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Assessing the adhesive performance in CLT exposed to fire

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ABSTRACT: Cross-laminated timber (CLT) became a popular engineered wood product in recent years for high-quality and innovative timber buildings. As for any building product, the fire behaviour of CLT panels requires careful evaluation in the design of such buildings. The adhesive used in the bond lines of CLT plays an important role in the fire design. However, currently, European standards do not provide a test method to assess the adhesive performance in CLT exposed to fire. This paper presents a series of fire tests performed with CLT panels glued with different adhesives. It is shown how the mass loss of the CLT panels in standard fire resistance tests can be used to assess the adhesive performance in CLT exposed to fire.

KEYWORDS: timber, cross-laminated timber, adhesive, fire exposure, temperature measurement, mass loss

1 INTRODUCTION

The performance of cross-laminated timber (CLT) during fire has been strongly discussed in the frame of the design and construction of the first generation of tall timber buildings worldwide in recent years. When the product was introduced onto the market, it was assumed that its behaviour was similar to solid timber. After performing a large number of fire tests, it was observed that CLT may show a different behaviour due to a possible fall off of charring layers. The discussions mainly included (1) increased charring rates and (2) the risk for a second flash-over in real fires. This behaviour is related to the adhesive used in the bond line of CLT [1]. Therefore, both the adhesive and the timber industry have a substantial interest in the development of a methodology to assess the performance of CLT exposed to fire.

During a standard fire test, the charring behaviour and in particular the location of the char front (approx. at 300°C) is usually analysed with temperature measurements using thermocouples (TCs) placed in the bond line of CLT. Thereby, the thermocouples are either installed during the production of the specimen (so-called *in-laid* TCs) or after the production by drilling channels (bore holes) from the fire unexposed surface of the specimen (so called *drilled-in* TCs). It can be assumed that the in-laid TCs measure the correct temperature since they are applied perpendicular to the heat flow, as already specified in old literature [2,3,4]. However, the installation of TCs during the production of CLT is often not possible or accompanied with a considerable amount of additional work. Therefore, in the majority of documented fire tests with CLT, TCs are installed after the production of the specimen by drilling channels from the unexposed, cold, surface parallel to the heat-flow.

This leads (a) to a time delay of the point in time when charring can be assessed and (b) to lower temperatures in the bond line if a charred layer would fall off. The latter, (b), would lead to the assumption that the bonding failure observed is related to an incorrect, i.e. lower, temperature. To conclude, the assessment of the bond line performance by means of thermocouple readings is either very work intense and sometimes not possible (in-laid TCs) or an error in the temperature readings is expected (drilled-in TCs), as shown in [5,6].

If charring layers of a CLT panel fall off before the char front has passed the bond line, fresh (i.e. uncharred) wood is directly exposed to fire. This phenomenon leads to higher charring rates than for solid wood specimens. Additionally, char which has fallen off can be considered as fire-load which will be consumed within the compartment and may lead to a fire re-growth in the cooling stage of a fire, i.e. a second flash-over within the compartment. Such behaviour can only be investigated in cost and time consuming fire experiments with compartments and are thus not appropriate for any standard fire tests. Recently, a large-scale fire test aiming for reproduction of the boundary conditions found in fire was presented in US/CAN to assess the bond line stability and risk for a second flash over [7].

This paper therefore describes a methodology to test CLT manufactured with different adhesives in a model-scale furnace test using the EN/ISO standard fire curve. Thereby, the mass loss of the specimen is used to evaluate specifically the ability of the bond lines to avoid premature fall off of charring layers and subsequently draw conclusions about the charring behaviour and the risk for a second flash-over in compartments when the product is exposed to fire.

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2 CHARRING BEHAVIOUR OF CLT

A large amount of fire tests on single CLT wall and floor elements have been performed in recent years [8]. In these tests, the layer thickness, the number of plies, the adhesive, the cladding for protected CLT specimens, and the support conditions have been investigated among other factors. Further, full-scale compartment fire experiments and ad-hoc testing with a radiant heat panel have been performed to analyse protected and unprotected CLT elements. Based on the performed experimental investigations, the following conclusions can be drawn for the charring behaviour of CLT elements:

- The calculation of the residual cross-section should consider the application of the CLT panel, being horizontally or vertically oriented. To determine the depth of the char layer of floor elements (horizontally), the following two boundary situations should be considered:
  1. If the individual charring layers of the CLT panel do not fall off (also referred to stickability, see standard series EN 13381-X [9]), the forming char layer protects the remaining CLT cross-section against heating. In this case, the CLT panel has a similar fire behaviour as solid wood.
  2. If fall off of the charring layers occurs (also referred to loss of stickability), the fire protective function provided by the charcoal is lost. After a charred layer has fallen off, an increased charring rate is expected. This phenomenon is similar to the increased charring observed for protected timber surfaces after failure of the fire protective cladding (lining) and can be considered using a double charring rate for the following layer during the development of a 25 mm thick char layer. The calculation according to this model is called "stepped charring model" (German: *Treppenmodell*) in this paper.
- For wall elements, the effect of fall off of charring layers was less pronounced in the performed tests. However, it is recommended that unprotected load-bearing wall elements are made of at least five plies in order to ensure a robust solution. With regard to the fire resistance, a thicker outer layer is generally beneficial so that a possible fall off of charring layers would occur as late as possible.

An overview of different simplified charring models for CLT floor and wall elements is presented in [8]

Whether a fall off of charring layers occurs, depends on the adhesive used in the bond line between the boards and the layup of the CLT element (number and thickness of layers). For a fire resistance rating of 30 minutes, fall off of charring layers is not expected when the outer layer has a minimum thickness of 25 mm, as only the first layer is expected to char. For a fire resistance 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 non-load-bearing layers with low stiffness and strength properties has no effect on the overall load-bearing capacity.

3 FIRE TESTS WITH CLT

3.1 METHODS FOR FIRE TESTING

In recent years, different types of tests and experiments (herein used if the test is not performed according to a standard) were performed to investigate the performance of CLT in a fire scenario, such as compartment tests, large-scale furnace tests, model-scale furnace tests and small-scale tests using either a Bunsen burner, an electrical oven or a radiant heat source. However, these tests have significant disadvantages, see also the characteristics in Table 1. Compartment tests or large scale furnace tests are very costly and subjected to more scatter while for small-scale tests the validity and significance of the results are to be questioned. While for furnace tests the thermal exposure, i.e. the combination of gas and radiation temperature, is similar to compartment fires with incident heat flux from zero to about 180 kW/m^2 after 2 hours [10], it is difficult to define for small-scale tests typically performed at ambient conditions. Further difficulties arise from the specimen size if one-dimensional heat flux cannot be achieved.

3.2 TEMPERATURE MEASURMENTS DURING FIRE TESTS WITH CLT

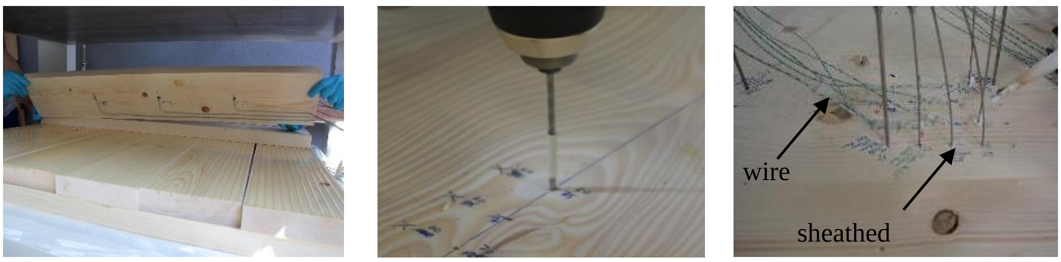
For the interpretation of experimental results and for conclusions about the member's response in fire, the temperature development is usually measured by means of internal thermocouples. In case of CLT, being a timber product and thus having a low conductivity, typically steep temperature gradients appear when exposed to fire [12]. Steep temperature gradients make the measurement more prone to errors, as for example a small change in the measurement position, i.e. the distance from the fire exposed surface has a considerable impact. Additionally, the heat loss due to conduction in the measurement device used may lead to a lower measured temperature and may cool down the surrounding material.

The accuracy of the temperature measurement readings of thermocouples is in general in the range of 1 K, however, the error caused by improper installation and/or choice of inappropriate thermocouple design can be in the range of several hundred K. This would result in an inaccurate estimation and late detection of any char temperature and char layer depth, leading to wrong charring rates and design models and thus to inappropriate design of CLT. Figure 1 shows commonly used options to measure the temperature during a fire test with CLT panels:

- Thermocouple wire, inlaid during the production, see Figure 2 (a)
- Thermocouple wire, drilled-in after the production, see Figure 2 (b&c)
- Thermocouple sheathed, drilled-in after the production, see Figure 2 (b&c)

Table 1: Characteristics of different types of fire tests (image source: ETH Zurich)

Compartment experiment	Furnace test	Radiant heat source
		
Characteristics		
- no standard test - various experimental set-ups available (with and without scientific measurements) - real fire exposure (significant scatter) - cooling phase evaluation possible - oxygen content < 5% in fully developed phase - temperature increase depending on the thermal inertia of the surfaces, not its combustibility - dependent on boundary conditions (weather) - complex experiments indoors - costly and time consuming - low reproducibility - significant share of the total heat release by outdoor flaming	- standards available - thermal exposure controlled by plate thermometer (EN/ISO) - many default curves possible - measure for comparison - no information about cooling phase in standard tests - fire exposure similar to real fires - oxygen content < 5% - no surface flaming for combustible elements (low oxygen content) - burner fuel consumption different for different furnaces and thermal inertia of the test element - in large-scale costly and time consuming	- no standard test - various experimental set-ups available (with and without scientific measurements) - thermal exposure difficult to describe - good reproducibility (for incombustibles) - ambient oxygen content ≈ 21% - surface flaming for combustibles - flames represent further energy source - convection coefficient not insignificant - validity and significance of results limited - cheap



(a) (b) (c)

Figure 1**:** Different options for the thermocouple design and installation in CLT: (a) Inlaid during the production, (b) drilled-in after the production from the fire unexposed side, (c) drilled-in wires and sheathed thermocouples.

Figure 2 presents the mean temperatures measured over time in different distances from the fire exposed side in one fire test performed with a horizontally orientated CLT panel tested on a model-scale furnace by ETH Zurich. The plot shows a significant temperature difference between the measurements of the inlaid wire thermocouples and the two other options for the same distance to the fire exposed surface.

In general, the temperature measurements with drilled-in thermocouples (wire and sheathed) showed up to several hundred K significant lower temperatures than the inlaid wire thermocouples at the same time of the measurement. At 25, 50 and 75 mm distance to the fire exposed surface, the 300°C isotherm (indicating the char front) was detected 6, 10 and 8 minutes, respectively, later when the thermocouples were *drilled-in* after the production in comparison to the *in-laid* thermocouples. As presented in [6,12], this difference can even reach 35 minutes in low conductive materials such as timber. A comparison of measurements using different channel diameters for sheathed thermocouples, i.e. constant channel diameter and staggered channel diameters with tight tips (equal channel diameter as sheathed thermocouple diameter), and comparison of sealed and not-sealed channels did not result in significant improvements [12]. It seems that the heat conduction in the thermocouple device when installed parallel to the heat flow in the solid is significant.

Since most of the fire tests with CLT presented in literature and also company owned fire tests with CLT used drilled-in thermocouples (simply because of ease of installation) to indicate the char development in the specimen during the fire test, many test results and also conclusions drawn from these tests are highly questionable. The correct installation and design of the thermocouples is crucial for the calculation of the char development and thus also for the evaluation of the fire performance of CLT. The authors of this paper strongly recommend to install the thermocouples along/parallel to the isotherms; in case of wire thermocouples; a minimum length of 50 mm along the isotherm should lead to correct measurements. *In-laid* wire thermocouples following this rule can be considered as the best option to measure the temperature in the cross-section exposed to fire; any other option to measure the temperature in timber members might lead to wrong evaluations and interpretations [6,12].

It can be concluded that evaluating the adhesive performance in CLT elements using temperature measurements might introduce significant measurement uncertainty and thus this type of measurement might be not appropriate to be used for the assessment of the adhesive performance in CLT elements.

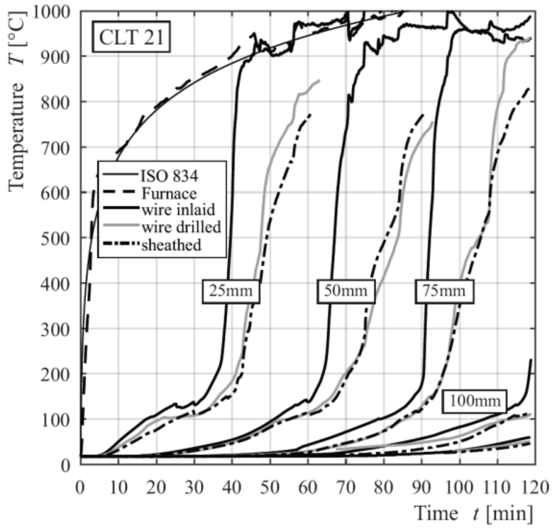
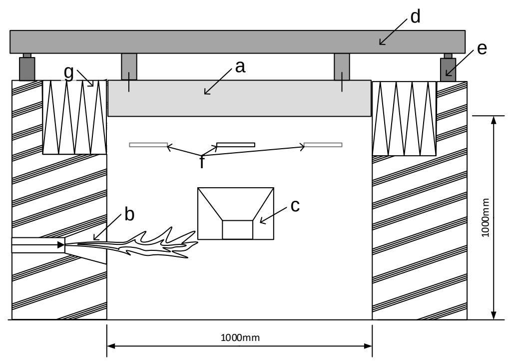


Figure 2: Time temperature curves for different types of thermocouple design; numbers in boxes indicate the distance to fire exposed surface.

3.3 FURNACE TESTS WITH CLT AT ETH

At ETH Zurich, nine fire tests were performed in model-scale with an approximate timber element size of 0.8 m^2. One solid timber panel (STP) and eight cross-laminated-timber panels (CLTs) made from spruce were tested exposed to EN/ISO standard fire exposure. The reason to use STP elements was that there is no risk for failure of bond lines, i.e. fall off of layers during charring, as the joints between the beams are vertically orientated (parallel to the heat flow). Further, thermocouples can be placed easily in any requested distance to the fire exposed surface before assembling the element. For CLT elements, thermocouples were inserted during the production between the layers (in-laid TCs). The CLT specimens were manufactured with four different structural adhesives, such as 1-component polyurethane (1C-PUR) and melamine urea formaldehyde (MUF) type of adhesives.

The furnace was controlled with plate thermometers and tests lasted between 60 and 120 min. Type K thermocouples (*wire inlaid*) were used to measure the development of the charring temperature. Figure 6 bases on the measurements with the following thermocouple setup: K-w-e-0.5/2.2/in-pa, see [12]. Elements were tested at approximate 12% equilibrium moisture content. In addition to standard fire resistance tests, the mass loss of the specimens was recorded continuously with load cells during these tests, see Figure 3. Further, the specimen was weighed before and right after the fire test to check measurements of the load-cells. Measuring the mass allows the calculation of the total mass loss due to charring and fall off of charring layers.



key:

a … hanging test specimen	e … load cell
b … oil burner	f … plate thermocouple
c … furnace window	g … fitting insulation
d … frame to carry the specimen	

Figure 3: End elevation of the model scale furnace showing the hanging test specimen (details up scaled).

Results of these tests are, among others, the mass loss of the timber specimens, the temperature development in the cross-section and the residual cross-sections (total depth including the char layer and depth of virgin wood) after the test. The development of the mass loss is shown in Figure 4 exemplary for three different tests.

In the test with specimen CLT 3, fall off of charring layers was observed leading to a considerable mass loss in comparison to fire test with specimen CLT 7. The loss of significant parts of the charring layers can be observed due to the change of the graphs' slope at approximately 42 min, 65 min, 82 min and 100 min. The specimen CLT 7 was manufactured with a novel type of one-component polyurethane (1C-PUR) adhesive and showed almost the same mass loss as with a solid timber deck plate (STP), which is used as benchmark.

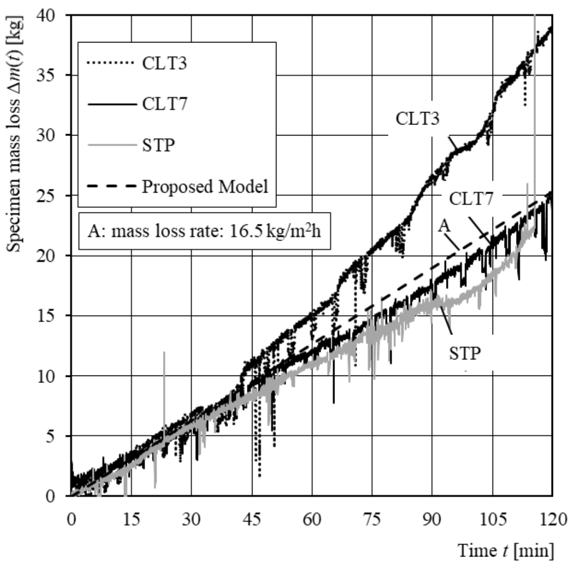


Figure 4**:** Specimen mass loss continuously measured over time of fire exposure using load cells for selected tests with CLT and STP (solid timber panel).

It should be noted that specimen CLT 6 was produced with a MUF adhesive resulting in approximate the same mass loss rate as observed for the solid timber deck specimen STP, see Table 2. The mean density of the specimens tested was 453 kg/m^3 with only a small deviation from this value (±20 kg/m^3), which means that the density should have no influence on the results and interpretations presented here.

Specimen CLT 7 (PUR1, lamella thickness 35mm) and CLT 2 (PUR1, lamella thickness 25mm) showed similar charring behaviour as given in Eurocode 5 [15] (see Figure 6) and thus a charring rate of 0.65 mm/min over 120 minutes of standard fire exposure. However, although glued with the same adhesive PUR1, the observed mass loss rate was higher for specimen CLT 2 with 25mm thick lamellas than for specimen CLT 7 with 35mm thick lamellas. A possible reason could be the macroscopic shrinkage effect of char pieces (approx. mean length 40 mm) which leads to bending of the char pieces and subsequently to tension perpendicular to the bond lines. Thus, it can be concluded that the behaviour of fall off is not solitary a characteristic of the adhesive used but the adhesive and the layup of the CLT.

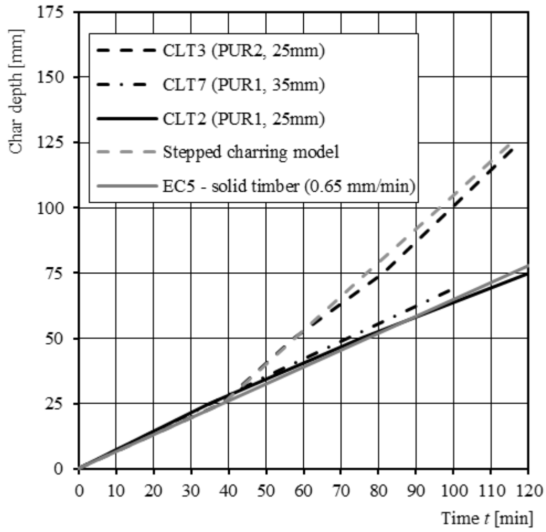


Figure 5**:** Development of char depth with time of fire exposure, calculated on the basis of wire *in-laid* thermocouple. Very good agreement between model (see Figure 1 and tests).

Table 2: Mass loss overview (* benchmark)

Specimen name	Adhesive[1]	Layer thickness [mm]	Density [kg/m³]	Fire time [h]	Total mass loss [kg]	Mass loss rate [kg/(m² h)]	[-]
CLT 1	PUR 1	10	463.5	1	14.4	18.8	1.22
CLT 2	PUR 1	25	471.4	2	27.6	18.0	1.17
CLT 3	PUR 2	25	447.5	2	40.7	26.5	1.73
CLT 4	PUR 1	25	438.7	2	28.4	18.5	1.21
CLT 5	PUR 1	20	471.0	1.5	22.6	19.6	1.28
CLT 6	MUF	25	448.7	2	23.7	15.5	1.01
CLT 7	PUR 1	35	456.8	2	25.3	16.5	1.07
CLT 21	PUR 3	25	433.0	2	33.2	21.6	1.40
Solid timber deck STP	-	-	454.0	2	22.4	15.4	**1.00***

[1] PUR: One-component polyurethane; PUR1 passes compartment test acc. to PRG 320-2018 [7]
MUF: Melamine-urea-formaldehyde; certified according to EN 301:2017 [13] for structural timber

3.4 COMPARTMENT TESTS WITH CLT AT SwRI

Compartment (or room) fire experiments have been performed in the past at various research institutes. Many experimental series aimed for convincing the fire brigades that extinguishing the fire in buildings made from combustible materials is not more complicated than for those made from incombustibles, e.g. [14]. More recent experiments aimed for testing other characteristics such as burn-out and behaviour of glued timber products such as CLT in more realistic fires, since a standard fire test cannot estimate the behaviour of a construction in the cooling phase. Generally, the fall off of charred lamellae of massive glued engineered products such as CLT counteract the capability to achieve burn-out, which might be required by authorities for certain buildings.

At the *Southwest Research Institute* (SwRI) in San Antonio (US), a fire performance test method for evaluating CLT adhesives was recently developed. It combines observations of experiments with a test method to allow for a better control of the test boundary conditions. During the development procedure, various fire tests have been performed with CLT floor elements (dimensions (width × height): 2.44 × 4.88 [m]) glued with different types of adhesives. 5-ply CLT elements were tested with a lamella thickness of 35 mm. The test room of the newly developed PRG 320-2018 [7] test method has the following properties, see also Figure 6:

- Interior dimensions of the test room: 2.74 × 5.79 × 2.44 [m] (width × length × height)
  - Dimensions of the opening in front wall: 0.91 × 1.90 [m] (width × height)
- Wall and floor elements are incombustible
- Gas burner controls the heat release rate profile at the centre of the ceiling, see Figure 8.

The pass/fail criteria to evaluate the fall off behaviour of charring layers leading to a second flash-over during the cooling phase, which lasts up to 4 h after the start of the burners, are as follows:

- Significant increase of room gas temperature during cooling phase
- Significant increase of measured incident radiant heat flux during cooling phase
- Occurrence of a second flashover
- Increased charring rate and char depth respectively of the CLT panel

For the evaluation presented in this paper, it is worth to note that the SwRI performed one compartment test investigating the performance of adhesive PUR1, as also tested in the ETH tests presented in chapter 3.3. In this compartment test, burn-out was observed and no second flash-over appeared, see Figure 7. Thus, the behaviour is similar to other tests with CLT glued with a MUF or a PRF (phenol-resorcinol-formaldehyde) type of adhesive. The PUR1 adhesive has been certified according to PRG 320-2018 standard for the use in load-bearing CLT elements on the North American market.

Figure 6: Impressions of compartment test with CLT (layer thickness 35mm) glued with PUR1 adhesive [16].

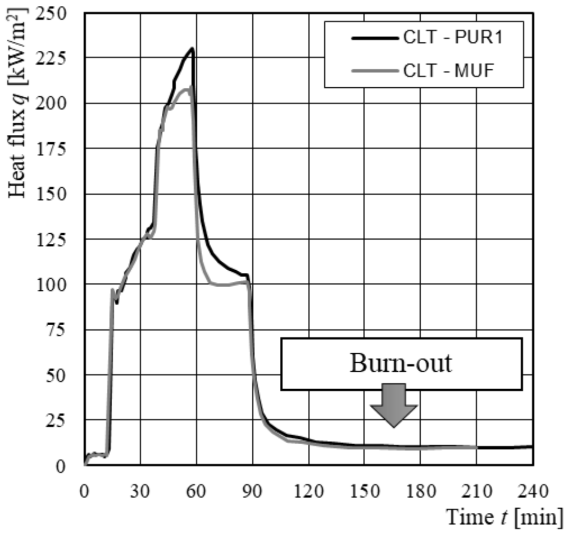


Figure 7: Incident radiant heat flux during compartment tests with CLT glued with PUR and MUF adhesive.

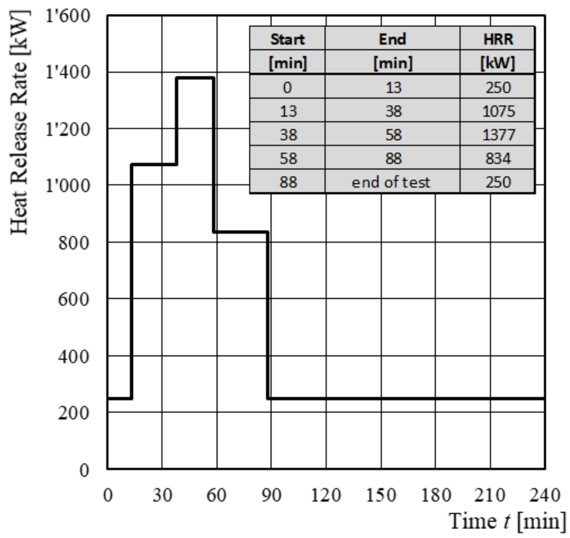


Figure 8: Heat Release Rate profile to follow at the centre of the ceiling [16].

4 FIRE TEST METHOD PROPOSAL FOR CLT

A standard test method to assess the adhesive performance in CLT exposed to fire should be reproducible and it should be possible to be performed with existing equipment by fire labs with reasonable effort and money. The installation of thermocouples in CLT has been controversy discussed, the evaluation of the performance of the bond line can be very subjective due to misleading temperature measurements resulting from crude installation of thermocouples [6,12]. It is important to develop a robust test method that allows for a clear evaluation of the performance of CLT exposed to fire for both the charring behaviour and the behaviour in the cooling phase of a real fire. Thus, it was decided to avoid temperature measurements but use the mass loss in standard fire tests to assess the fire performance of the bond line.

The test method to assess the adhesive performance in CLT exposed to fire presented in the following bases mainly on two comparisons:

(1) The comparison of the mass loss of a CLT product during a fire resistance test with the expected mass loss of a solid timber deck panel (STP in chapter 3.3).

(2) The comparison of model-scale fire tests performed at ETH and the compartment test according to PRG 320-2018, as performed at SwRI.

With regard to (1) the comparison of mass loss of CLT and STP in standard fire tests:

In these tests, the mass loss of the specimens was documented after 120 minutes standard fire exposure. The mass of the CLT panel can be taken easily with e.g. a crane scale when lifting the specimen on the furnace and removing it after the test. Alternatively, the mass of the specimen can be taken with a standard scale before testing and right after the stop of the fire test and before extinguishing it. The advantages of this procedure are manifold and cover the charring of a timber specimen under variable, continuously increasing thermal exposure as in standard furnace tests (incident heat flux up to 180 kW/m^2). There is no need of extra instrumentation, e.g. thermocouples, it still offers the possibility to do loaded tests, subjective evaluation is eliminated especially with respect to visual detection of charring layer fall off and, in addition, the procedure is independent on the specimen size.

The tests performed at ETH (see chapter 3.3) showed a mass loss rate of about 15 kg/m^2h for a solid timber floor element (STP) without fall off of charred parts. Analysing the charred specimen it was confirmed that no fall off of char pieces had occurred during the test; the total depth of the specimen (virgin wood depth plus char depth) was as before the fire test. Preferably, glued engineered wood products such as CLT should show the same charring behaviour as solid timber in fire. Consequently, the mass loss rate measured in the STP test should be used to define a default (maximum) mass loss rate for CLT exposed to standard fire. Taking into account the usual variability of the charring behaviour in fire tests, a maximum deviation of this mass loss rate of 10% is considered to be still acceptable, which leads to a maximum allowed mass loss of about 16.5 kg/m^2h for solid wood products. Thus, if the determined mass loss rate of CLT is below this threshold for (a to be defined time of) standard fire exposure, the charring behaviour in standard fire tests can be stated as similar to a solid timber element, for which no fall off of charred parts are expected.

With regard to (2) the comparison of model-scale fire tests performed at ETH and the compartment test according to PRG 320-2018:

In both test series a 5-ply CLT element with lamella thickness of 35 mm and glued with adhesive PUR1 was tested. This element did not show a second flash-over in the compartment test and thus burn-out was achieved. Further, the CLT panel with the same configuration resulted in a mass loss rate of 16.5 kg/m^2h in a standard fire resistance test on the model-scale furnace (exposure area ca. 0.8 m^2).

As a consequence, it can be concluded that a CLT panel tested in a (model-scale) fire resistance test furnace showing a maximum mass loss rate of 16.5 kg/m^2h exhibits burn-out in the compartment test according to PRG 320-2018.

Consequently, for the products which show less than the maximum mass loss in standard furnace tests, it is not expected that a second flashover would occur in real fires; the basic requirement for a favourable compartment burn-out would be given.

5 CONCLUSION AND OUTLOOK

This paper proposes a reliable method to assess the adhesive performance of bond lines of CLT exposed to fire. This is relevant for the overall fire dynamics in general, the ability to sustain burn-out in particular and the application of calculation and simulation models, e.g. [17] for the design of fire exposed CLT. This paper shows that mass loss measurements of non-glued solid timber plates in standard fire resistance tests (mass loss rate about 15 kg/m^2h), where no fall off of char pieces occur, could be used as benchmark to verify the behaviour of CLT for both (1) the charring model used in calculation of the load-bearing resistance and (2) to assess the risk of a second flash-over.

The comparison of recently presented compartment experiments and two hours model-scale standard fire resistance tests allowed the conclusion that a mass loss rate of CLT panels of maximum 16.5 kg/m^2h seems to allow for burn-out in real fires. It is content of future research to check (1) whether CLT elements with less than 35 mm lamella thickness can be covered with this approach or (2) whether this maximum mass loss threshold can further be increased to allow for burn-out in real fires.

Analysing the test results it was observed that the charring rate of the solid timber plates (STP; benchmark test) was lower than the value given in Eurocode, i.e. 0.65 mm/min, which is a mean value of charring rates observed in tests up to 90 min. CLT 2 showed a charring rate of 0.65 mm/min but a mass loss rate higher than the benchmark test including a 10% tolerance. Future research should cover this possible inconsistency and should investigate further the influence of the lamellae thickness, as it seems that the behaviour of the bond line in fire exposed timber products is not sorely based on the adhesive but also on the CLT layup.

It should be noted that the presented numbers are first indication and the database shall be enlarged with further fire tests allowing a connection of CLTs behaviour in fire compartments and standard furnace tests. The presented proposal to assess the adhesive performance of CLT may also be used for other glued engineered wood products such as laminated veneer lumber (LVL) or glued-laminated timber. The authors of this article recommend the industry to ask fire labs to extend standard fire tests with additional mass loss measurements, since this information could be of high value and is certainly not a big effort to document.

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REFERENCES

[1] Frangi A, Fontana M, Hugi E, Jöbstl R. (2009), Experimental analysis of cross-laminated timber panels in fire. Fire Saf. J. 2009; 44: 1078–1087.

[2] William D. Brewer (1967), Effect of thermocouple wire size and configuration on internal temperature measurements in a charring Ablator. National Aeronautics and space Administration, Washington DC.

[3] VDI/VDE 3511-5 (1994), Temperature measurement in Industry – Installation of Thermometers. Verein Deutscher Ingenieure. Düsseldorf, Germany.

[4] James V. Beck (1962), Thermocouple Temperature Disturbances in Low Conductivity Materials. Journal of heat transfer.

[5] Fahrni R., Schmid J., Klippel M, Frangi A. (2018), Temperature measurements in timber members for experimental fire testing. Fire and Materials, Paper submitted.

[6] Fahrni, R., Schmid, J., Klippel, M, Frangi, A. (2018), Investigation of different designs and installations of temperature measurements in wood as low conductive materials, Conference Structures in Fire SIF'18, Belfast, 2018.

[7] ANSI/APA PRG 320-2018, Standard for Performance-Rated Cross-Laminated Timber. American national standard. ANSI / ARPA 2018.

[8] Klippel M., Schmid J. (2017) Design of Cross-Laminated Timber in Fire, Structural Engineering International, 27:2, 224-230, DOI: 10.2749/101686617X14881932436096

[9] EN 13381-7: Test methods for determining the contribution to the fire resistance of structural members - Part 7: Applied protection to timber members, CEN European Committee for Standardisation, 2003.

[10] Schmid J., Brandon D., Werther N., Klippel M. (2018), Technical note - Thermal exposure of wood in standard fire resistance tests. Fire Safety Journal. https://doi.org/10.1016/j.firesaf.2018.02.002

[11] ISO 834-1:1999, Fire - Resistance Tests - Elements of Building Construction - Part 1: General Requirements. International Organization for Standardization, Geneva, 1999.

[12] Fahrni R., Schmid J., Klippel M., Frangi A. (2018) Correct temperature measurements in fire exposed wood, World Conference on Timber Engineering WCTE 2018, 20-23 August, Seoul, Republic of Korea.
[13] EN 301:2017, Adhesives, phenolic and aminoplastic, for load-bearing timber structures – Classification and performance requirements.
[14] Lange, D., Sjöström, J., Schmid, J., Daniel, B., Timber and the fire resistance furnace – A comparative Study of the conditions in a fire Resistance furnace when testing combustible and non-combustible construction, Conference Structures in Fire SIF'18, Belfast, 2018.
[15] EN 1995-1-2 (Eurocode 5). Design of Timber Structures, Part 1–2: General – Structural Fire Design, CEN: Brussels, 2010.
[16] Janssens M., (2017) Development of a Fire Performance Test Method for Evaluating CLT Adhesives, PRG 320 Webinar, October 18, 2017.
[17] Schmid, J., Klippel, M., Just, A., Frangi, A., Tiso, M., 2018 Simulation of the Fire Resistance of Cross-laminated Timber (CLT), Fire Technology.