manufacturing process, whereas for the PRF boards larger air gaps remain in-between the boards. Therefore, the fire could spread easily through the panels, amplified because of the pressure difference between the furnace and the ambient air. This led to very early integrity failures. The average charring rates were calculated based on the thermocouples temperature recordings and range from 0.48 mm/min to 0.62 mm/min. These values are even lower than the one dimensional charring rates given by the Eurocode 5 [13] and the National Design Specifications of the United States [15]. The gypsum boards started cracking after around 50 minutes and fell off after about 100 minutes. All these time values agree well with the values based on the Eurocode 5 [13] predictions. The non-edge-glued polyurethane panel reached a 4 minutes longer failure time than the edge-glued panel, which can be explained by the way the charcoal falls off. For the edge-glued panel, the charcoal layer fell off all at once and for the non-edge glued panel the charcoal layer fell off in pieces, leading to a longer protection time.

In a following project at FPInnovations, eight full-scale tests were performed [11]. The assemblies tested consisted of three wall and five floor tests and were subjected to the standard ULC S101 fire exposure [14]. Each panel had a width of 763 mm. The floor panels were 4786 mm and the wall panels were 3048 mm long. The plies were glued together with a polyurethane (PUR) adhesive, which fulfils the CSA O112.10 standard [16]. The tests were carried out in the NRC’s (National Research Council) floor and wall furnaces. Three or five ply CLT panels were tested. Some of the CLT panels were fully exposed to fire (unprotected) while some panels were initially protected by Type X gypsum board. The panels were subjected to a constant loading during the test, which was determined based on the L/240 deflection criterion and the load-carrying capacity, respectively. In the tests, significant fire resistance of about three hours was achieved under full loading conditions. Either integrity or structural failure was observed as failure mode. By means of thermocouple measurements in the cross-section between the CLT plies, the temperature distribution during the fire tests was recorded. The overall average charring rate based on these measurements was between 0.41 and 0.80 mm/min. Osborne et al. [11] concluded that an overall charring rate of 0.65 mm/min can be assumed.

Based on the various test results presented above, it can be concluded that the fire resistance of cross-laminated solid timber panels depends upon several parameters such as the number and thickness of layers, the use as floor or wall component and the adhesive in the bondline between the different layers. In the following section, a University of British Columbia project to evaluate the fire response of different CLT panels in full scale fire tests performed at CNR-IVALSA is presented. In these fire tests, the influence of different cross-section layups was studied for CLT floor and wall elements from British Columbia, Canada. Further, the influence of two different bottom fixations for wall elements was investigated. In the final section of this paper, the results are compared to a proposed charring model by Frangi et al. [2] to account for falling off of the charred layers in the fire design. This section also investigates the influence of falling off of charred layers during a fire on the assembly of a CLT panel.

The fire tests presented in here were performed as collaboration between the Department of Wood Science at University of British Columbia, Canada and the Trees and Timber Institute CNR-IVALSA, Italy. The project was further accompanied by the Institute of Structural Engineering of ETH Zurich, Switzerland.

FIRE TESTS

The test specimens consisted of timber panels made of Spruce-Pine-Fir (SPF) lumber as classified in [17]. In British Columbia the lodegpole pine (*Pinus contorta)* species represents the majority of the SPF lumber production wood. The boards used to produce the CLT specimens were classified as kiln dried No. 2, which is similar to timber strength class C16 according to EN 338 [18].

One of the main objectives of the current study is to analyze the influence of different cross-section layups on the fire behavior of the CLT panels. Therefore, three different cross-sections were manufactured (see Table 1). The 3 ply cross-section consists of three boards with a thickness of 34 mm each, leading to a total thickness of 102 mm. For the 5 ply cross-section, a strong version and a weak version were manufactured. The strong version (abbreviated as SR) consisted of four plies in longitudinal direction and one crosswise ply in the center of the cross-section, with the following thicknesses: 34-24-24-24-34 [mm]. The weak version (abbreviated as WR) has three plies in longitudinal direction (the two outer plies and the middle ply, each 34 mm thick) and two plies oriented crosswise (each 19 mm thick). The total thickness of the 5 ply panel is 140 mm for both the SR and WR versions. It is assumed that the (p)arallel/(c)rosswise/p/c/p version will have a lower bending strength out of plane and, therefore, this cross-section is designated as the “weak resistance (WR)” layup. The p/p/c/p/p should have a higher bending strength out of plane and is therefore designated as the “strong resistance (SR)” layup. For the wall tests, two different support types were designed. One is a T-shape steel connector slotted into the CLT element and fixed with dowels, called SC for strong connection. The second support type consists of two angle brackets, fixed with nails to the CLT element, herein designated as the weak connection (WC). The SC support should have a higher resistance against out of plane bending than the WC. The floor panels were tested in 4-point bending tests, where the load was applied in two points, hence the designation 2P. In total, four tests were performed on floor elements with different connection and load level ((see Table 1).

Table 1. Overview of the fire test set-ups.

Type	**No of plies**	**Orientation** [a]	**Panel thickness [mm]**	**Thickness of layers [mm]**	**Information on support, load**	**Designation** [b]
Wall	3	p/c/p	102	34-34-34	T-support (3.34MPa)	W-3P-SC
Wall	3	p/c/p	102	34-34-34	L-support (3.34MPa)	W-3P-WC
Wall	5	p/c/p/c/p	140	34-19-34-19-34	T-support (3.06MPa)	W-5P-WR-SC
Wall	5	p/c/p/c/p	140	34-19-34-19-34	L-support (3.06MPa)	W-5P-WR-WC
Wall	5	p/p/c/p/p	140	34-24-24-24-34	T-support (2.69MPa)	W-5P-SR-SC
Wall	5	p/p/c/p/p	140	34-24-24-24-34	L-support (2.69MPa)	W-5P-SR-WC
Floor	5	p/c/p/c/p	140	34-19-34-19-34	2P (F=14.6kN)	F-2P-WR-1
Floor	5	p/c/p/c/p	140	34-19-34-19-34	2P (F=18.4kN)	F-2P-WR-2
Floor	5	p/p/c/p/p	140	34-24-24-24-34	2P (F=16.8kN)	F-2P-SR-1
Floor	5	p/p/c/p/p	140	34-24-24-24-34	2P (F=21.2kN)	F-2P-SR-2

[a] p stands for parallel orientation of the layers, c for crosswise orientation

[b] (W)all or (F)loor element, 3 or 5 (P)lies, (W)eak or (S)trong (R)esistance (see orientation of the layers), (W)eak or (S)trong (C)onnection

Before the production process, each board was tested to determine its elastic modulus (MOE). A Metriguard Model 340 Transverse Vibration E-Computer was used to conduct a non-destructive dynamic test. In addition to the modulus of elasticity, the exact board dimensions were recorded. Table 2 shows a summary of the measurement results. The mean moisture content of the boards was 12% when the MOE was determined. All boards were of sufficient length for the CLT production and thus no finger jointing was necessary. The panels were produced according to the Standard for Performance-Rated CLT [19] by CST Innovations. The boards were bonded with a polyurethane adhesive (PUR) certified according to ASTM D7247 [20] for the use in structural timber elements.

Table 2. Summary of the vibration MOE tests.

	2x4 SPF[a], Length = 5500 mm			**2x4 SPF[a], Length = 4285 mm**		
	Width [mm]	**Depth [mm]**	**MOE [Gpa]**	**Width [mm]**	**Depth [mm]**	**MOE [Gpa]**
Avg.	137.87	37.65	11.36	138.94	38.31	10.66
Stdev.	5.79	0.47	1.81	1.10	1.55	2.09
COV	0.04	0.01	0.16	0.01	0.04	0.20
Count	480	480	480	435	435	435

[a] SPF stands for Spruce-Pine-Fir, the species combination to which lodgepole pine is attributed according to the Canadian Code [17].

The wall elements tested had a width of 660mm (for 5ply) or 480mm (for 3ply) depending on the CLT panel thickness. Hence, the testing wall was composed of three pieces; the CLT test specimen in the middle

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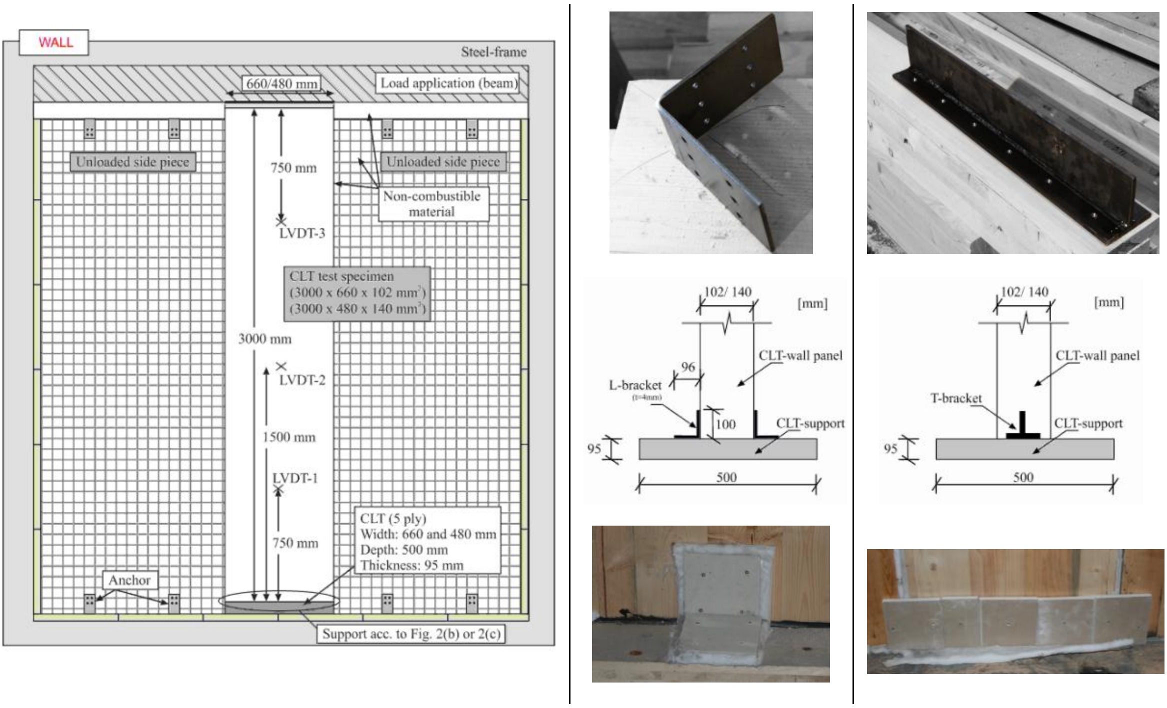
and two unloaded side pieces, which were protected by non-combustible material (see Fig. 2a). Between the pieces, insulation guaranteed a one-dimensional heat transfer. For the wall tests, the load-level was chosen based upon the load-carrying capacity on the bottom rail of the wall, as this is the governing design case (compression perpendicular to the grain) for this type of assembly (wall-floor assembly). The load-carrying capacity was calculated according to the Canadian Code [17]. During the fire test, the total load of 150 kN was evenly distributed via a steel beam. This load corresponds to the stresses given in Table 1 for the specimens.



(a) (b) (c)

Fig. 2. Test-setup for wall fire tests showing details of the weak and strong connection assembly. (a) Wall test setup. (b) L-brackets (weak connection). (c) T-bracket (strong connection).

Two different supports were tested in the wall tests. The weak support version was assembled using L-brackets as shown in Fig. 2b. The strong support version was assembled using a T-bracket as illustrated in Fig. 2c. Compared to the L-bracket system, the T-bracket support was expected to provide a higher moment resistance against bending at the base of the wall. For each support, three fire tests were performed. The wall panels were fastened to the ground and to the top floor with L-brackets. Only for the loaded middle part of the strong connection wall (SC), a T-bracket was inserted into a pre-sawed slot in the CLT-panel (see Fig. 2c). In order to avoid failure in the connection, the support area was covered with gypsum board. So far, most full-scale fire tests on CLT walls have not considered the influence of the support on the fire performance. The walls were usually attached at the borders of the furnace, so that the connection was outside the furnace and not exposed to fire. Indeed, the main objective of this research project is not to analyze the fire performance of the connection itself, but to study the influence of the support type on the wall deflection under thermal load. Thus, in order to limit the number of parameters influencing the results, extra heat transfer through the steel elements and softening of the steel should be avoided. Therefore, the steel elements were protected by gypsum board of sufficient thickness to ensure thermal protection (see Fig. 2 b,c).

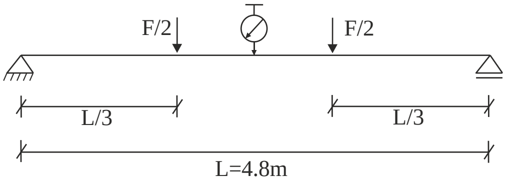


Fig. 3. 4-point bending test set-up for the floor fire tests.

For the floors, it was assumed that the maximum deflection criterion according to [17] of L/240 governs the load-carrying capacity. The span of the floors between the supports was 4.8 m (see Fig. 3). The width of the floor panels was chosen to be 1.2 m because of manufacturing and shipping limits. The rest of the furnace area was closed with side panels. For the 4-point-bending test, the calculated total loads F are 14.6 kN for the weak layup (p/c/p/c/p) and 16.8 kN for the strong layup (p/p/c/p/p). Half of this load was applied at each of the two loading points.

For all tests, the deflections of the specimen were recorded. For the wall tests, the deflection was measured at three points (LVDT 1-3 in Fig. 2 a). During the floor tests, the deflection was measured at midspan.

RESULTS

Fire tests on wall elements

In total, six wall elements were tested with the ULC/ASTM standard fire curve [21]. Table 3 shows a summary of the test results. Fire time is the time where the tests had to be stopped because of integrity failure between the loaded and the unloaded panels. No integrity failure of the panel itself was observed. After that time the wall panel was moved away from the furnace and the fire was quickly extinguished. After the panel had cooled down, the remaining thickness of the cross-section was measured at mid-height each 15 mm. The charring depth d_{char} [mm] and the one-dimensional charring rate β_0 [mm/min] could then be derived. During the tests, vertical and horizontal deflections were measured. Table 3 shows that the mean one-dimensional charring rate β_0, calculated on the basis of the residual cross-sections, in all wall tests was only slightly higher than the one-dimensional charring rate of solid wood (0.65 mm/min) given in Eurocode 5 [13]. The vertical deflection progressed in all tests more or less linearly over time (Table 3 and Fig. 4a). The vertical deflections remain very small even though the load-bearing cross-section of the wall was reduced by at least 30% during the fire test.

It has to be noted that the load level of 150 kN corresponds to a compressive stress of about 3 MPa in the load-bearing (parallel) boards, which is about 12% of the mean compressive strength $f_{c,m}$ of a regular softwood timber element. Fig. 4b shows the horizontal deflection recorded at mid-height of the wall (see Fig. 2a, LVDT-2). The horizontal deflection is influenced by thermal expansion, the increasing stress on the remaining cross-section and the increasing eccentricity of the applied load. In the first phase of the fire tests, the wall deflects slightly in the direction of the fire exposed side. Later, it is not possible to clearly describe the behavior in terms of deflection. Therefore, the influence of any of the studied parameters on the deflection behavior of the wall cannot be given without contradiction.

Table 3. Test results of fire tests on CLT wall panels.

Test name	**Fire time[a] [min]**	**d_{char} [mm]**	**β_0 [mm/min]**	**Max vertical deflection [mm]**
W-3P-SC	100	63.7	0.64	9.6
W-3P-WC	88	63.0	0.72	10.0
W-5P-SR-WC	100	73.6	0.74	2.1
W-5P-SR-SC	89	66.1	0.74	6.3
W-5P-WR-WC	97	74.3	0.74	8.3
W-5P-WR-SC	100	72.5	0.73	9.1

[a] No failure, only integrity failure in-between the panels occurred.

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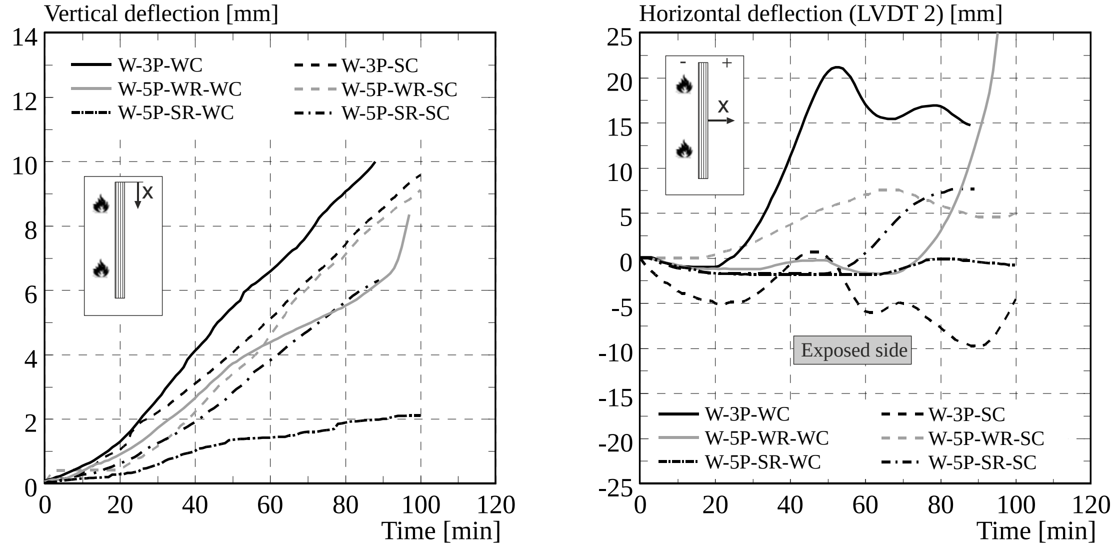


(a)

(b)

Fig. 4. Vertical (a) and horizontal (b) deflection of the walls.

As the tests were stopped before structural failure occurred, no conclusions about the fire resistance of the walls can be drawn. The walls reached at least a fire resistance of 88 minutes at the stopping point of the fire test.

Fire tests on floor elements

Four floor tests were carried out on the horizontal furnace at CNR-IVALSA, using the standard ISO temperature fire curve [12]. All tests on floor elements were performed as 4-point-bending tests, whereas the load was slightly varied. Table 4 gives an overview of the fire test results on the CLT floor panels. The tests were stopped after one hour, as the goal was to measure the charring rates and deflections and not to determine the fire resistance time. At the end of the test, the load was first removed, the panels were lifted from the furnace and the fire was extinguished. After the panels had cooled down the thickness of the remaining cross-section was measured and the mean charring rate calculated. The charring rates were in the range of 0.75 to 0.81mm/min. and were greater than the one-dimensional charring rate indicated by the Eurocode 5 [13]. The vertical deflection was measured with LVDT's at the unexposed surface at midspan (Table 4 and Fig. 5).

Table 4. Test results of fire tests on CLT floor panels.

Test Name	**Fire Time**[a] **[min]**	**Load [kN]**	**d_{char} [mm]**	**β_0 [mm/min]**	**Max vertical deflection [mm]**
F-2P-WR-1	67	14.6	54.5	0.81	55.5
F-2P-WR-2	57	18.4	46.2	0.81	67.7
F-2P-SR-1	67	16.81	50.5	0.75	63.4
F-2P-SR-2	57	21.2	45.5	0.80	76.2

[a] No failure, stop of the fire test due to safety reasons.

The deflection at midspan increased with the time of fire exposure. The measurement devices were removed before the fire test was stopped. As the fire progresses the cross-section is reduced, leading to higher stresses in the residual cross-section and hence higher deflections. The deflections were not influenced by the cross-section layup (weak resistance (WR) vs. strong resistance (SR)). However, a slight influence of the load level was observed. In the tests with increased loading, higher deflections were measured than in the tests with lower loading. The deflections reached maximum values of about L/75, i.e. a value four times higher than the maximum deflection (L/240) accepted according to [17] for normal serviceability conditions.

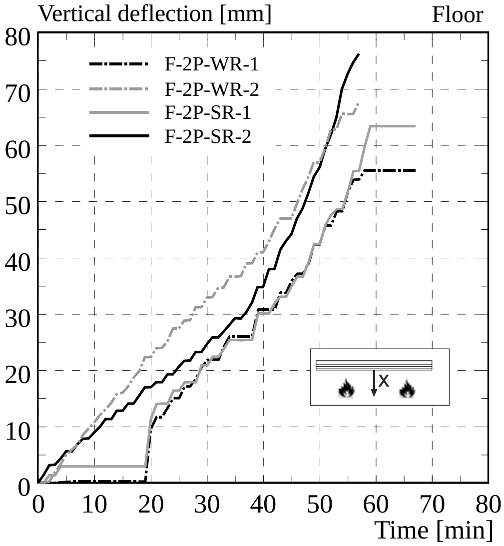


Fig. 5. Deflection at midspan against time of fire exposure for floor elements.

Comparison between wall and floor elements

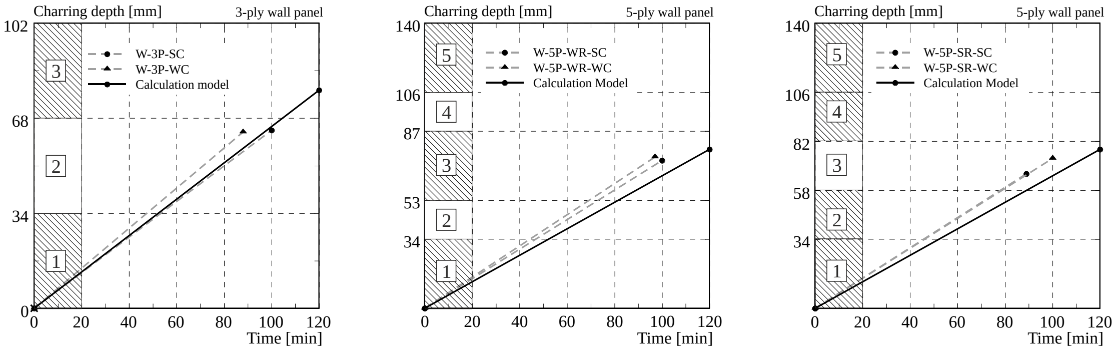
The overall behavior of the wall elements and the floor elements can be compared based on the mean charring rates (Tables 3 and 4). The mean charring rate for all wall elements corresponded to 0.72 mm/min. For the floor elements, the mean charring rate was 0.79 mm/min. This small difference may be explained by a higher tendency of falling off of charred layers for horizontal elements.

COMPARISON WITH SIMPLIFIED CHARRING MODEL

Based on various fire tests on CLT panels, a simplified charring model to determine the residual cross-section for CLT has been proposed [2]. If layers are expected to fall off, the timber panel can be treated like an initially protected timber element. After the first layer is completely charred, this layer falls off and the second layer starts to char with twice the one dimensional charring rate until a new charcoal layer of 25 mm thickness has been formed [2]. Then the charring rate can be reduced to the one dimensional charring rate again until the next layer falls off. If no falling off of charred layers is expected, the same one dimensional charring rate as for solid wood can be used for all layers. For a fire resistance of 30 minutes there will be nearly no influence of falling off of charred layers, as only the first layer will be charred, but for a fire rating of 60 and more minutes a clear difference in the residual cross-section is expected. However, it has to be noted that the fire resistance of a CLT element is not linearly related to the charring rate, as the charring of a perpendicular layer with low stiffness and strength properties, has nearly no effect on the overall load-carrying capacity.

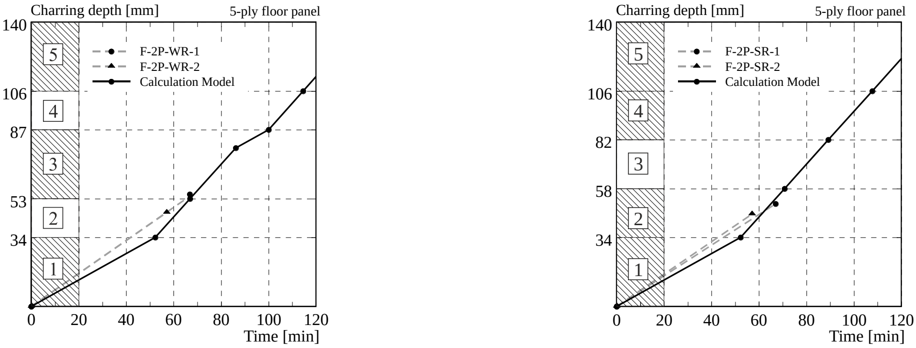
The charring rate for the CLT panels studied in this investigation was calculated according to the procedure described above. Fig. 6 and Fig. 7 show the charring depth as a function of time for all fire tests performed in comparison to the calculated charring depth according to the charring model proposed in [2]. The curves for the calculation model assume a one-dimensional charring rate of 0.65 mm/min. Falling off of charred layers was considered only for the floor elements. Since no information about the temperature development between each layer was available, the graphs in Fig. 6 and Fig. 7 are shown as dotted lines. These lines do not reflect the real behavior of the charring depth during the fire test. The following conclusions can be drawn:

- For the wall elements tested, similar charring rates were observed in all tests. The charring rates were slightly greater than the one-dimensional charring rate for solid wood of 0.65 mm/min given in Eurocode 5 [13].
- For the floor elements tested, the one-dimensional charring rate in the tests exceeded the value of 0.65 mm/min given in Eurocode 5 [13]. The greater charring rate could be addressed to a falling off of the charred layers. The calculation model considers falling off of the charred layers and the calculated charring depth agrees well with the measured charring depth after about 60 minutes fire exposure.



(a) (b) (c)

Fig. 6. Comparison of the test results on walls with the calculation model by means of charring depth as a function of time of fire exposure for different panel configurations.



(a) (b)

Fig. 7. Comparison of the test results on floors with the calculation model by means of charring depth as a function of time of fire exposure for different panel configurations.

INFLUENCE OF FALLING OFF OF CHARRED LAYERS

Depending on the adhesive used in the bondline between the different layers, falling off of the layers was observed in previous investigations as well as in this study. However, the load-bearing behavior of CLT elements is not linearly related to the charring. In CLT elements the layers are arranged crosswise, therefore the second layer on the fire-exposed side is usually statically ineffective as the stresses act perpendicular to the grain. For common cross-laminated timber panels with the thickness of the single boards in the range of 19–35mm the effect of falling off of charred layers on the load-carrying capacity in fire may not be relevant. In order to assess this hypothesis, commercially available CLT panels with different total thicknesses and thicknesses of the layers were studied. On the basis of the example in the BSPHandbuch [22], the CLT panels were designed according to Eurocode 5 [13] for normal temperature and for a fire resistance of 60 minutes.

The fire design was performed with and without considering falling off of the charred layers. Table 5 shows some selective results for different panel configurations with 5 plies. Results are shown for panels having a thick or thin thickness of the outermost fire exposed layer and for CLT panels with different total thickness. Table 5 shows the quotient of the design bending moment acting on the panel in fire $M_{d,fi}$ and the design bending resistance of the panel in fire $M_{R,d,fi}$ with and without considering falling off of the charred layers.

Table 5. Results of fire design examples for fire exposure time of 60 minutes.

CLT-panel configuration [mm]	24/24/24/ 24/24	19/34/19/ 34/19	19/44/19/ 44/19	34/22/34/ 22/34	35/35/35/ 35/35
Thickness outermost fire exposed layer [mm]	24	19	19	34	35
Total thickness CLT-panel [mm]	120	125	145	146	175
Fire design with falling off layers: $M_{d,fi}/M_{R,d,fi}$ [-]	0.44	0.68	0.23	0.14	0.11
Fire design without falling off layers: $M_{d,fi}/M_{R,d,fi}$ [-]	0.22	0.24	0.20	0.14	0.11

The examples confirmed that the fire design taking into account falling off of the charred layer is always fulfilled (quotient $M_{d,fi}/M_{R,d,fi} \leq 1$). For common cross-laminated timber panels and typical fire design situations, the fire design does not govern the design of the panel configuration.

CONCLUSIONS

Large-scale fire tests on unprotected wall and floor elements of cross-laminated solid timber panels from Canadian SPF wood were performed at CNR-IVALSA in San Michele all'Adige, Italy. A polyurethane adhesive was used for face gluing the laminations. In the wall tests, two different types of support conditions were studied. Further, the influence of 3 and 5 ply CLT panels with different orientation setup of the plies on the charring behavior was studied. All tests were performed under constant loading of the specimens. The following conclusions can be drawn:

- In the wall tests, the average charring rate after about 100 minutes of fire exposure was determined to be 0.72 mm/min, which is slightly higher than the one-dimensional charring according to EN 1995-1-2 (0.65 mm/min). This means, that the effect of falling off of charred layers is not significant, mainly due to the quite large thickness of the layers in the range of 19 to 34mm.
- No significant influence of the support conditions studied in this investigation could be observed on the fire behavior of the CLT wall panels.
- In the floor tests, the average charring rate after about 60 minutes of fire exposure was determined to be 0.79 mm/min. The observed increased charring rate in comparison to the one-dimensional charring according to EN 1995-1-2 (0.65 mm/min) can be attributed to the effect of falling off of charred layers and is in agreement to tests performed in the past on floors. An influence of the orientation of the layers on the charring behavior was not observed.

The experimental results of the floor tests were compared to a simplified charring model assuming double charring rate for the second layer (and the subsequent layers) for the first 25 mm of depth when falling off of the first layer occurs. The comparison shows that the calculation model can predict well the charring depth of the floor tests performed for about 60 minutes of fire exposure. For the wall tests no falling off was assumed for the simplified calculation model leading to slightly non-conservative results, i.e. the measured charring depth is higher than the calculated charring depth; however, the difference is quite small.

A parametric study showed that falling off of charred layers for common cross-laminated timber panels and typical fire design situations has no influence on the design of the panel configuration.

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