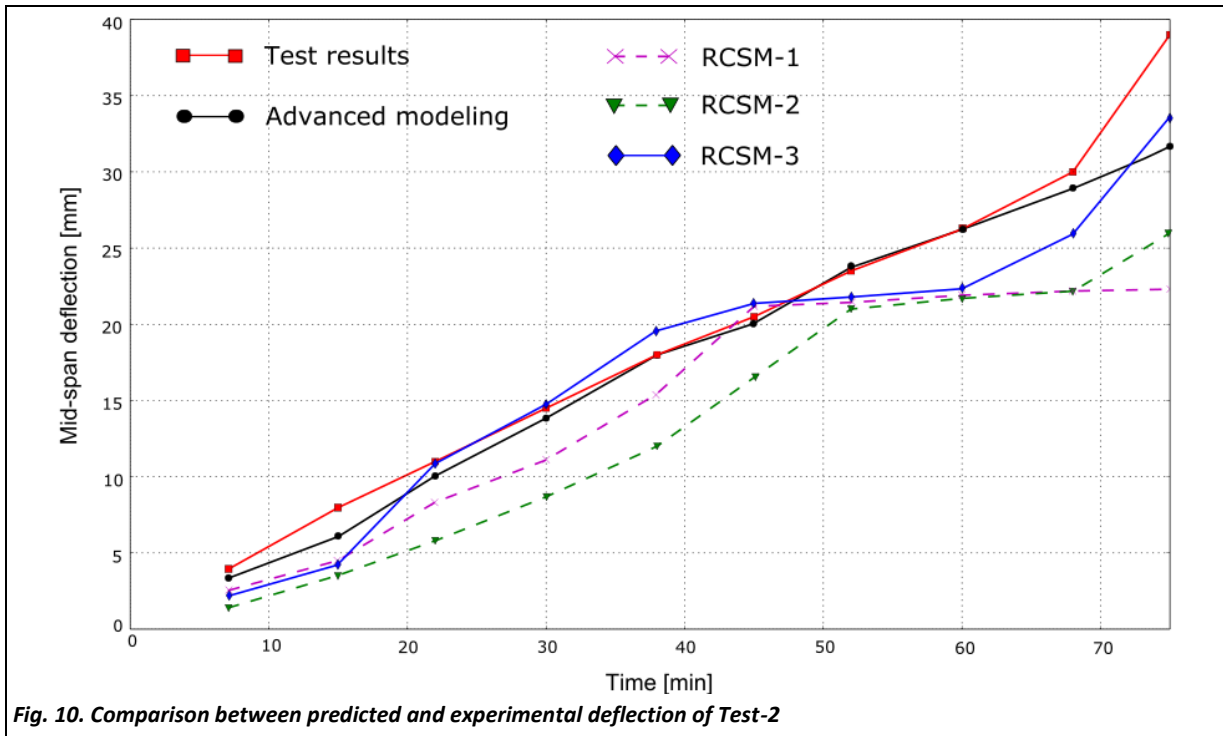


Fig. 10. Comparison between predicted and experimental deflection of Test-2

304

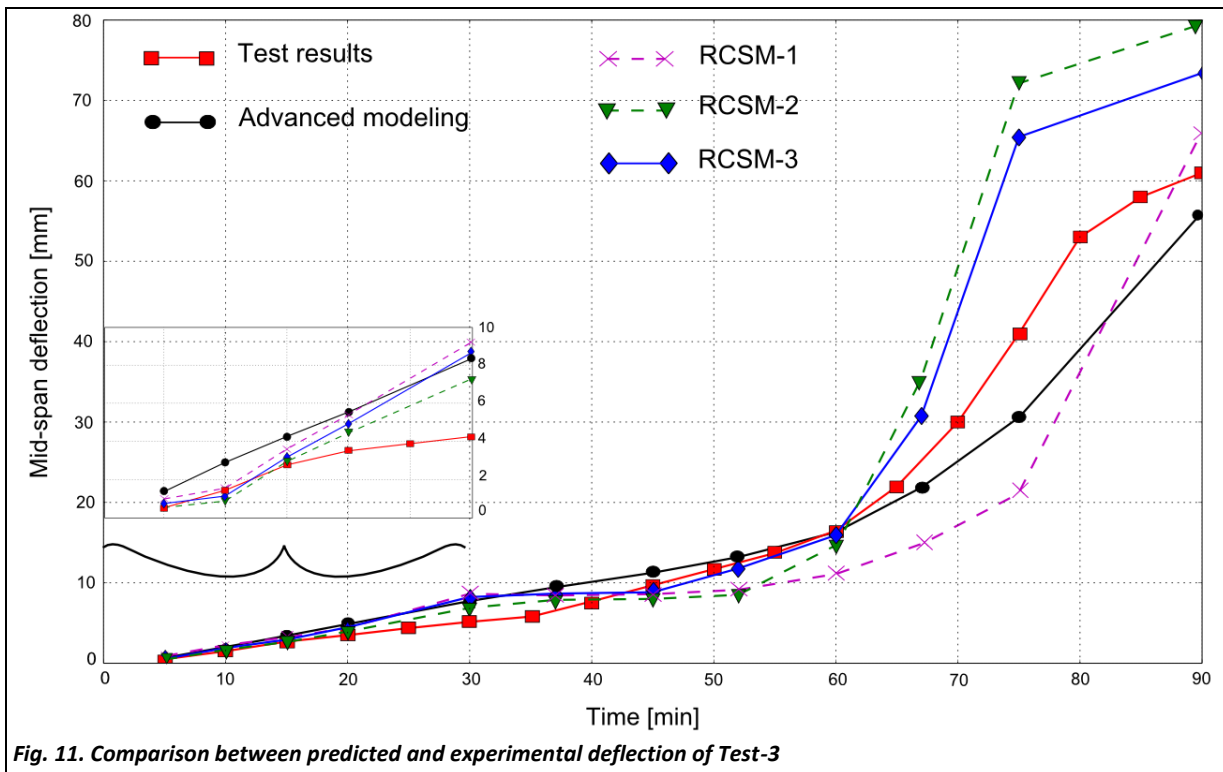


Fig. 11. Comparison between predicted and experimental deflection of Test-3

305

306 The advanced modeling based on reduced properties returns the mid-span deflection that less
307 deviates from experimental results for the three tests. The evolution of the deflection predicted by
308 all RCSM methods shows plateau corresponding to the non-contribution of cross layers to global
309 stiffness but not highlighted by test results. By contrast, the advanced modeling based on reduced
310 stiffness is able to follow the experimental evolution of deflection, showing that the actual
311 phenomenon is a progressive reduction of properties and not a reduction of geometry. The RCSM-3
312 based on the time-dependency of the ZSSL gives a better description of the measured deflection



313 compared to other RCSM approaches. The RCSM-1 approach underestimates the deflection of the
314 three fire tests. Despite of the delamination of the first layer in Test-1 previously highlighted, the
315 RCSM-2 (derived to take into account such phenomenon) overestimates the Test-1 deflection. The
316 deflection of Test-2 is underestimated by both existing RCSM approaches. Dealing with Test-3, all
317 the RCSM methods show similar slope of the deflection evolution trend, but with an offset due to
318 the different ways of estimating the residual cross section. Indeed, the double charring rate
319 considered by RCSM-2 compensates somehow the higher values of the additional layer to remove of
320 RCSM-3, while RCSM-1 predicts lower deflection since it considers lower values of d_0 .
321 In the final parts of Figures 11 and 12, most of the methods underestimate the deflection. This is
322 because both of specimens were close to failure at those high exposure times and hence the
323 increasing non-linear contributions to deflection cannot be taken into account by the plate theory.

324 Discussion

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

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

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

345 The delamination phenomenon is a complex mechanism influenced by a multitude of parameters
346 and therefore very difficult to predict. It can occur locally, with delamination of small pieces of
347 wood, or with a complete falling-off of layer. The charring rate estimation with thermocouples
348 registration pointed out partial delamination phenomena for the three considered tests. In
349 particular, the calculated charring rates of Test-3 pointed out delamination of more than the first
350 layer. The same Test-3 showed an acceleration of mid-span deflection that may be due to such
351 delamination phenomenon. On the contrary, the less pronounced delamination of Test-1 and Test-2
352 had no visible influence on the global evolution of deflection. This discrepancy confirms the
353 complexity of this phenomenon and suggests enhancing the studies about the effective influence of
354 delamination on structural fire safety of laminated timber structures. It seems that the existing
355 RCSM-2 model can lead to quite conservative results in the cases without delamination and to better
356 results in cases of delamination. The suggested RCSM-3 based on the time-dependency of ZSSL is
357 based on heat-transfer prediction of solid wood, neglecting the delamination. Taking into account
358 this phenomenon would lead to higher predicted temperatures profiles, further increasing the
359 already rather high values of ZSSL.

360



361 Conclusion

362 In the present paper, the experimental deflection of fire exposed CLT floors has been predicted with
363 advanced modeling based on reduced properties and the simplified approach of the RSCSM. The best
364 way to correctly simulate the fire behavior of CLT floors is by means of an advanced modeling.
365 However, the methods based on the RSCSM approach are more convenient for practical applications
366 by engineers. This is the reason why it would be interesting to find the best RSCSM method for the
367 calculation of deflection and perhaps the design of CLT in fire conditions.

368 The results presented in this paper show that RSCSM-3 based on the time-dependency of the
369 additional layer to remove could be a relevant method for simulating the fire behavior of CLT floors.
370 The approach of the present paper is a research path which seems interesting to investigate, in
371 order to define the relevant method for the fire design of CLT floors to be taken into account by the
372 on-going revision process of EN 1995 1-2 (CEN, 2004). However, this method has to be further
373 investigated for different configuration of floors and under different load conditions.

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