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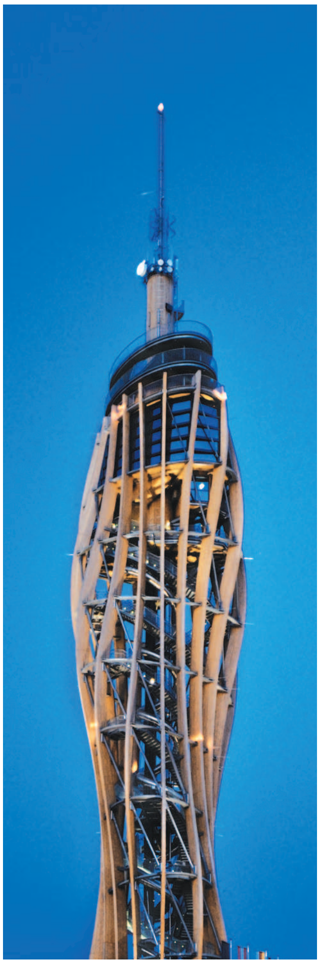

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SELF-EXTINGUISHMENT OF CROSS-LAMINATED TIMBER

Roy Crielaard[1], Jan-Willem van de Kuilen[2], Karel Terwel[3], Geert Ravenshorst[4], Pascal Steenbakkers[5], Arnoud Breunese[6]

ABSTRACT: Cross-laminated timber, or CLT, is receiving attention for its potential use in tall buildings. As a combustible material, one of the challenges for the construction of these buildings is the fire risk that results from its use in the structure. Unprotected CLT can burn along with the fuel load present in a compartment. Irrespective of its fire resistance rating, it is uncertain whether the structure will be totally consumed in the event of a complete burnout, or whether a fire would decay by self-extinguishment.

Self-extinguishment of CLT was investigated by first creating a theoretical model that determined the conditions under which it could be achieved. Two series of experiments were subsequently conducted to quantify these conditions. Based on these experiments it was concluded that there is a potential for self-extinguishment of CLT if: delamination and fall-off of charred layers are prevented by applying sufficiently thick lamellae; the heat flux on the CLT during smouldering is below 5 to 6 kW/m^2; and the airflow over the CLT surface during smouldering is limited to a speed of 0,5 m/s at heat flux exposures below 6 kW/m^2.

KEYWORDS: Cross-laminated timber, CLT, structure, fire, self-extinguishment, experiments

1 INTRODUCTION

Architects and engineers are witnessing an increased interest in timber. Although wood has been a construction material for a long time, it is currently receiving attention for its potential use in increasingly taller buildings [1-3].

On the one hand, this development has to do with new engineered timber products and the potential economic benefits of prefabricated timber. On the other hand, the shift towards more sustainable architecture makes new applications of timber interesting.

Because timber is a combustible material, one of the challenges for the construction of tall timber buildings is the potential fire risk that results from its application in the structure. Architects and owners are asking for more wood to be exposed and previous studies have identified issues that will need to be addressed to warrant the safety of these tall buildings with exposed timber [4, 5].

One of these issues is the fundamental tenet of tall building fire safety design that the structure shall withstand the burnout of all the combustible material present. A key question for the fire safe design of tall timber structures therefore is: will the timber structure extinguish or continue to burn?

2 PROBLEM DESCRIPTION

Building codes typically assume a structure not to be part of the fuel load during a fire and implicitly or explicitly restrict the use of combustible materials for construction. Traditional forms of timber construction do not deviate significantly from this assumption. Either the amount of exposed timber is small, e.g. heavy timber frame construction with columns and beams; or the timber is fully protected by encapsulation, e.g. light timber frame construction.

2.1 EXPOSED CLT DURING BURNOUT

However, an unprotected CLT structure consisting of walls and floors will result in a larger amount of timber exposed. This structure can then burn along with the fuel load present in a compartment during a fire. The assumption that the structure is not a part of the fuel is no longer valid.

In the event of a complete burnout the fire will continue until all fuel has been consumed. Because the exposed timber structure will contribute to this fuel, it is uncertain whether the timber structure will be completely consumed. If the structure continues burning, it can no longer be expected to be able to maintain its load-carrying capacity or provide acceptable compartmentation. This could result in failure of the structure and collapse.

2.2 CONSEQUENCES OF COLLAPSE

The potential collapse as a result of a compartment burnout is especially important considering the

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envisioned use of timber in tall building. For tall buildings, there is an increased severity of the consequences of structural failure as result of a fire [6]. In order to obtain a desired level of safety, building codes typically compensate for these severe consequences with a higher level of reliability of the fire safety measure. This is often achieved by specifying a higher fire resistance rating. However, irrespective of the fire resistance rating, the performance of the timber in a burnout scenario is uncertain, because it is unknown whether it continues burning.

Eurocode also recognises the risk associated with failure of a tall buildings and indicates that it is to be designed according to consequences class 3; i.e. failure of the structure is highly undesirable and the structure needs to be reliable, safe, and robust. The design in consequence class 3 requires a high degree of insight into the structural fire behaviour. An in-depth investigation of risks associated with the fire behaviour and the structural fire response is needed.

2.3 POTENTIAL SELF-EXTINGUISHMENT

An alternative to the sustained burning of CLT after a compartment burnout is potential self-extinguishment. Self-extinguishment would mean the combustible contents in the compartment have been consumed, while the timber structure is no longer burning and still able to maintain its load-carrying capacity. As a result, the CLT structure might be able to survive the fire and collapse is prevented.

Self-extinguishment is not yet well understood. Fire tests are generally stopped and cooled with water before self-extinguishment can manifest, normally because a pre-determined period has elapsed, corresponding to the fire resistance period of interest.

This research aims to increase insight into the behaviour of unprotected CLT in a compartment burnout by explicitly investigating self-extinguishment and the conditions under which it can occur. In reality, extinguishment could be achieved in combination with active measures, such as sprinkler activation or fire-brigade intervention. However self-extinguishment was investigated on its own as a passive protection mechanism in this research. The main research question is: “Under what conditions is there a potential for self-extinguishment of cross-laminated timber?”

3 SELF-EXTINGUISHMENT MODEL

In order to quantify the conditions for self-extinguishment, it is important to identify the phases of a self-extinguishing CLT room fire.

3.1 INDICATION OF SELF-EXTINGUISHMENT

An indication of self-extinguishment of CLT was observed in tests conducted by McGregor *et al.* [7]. His observations indicate that CLT can be expected to decay along with the “initial” fire of compartment contents, e.g. the burning of furniture in the test room or the fire created by propane burners.

In some tests by McGregor the CLT subsequently transformed from flaming to smouldering combustion. This smouldering then faded, which could indicate self-extinguishment. However, actual self-extinguishment was not observed because the tests were stopped.

In other setups tested by McGregor, the CLT delaminated. Delamination occurs when the adhesive between the lamella of the CLT loses bonding at elevated temperatures, resulting in a separation of the layers. In these tests the fire was observed to either remain in flaming combustion or revert back to it.

These observations suggest that if a potential for self-extinguishment exists, it will likely be reached when the CLT does not delaminate and the fire can enter a smouldering phase.

3.2 THE INFLUENCE OF DELAMINATION

The influence of delamination and the performance of the adhesive on the burning behaviour of CLT have been investigated by Frangi *et al.* [8]. Common types of CLT use polyurethane (PU) based adhesives. The PU based adhesives investigated were found to be prone to delamination when the CLT was tested in a horizontal configuration with a standard fire exposure (a time-temperature curve commonly used to assess the fire-performance of materials and structural elements) from below. The delaminated lamella fell off; exposing the next uncharred layer, resulting in a sudden increase of the burning and charring rates. Delamination occurred after a layer was completely charred, i.e. when the 300 °C isotherm reached the adhesive. The influence of the thickness of lamellae was also investigated in these tests. It was found that less lamellae but greater thickness decreases the amount of layers that can delaminate, while increasing the time before it occurs.

These observations suggest that PU based CLT can be prone to delamination and fall-off. When this is combined with the observations made by McGregor, it seems that self-extinguishment is difficult to achieve if delamination occurs. However, there is a potential to increase the lamella thickness in order to delay delamination and allow the fire to transform from flaming to smouldering within the thickness of a single lamella.

3.3 SMOULDERING

Once the CLT has reached a smouldering phase, it still needs to extinguish. Ohlemiller [9-11] investigated smouldering wood and found that it does not smoulder along its surface unless supplemented by a radiant flux of ~10 kW/m^2. Smouldering was found to be controlled by the rate of diffusion of oxygen to the reaction zone, rather than by the amount of oxygen available in the ambient air. A forced oxygen supply due to an imposed airflow over the surface increased smouldering.

Beyler *et al.* [12] and Swann *et al.* [13] found that a radiative flux of ~8 kW/m^2 was required for the onset of glowing on the surface of plywood. Glowing was not sustained in absence of the heat flux. The idea that wood is not able to sustain its own combustion is supported by the experience that wood will not burn in flaming combustion unless supported by heat from another source. Tewarson and Pion [14] observed that the heat transfer from the flames to the wood is theoretically just sufficient to match the heat losses, while the results obtained by Petrella [15] indicate that the losses are even slightly higher.

These observations suggest an externally applied heat flux is required to sustain smouldering. In a real compartment fire, this heat flux would be provided by mutual cross-radiation, depending on the amount of, geometry, and orientation between the CLT surfaces and other hot objects or flames. If this flux drops below a certain threshold value, the CLT can be expected to transform from smouldering to self-extinguishment. Furthermore, it can be assumed that smouldering is more likely to be sustained with a forced oxygen supply.

3.4 THE ROUTE TO SELF-EXTINGUISHMENT

Based on the work discussed above, a model is formulated that describes self-extinguishment of CLT (figure 1).

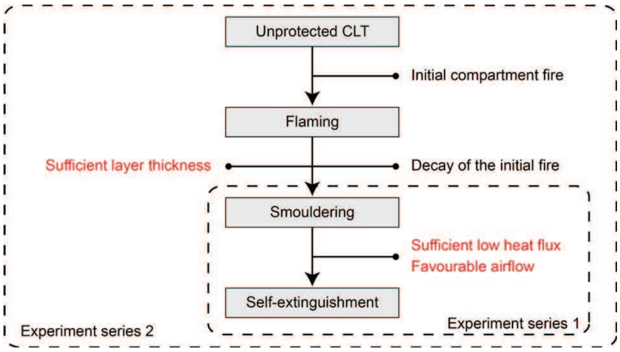

Figure 1: *Model of self-extinguishment of CLT*

Under the influence of an "initial" fire due to burning of compartment contents, an exposed CLT structure can be expected to become involved in flaming combustion. In a compartment burnout scenario, the initial fire will decay once compartment contents have been largely consumed, resulting in a decrease of the CLT's contribution to the fire, instigating its transformation from flaming to smouldering combustion.

Subsequently, the CLT can transform from smouldering to self-extinguishment if a sufficiently low heat flux is present and if the airflow over the surface is favourable. However, delamination and fall-off can interfere with these transitions by sustaining flaming or reverting smouldering back to flaming. As a result, the CLT might not self-extinguish.

Alternatively, delamination may be prevented if the lamellae are sufficiently thick and the charring front does not reach the adhesive, so that the transformations may occur within the thickness of the first lamella.

4 EXPERIMENT SET-UP

Two series of experiments were conducted to investigate the model of self-extinguishment and quantify the conditions under which self-extinguishment can take place.

4.1 FIRST SERIES OF EXPERIMENTS

The first series of experiments quantified the conditions of heat flux and airflow under which the transition from smouldering to self-extinguishment can occur.

4.1.1 Approach

The approach was to subject small CLT samples to a two-step heat flux (figure 2). This two-step exposure represents the heat flux unprotected CLT receives in a room fire, assuming no delamination occurs.

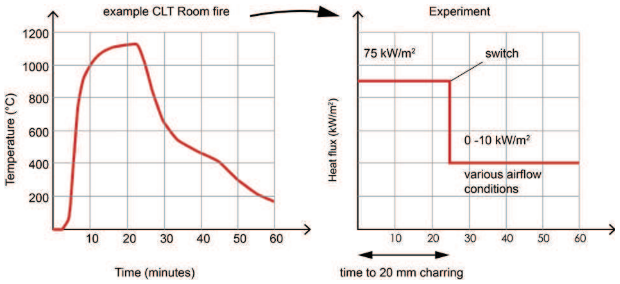

Figure 2: *Approach of the first series of experiments*

The first heat flux of 75 kW/m^2 simulated the fully developed fire. When the samples were charred to a degree that can be expected in a real fire they were switched to a variable second heat flux of ≤ 10 kW/m^2. This switch represented the decay of the room contents with the second heat flux simulating the subsequent cross-radiation of smouldering CLT surfaces and other hot objects.

Samples were expected to self-extinguish if the second heat flux dropped below a certain threshold value. In some experiments, an additional air flow was led over the samples during smouldering.

4.1.2 Equipment

A cone calorimeter (figure 3) was used to provide the first high heat flux exposure. The cone calorimeter consists of a radiant heater that can impose heat upon the face of a sample, while measuring the sample mass and analysing exhaust gases to determine the heat release rate. Samples were oriented with the lamella in a horizontally configuration to prevent fall-off under the influence of gravity.

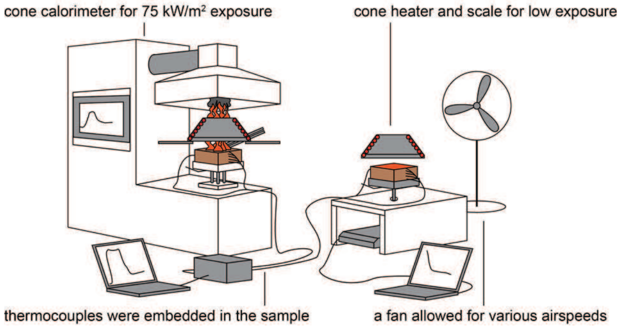

Figure 3: *Test setup of the first series of experiments*

A separate cone heater was used to impose the low heat flux. A fast transition between the heat fluxes was possible by switching the sample from one device to the other. Simultaneously, samples were placed on a scale to measure the mass to provide an indication of self-extinguishment. In the experiments with an additional air flow over the sample surface, a domestic fan was used.

4.1.3 Samples

The samples were cut to sizes of 100 by 100 mm and 50 mm thick from 100 mm thick CLT plates (figure 4). These plates were built-up of five cross-wise oriented 20 mm thick lamella, made of spruce, grade C24, glued with a polyurethane adhesive for face and finger jointing and an emulsion polymer isocyanate glue for edge joints.

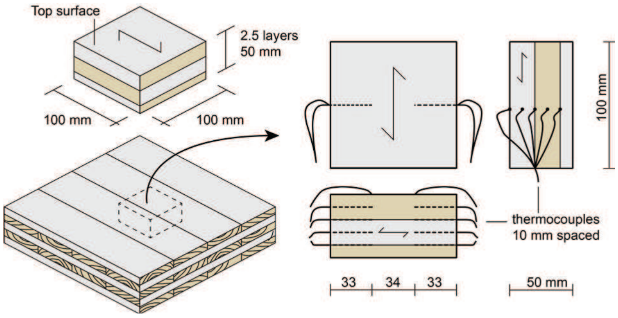

Figure 4: *Sample for the first series of experiments*

The samples were conditioned at a relative humidity of 50 % and a temperature of 23 °C for 2 weeks until a stable weight was achieved. After conditioning, 33 mm long canals were drilled from two sides of the samples at distances of 10, 20, 30 and 40 mm from the top surface, to accommodate thermocouples. Two thermocouples were also installed at the top surface. The thermocouples provided temperature data through the samples, which allowed for the determination of charring rates and would indicate if samples had extinguished. Finally, the samples were weighed and edges wrapped in aluminium foil to reduce the effect of sideward heating.

4.1.4 Procedure

At the start of an experiment, the CLT sample was placed on the cone calorimeter load cell with the top surface 25 mm below the heater. The shutters opened, exposing the sample to a 75 kW/m^2 heat flux and an automatic igniter provided piloted ignition.

When 20 mm of the CLT was charred, i.e. when the thermocouples at 20 mm depth exceeded 300 °C, the sample was removed from the calorimeter and quickly placed on the scale under the separate heater during a 10 second interval. A 20 mm char layer represented a steady thickness that can be expected to develop in a fully developed fire, while leaving sufficient uncharred material to disregard edge disturbances.

The sample was subsequently exposed to the second flux between 0 and 10 kW/m^2 and in some cases to an additional airflow over its surface. An experiment was stopped if the sample had extinguished or burned through. A sample was considered to be extinguished when the 300 °C isotherm no longer propagated through the CLT and when temperatures were below 200 °C. This indicated no volatiles (gaseous fuel vapours) were produced and no wood was decomposed into char: the combustion reaction had stopped. Another indication was the ceasing of further mass reduction. A sample was considered to be burned through if the 300 °C isotherm reached the thermocouples at 40 mm depth and if the sample kept losing mass.

4.2 SECOND SERIES OF EXPERIMENTS

The second series of experiments investigated the complete model of self-extinguishment, including the influence of delamination and fall-off of char.

4.2.1 Approach

The approach was to subject small CLT compartments to a simple design fire with a constant heat release rate of 41 kW and a decay phase (figure 5). This design fire simulated the burning of an initial fire in a room, excluding burning of CLT. The CLT became involved in the fire and once it was charred to a degree that can be expected in a real fire, the initial fire was stopped, representing the depletion of the initial fire load.

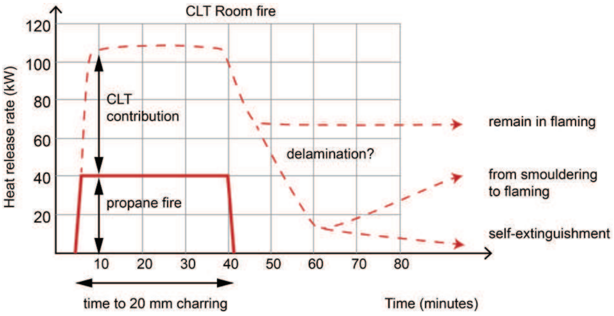

Figure 5: *Approach of the second series of experiments*

The CLT was then expected to transform from flaming to smouldering. Alternatively, it could remain in flaming combustion, potentially as a result of delamination and fall-off. If the fire did transform to smouldering, the CLT could transform back to flaming due to delamination and fall-off, continue smouldering if the heat flux was high enough, or self-extinguish if it was sufficiently low. The influence of airflow was not investigated.

The heat flux received by the CLT after cessation of the propane flow was provided by mutual cross-radiation between CLT surfaces. Various heat fluxes were created by varying the amount of exposed CLT compared to non-combustible surface. The CLT was orientated vertically, such that fall-off of char could occur and its effects on the fire could be investigated.

The idea that a sufficient thick lamella can assist in achieving self-extinguishment was tested in one experiment by increasing the top lamella to 40 mm.

4.2.2 Equipment

The design fire was created by a square propane burner bed with seven rows of five burners, each with a capacity of 26 kW (figure 6). Compartments were placed on top of this bed so that the burners were level with the compartment floor. This required perforation of the floor. A mass flow controller allowed the propane to be regulated to deliver the desired heat release rate.

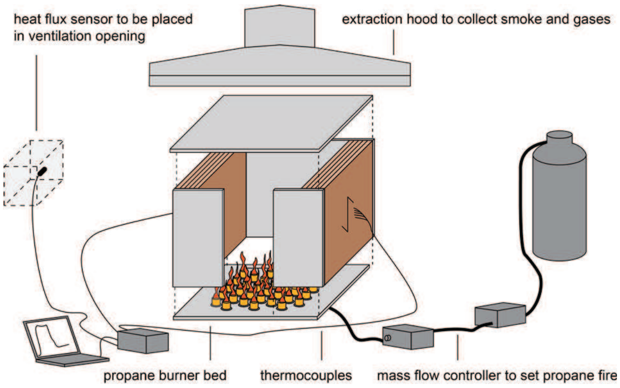

Figure 6: *Test setup of the second series of experiments*

In order to evaluate the severity of the fire and potential self-extinguishment, smoke and gases were extracted and analysed by an oxygen consumption calorimeter that determined the heat release rate. A heat flux sensor was placed in the middle of the opening. The heat flux measurement was used to estimate the heat flux on the CLT, considering the configuration of the rooms.

4.2.3 Samples

The samples were boxes of 0.5 by 0.5 by 0.5 m internal dimensions with an opening 0.18 m wide over the full height. Floor, ceiling, and front were made of 20 mm thick non-combustible board. Back- and side walls were either CLT or also non-combustible board (figure 7).

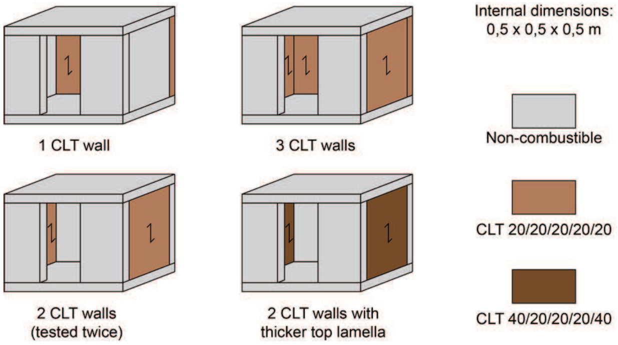

Figure 7: *Samples for the second series of experiments*

The same CLT and way of conditioning were applied as in the first series of experiments. To accommodate thermocouples, five canals were drilled from the cold-side to a depth of 20, 30, 40, 50, and 60 mm from the fire-side surface. Such a set was typically located in the middle of a CLT wall, or in the middle of a corner connecting two CLT walls. The thermocouples were closely spaced to provide temperatures through the CLT at these locations, which allowed for the determination of charring rates and provided an indication of self-extinguishment. Thermocouples were installed in the middle of the boxes at 400 and 200 mm heights, to obtain “room” temperatures. Joints and canals were sealed with a non-combustible fire-resistant glue to avoid spreading of the fire and samples were weighed.

4.2.4 Procedure

At the start of an experiment the burners were ignited and the heat flux sensor was placed in the opening. The propane flow was increased to the flow corresponding to a heat release rate of 41 kW for the initial fire.

The CLT became involved in flaming combustion, contributing to the total fire. When 20 mm of the CLT was charred the propane flow was stopped and the initial fire decayed. Without the initial fire, the behaviour of the CLT on its own was investigated.

Similar to the first series of experiments, an experiment was stopped if the sample had extinguished or burned through. A sample was considered to be extinguished when the 300 °C isotherm no longer propagated through the CLT and when temperatures were near or below 200 °C. Another indication was the heat release rate dropping to approximately 0 kW. A sample was considered to be burned through if the 300 °C isotherm reached the thermocouples at 60 mm depth from the fire-side surface and when the heat release rate remained positive.

4.3 OVERVIEW OF EXPERIMENTS

An overview of experiments is given in tables 1 and 2.

Table 1: *overview of first series of experiments*

Experiment	Second heat flux	Additional airflow
1.1, 1.2	0 kW/m^2	-
1.3, 1.4	5 kW/m^2	-
1.5, 1.6	10 kW/m^2	-
1.7 , 1.8	8 kW/m^2	-
1.9, 1.10	6 kW/m^2	-
1.11	6 kW/m^2	0,5 m/s
1.12	6 kW/m^2	1,0 m/s

Table 2: *overview of second series of experiments*

Experiment	CLT elements	Top lamella thickness
2.1	back wall	20 mm
2.2	back- and side	20 mm
2.3	side walls	20 mm
2.4	side walls	20 mm
2.5	side walls	40 mm

5 RESULTS

5.1 FIRST SERIES OF EXPERIMENTS

During the initial 75 kW/m^2 exposure, all CLT samples became involved in flaming combustion within 10 seconds. Without a protective char layer, temperatures in the wood rose rapidly, typically to 700-750 °C, followed by a more gradual increase to 770-880 °C. Temperatures in deeper layers also increased, although less rapidly and reaching lower peak values. Significant differences between temperatures in adjacent layers indicated a steep temperature gradient in the material, reinforcing the idea of wood as an insulator of heat.

As a result of the increased temperatures, thermal degradation of the wood occurred. Volatiles were released and the samples lost mass. The volatiles were ignited and heat was generated. Both mass loss and heat release rates peaked after 20 seconds: on average 0,18 g/s and 237 kW/m^2. This early peak can be attributed to the absence of char at the start of an experiment.

As a result of the continued thermal degradation, a char layer developed. This char protected the wood underneath, which was reflected in mass loss rates and heat release rates decreasing after the initial peak. This suggested the char layer decreased the flow of heat to the thermal degradation zone, slowing down the production of volatiles. Typically, the mass loss and heat release rates stabilised after 5 minutes. From that moment to just prior to switching, the average mass loss and heat release rates were 0,05 g/s and 73 kW/m^2 respectively.

On average the temperatures at 20 mm depth exceeded 300 °C after 20 minutes 40 seconds. The samples were switched to a lower flux in the range of 0-10 kW/m^2. Flaming ceased within 1 minute and the CLT smouldered. Depending on the level of heat flux and any additional airflow, either smouldering was sustained and the sample burned-through, or the smouldering ceased and the sample self-extinguished. Table 3 presents an overview of extinguishment and burning-through.

Table 3: *results of first series of experiments*

Experiment	Second heat flux + airflow	Self-extinguished
1.1, 1.2	0 kW/m^2	yes
1.3, 1.4	5 kW/m^2	yes
1.5, 1.6	10 kW/m^2	no
1.7 , 1.8	8 kW/m^2	no
1.9, 1.10	6 kW/m^2	yes
1.11	6 kW/m^2+0.5 m/s	yes
1.12	6 kW/m^2+1.0 m/s	no

5.1.1 Heat flux condition for self-extinguishment

Samples extinguished at a heat flux of 0 or 5 kW/m^2 and a heat flux of 5 kW/m^2 can be taken as a lower bound for the threshold at which self-extinguishment takes place. At a heat flux of 8 or 10 kW/m^2 the samples continued smouldering and burned-through. Samples exposed to a 6 kW/m^2 flux initially smouldered; the 300 °C isotherm penetrated to 30 mm depth, and the sample kept losing mass. However, the 300 °C isotherm did not reach 40 mm depth, all temperatures dropped below 200 °C, and the weight stabilised. The samples had extinguished after some initial smouldering. This extinguishment after initial smouldering can be explained by a slowly decreasing heat flux received by the samples, as a result of an increasing distance between the sample surface and the cone heater, due to a reduction in volume when wood is transformed to char and ash. Therefore, a heat flux of 6 kW/m^2 can be considered to be an upper bound for the threshold at which self-extinguishment takes place. Based on this analysis, the threshold flux at which self-extinguishment occurs is in the range of 5 to 6 kW/m^2.

5.1.2 Air flow condition for self-extinguishment

The influence of additional air flow over the sample surface was investigated only in combination with a 6 kW/m^2 heat flux. An additional airflow speed of 0.5 m/s resulted in self-extinguishment more quickly than without, while an additional airflow of speed 1.0 m/s resulted in intense smouldering and burn-through. Based on this limited data, it can be expected that an additional airflow speed of 1.0 m/s results in less favourable conditions for self-extinguishment, while an additional airflow speed of 0.5 m/s results in more favourable conditions. Based on this analysis, it can reasonably be assumed that at a heat flux < 6 kW/m^2, an airflow with a speed limited to 0.5 m/s results in self-extinguishment.

5.1.3 Charring rates

Charring rates were obtained by estimating the location of the 300 °C isotherm, based on the average thermocouple temperature at a certain depth. Charring rates varied as the smoulder front propagated through the material and were expressed as an average for each layer of 10 mm material. The average charring rate during 75 kW/m^2 exposure was 1.67 mm/min for the first 10 mm and 0.78 mm/min for the second 10 mm. Two additional experiments were conducted in addition to those listed in table 1, in which the samples were not switched, resulting in a charring rate of 0.78 and 0.67 for the third and fourth 10 mm respectively.

Charring rates for the second lower exposures were found to depend on the level of heat flux and any additional airflow. For a 0 and 5 kW/m^2 heat flux, no charring rates were obtained, because these samples extinguished. For the 6 kW/m^2 exposure, the average charring rate for the third 10 mm of material was 0.15 mm/min, but for deeper layers no charring rate was recorded, because these samples also extinguished. For 10 and 8 kW/m^2 exposures, the average charring rates were 0.20 and 0.16 mm/min for the third 10 mm of CLT, and 0.28 and 0.21 mm/min for the fourth 10 mm of CLT. In the experiment with an additional airflow, no charring rates were recorded at an airspeed of 0.5 m/s, while high charring rates of 0.48 mm/min and 0.56 mm/min for the third and fourth 10 mm of CLT were obtained at an airspeed of 1.0 m/s.

5.1.4 Delamination

Inspection of the samples revealed delamination had occurred, typically as the 300 °C isotherm reached the PU adhesive. This did not result in fall-off, because the delaminated layer would lie on top of the sample due to the horizontal orientation. As a result, delamination had no significant influence on the burning behaviour.

5.1.5 Temperature profiles

The distribution of temperatures through the CLT provided insight into how the samples smouldered. Figure 8 shows a temperature profile of an experiment using a 10 kW/m^2 exposure. The various zones of the smouldering mechanism can be observed propagating through the material.

At the surface a residual ash and char layer was present. Its temperature was relatively low, approximately 400 °C, because the surface is subjected to significant heat losses. Temperatures eventually decreased below 400 °C, but only once thermocouples became exposed to the ambient air. The surface temperature is important, because in a real fire, the heat flux received by other surfaces depends in part on the surface temperature of the smouldering CLT. For the purpose of estimating this heat flux, a surface temperature of smouldering CLT of 400 °C can be used.

Below this residual layer is a reaction zone where char is oxidized. The energy and heat that are produced drive the smouldering process. The temperature is high; 400-600 °C. Heat is conducted from this zone to the surface and deeper into the sample to the thermal degradation zone. While the reaction zone is insulated by the ash and char layer, the losses can become too large. If these losses are not sufficiently compensated by an externally applied heat flux, the smoulder process cannot be sustained and the sample self-extinguishes.

The heat conducted from the reaction zone to the deeper layers elevates the temperature above 200 °C, which results in thermal degradation of the wood. When the temperature is above 300 °C, the wood can be considered to be transformed into char. While the zones propagate through the sample, this char becomes the reaction zone, and the former reaction zone becomes a residual layer.

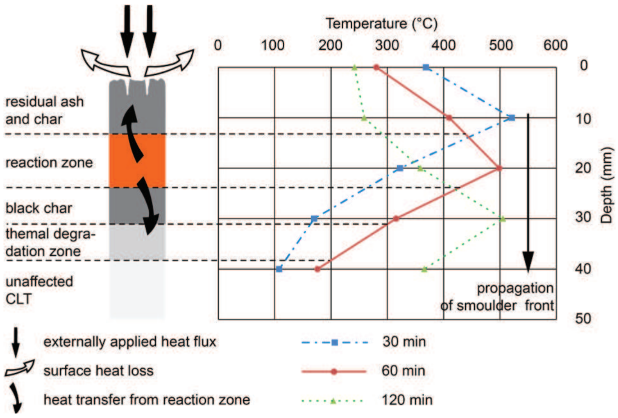

Figure 8: *Temperature profiles in experiment 1.6*

Investigation of temperatures also showed additional airflow had two effects: increased surface cooling and additional heat generated due to an increased reaction speed as a result of forced oxygen supply. These effects seemed to compete in slowing down and speeding up the reaction and the net result appears to be dependent on the speed of the additional airflow.

5.2 SECOND SERIES OF EXPERIMENTS

In the second series of experiments, after ignition of the propane fire, the CLT walls became involved in flaming combustion within 2 minutes. The heat release rate of the propane fire was 164 kW/m^2 over the floor area, but the total heat release rate rose rapidly to an average of 354 kW/m^2 due to involvement of the CLT. On average, the CLT contributed 90 kW/m^2 over its surface area during burning of the propane fire.

Contrary to the first series of experiments, the heat release rate and mass loss rate did not peak early. This seemed due to the fact that the CLT was not instantly exposed to a high heat flux, but was exposed to it more gradually. Temperatures in the compartments rose rapidly to 900 °C, followed by a more gradual increase to 1000-1170 °C.

During burning of the propane fire, some fall-off of char occurred in experiments 2.2, 2.3, and 2.4, even though the 300 °C isotherm had not yet reached the PU adhesive. This suggested not that these pieces had delaminated, but that pieces were breaking off. Furthermore, the amount of fall-off was minor compared to when charring had progressed further into the CLT.

When thermocouples indicated temperatures at 20 mm depth exceeded 300 °C, the propane flow was reduced to 0 % and the initial fire decayed. The behaviour of the various compartments, in terms of the model of self-extinguishment, is shown in figure 9. Delamination and fall-off played a major role in the behaviour.

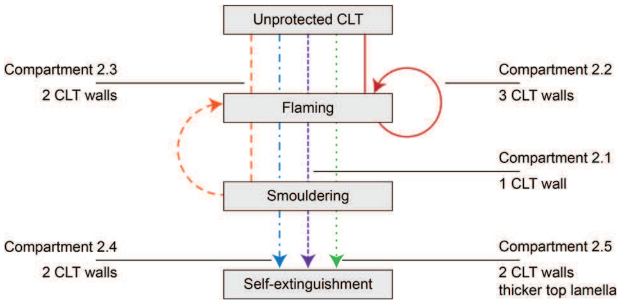

Figure 9: *results of second series of experiments*

5.2.1 Compartments that burned-through

In compartment 2.2 with three CLT walls, delamination resulted in sustained flaming combustion. A smouldering phase was never reached (figure 10). New wood became exposed when the temperatures in the compartment were relatively high, 700-900 °C, as was the heat flux on the CLT, 49 kW/m^2 at the middle of the side walls and 43 kW/m^2 at the middle of the back wall.

In compartment 2.3 with two side walls, the fire transformed from flaming to smouldering when room temperatures were in the range of 400-500 °C and the estimated heat flux on the middle of the side walls was 12 kW/m^2. However, delamination and fall-off during smouldering resulted in local flaming and eventually in reverting back to flaming combustion of all CLT in a "second flash-over". Just before this second flash-over room temperatures had dropped to 250-350 °C and the heat flux on the side walls was approximately 8 kW/m^2.

***Figure 10:** Compartment 2.2 with three CLT walls remained in flaming combustion after the initial fire was stopped due to fall-off of delaminated layers.*

5.2.2 Compartments that extinguished

In compartment 2.1 with one CLT wall, the fire transformed from flaming to smouldering when room temperatures were 400 °C and the heat flux on the middle of the CLT wall was 12 kW/m^2. Fall-off occurred during smouldering when room temperatures were relatively low, < 225 °C, as was the heat flux on the middle of the side wall, < 3,5 kW/m^2. Fall-off did not result in a transformation from smouldering back to flaming. The smouldering decreased in intensity and the CLT eventually self-extinguished.

In compartment 2.4 with the same configuration as compartment 2.3, the fire was able to transform from flaming to smouldering when room temperatures were 450-600 °C and the heat flux on the middle of the side walls was 12 kW/m^2. During smouldering of the CLT delamination and fall-off occurred when room temperatures were < 250 °C, and when the estimated heat flux on the middle of the side wall was < 4 kW/m^2. Some local flaming occurred, but this did not result in a second flash-over. The smouldering decreased in intensity and the CT eventually self-extinguished.

In compartment 2.5, with two CLT side walls and a 40 mm top lamella, the fire transformed from flaming to smouldering within minutes of the propane fire being turned off. Room temperatures were 400-550 °C and the heat flux on the middle of the side walls was 12 kW/m^2. No fall-off was observed. The smouldering quickly decreased in intensity and the CLT self-extinguished. Inspection of the sample showed the charring front had penetrated just past a depth of 20 mm.

5.2.3 Lamella condition for self-extinguishment

The experiments showed that the conditions in the compartment have an influence on the effect of delamination and fall-off (figure 11). In experiment 2.2 flaming was sustained because compartment conditions were sufficiently "hot". The exposed wood was subject to high temperatures and heat flux, resulting in the release of more combustible gases that burn in flaming combustion.

In experiment 2.3, fall-off occurred when the room temperature was > 250 °C and the heat flux was > 8 kW/m^2. These conditions were cooler than during the transformation from flaming to smouldering, but hot enough to result in local flaming at multiple locations. As a result, temperatures remained high, which made sustained burning and delamination of other surfaces more likely. When even more pieces delaminated, this resulted in a "chain reaction" and a second flash over.

In experiments 2.1 and 2.4 delamination and fall-off did not result in sustained flaming. Compartment conditions were sufficiently "cool" by the time fall-off occurred. Either insufficient combustible gases were released when new wood became exposed, or some local flaming occurred that was insufficiently to start in a chain reaction. The conditions at which delamination was "safe" were found to be room temperatures of < 250 °C and a heat flux to the CLT wall of < 4 kW/m^2.

However delamination and its effects were found to be unpredictable. For example, experiments 2.3 and 2.4, which had the same configurations, showed completely different outcomes; one exhibited self-extinguishment whereas the other showed burn-through after a second flashover. Therefore, relying on compartment conditions to sufficiently cool down to allow for "safe" delamination seems risky.

Alternatively, as shown in experiment 2.5, an increased thickness of the lamellae can prevent delamination. The charring front did not reach the adhesive and no delamination and fall-off occurred. The fire transformed from flaming to smouldering and could then make the transition to self-extinguishment if the conditions of heat flux and air flow were favourable. This was indeed the case in experiment 2.5 where the configuration with two CLT walls opposite each other resulted in a heat flux received by the CLT during smouldering below the threshold value of 5 to 6 kW/m^2.

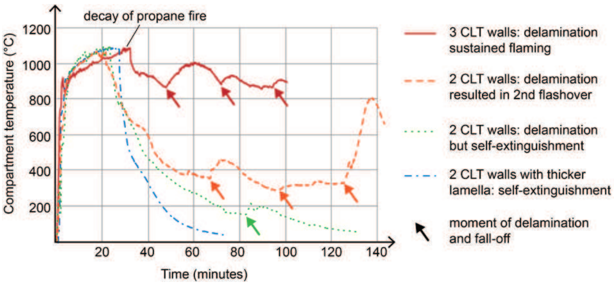

***Figure 11:** Compartment temperatures at 400 mm height in four of the samples of the second series of experiments*

5.2.4 Total energy released by the CLT

The contribution of the CLT to the fire can be expressed in terms of the total energy released. Table 4 shows the energy released by the propane fire and by the CLT.

In the experiments where the compartments did not self-extinguish, the CLT contributed significantly to the fire. This contribution was 412 MJ/m^2 over the CLT surface in the experiment with three CLT walls (an increase of 401 % compared to the propane fire load). In the experiments where the CLT did extinguish, the contribution of the CLT did not exceed 242 MJ/m^2. The lowest contribution was in compartment 5 where no delamination occurred; 142 MJ/m^2. Note that these values were obtained under specific conditions of the experiments, with a high ratio of CLT to floor area.

***Table 4:** energy released in the second series of experiments*

Experiment	Propane fire MJ (/m^2 floor)	CLT MJ (/m^2 CLT)
2.1	112 (448)	57 (228)
2.2	77 (308)	309 (412)
2.3	55 (220)	185 (370)
2.4	62 (248)	121 (242)
2.5	63 (252)	71 (142)

Figure 12 illustrates the contribution of the CLT to the fire in experiments with two CLT walls where burn-through (2.3) and self-extinguishment (2.5) occurred.
Exposed CLT can significantly increase the total energy released in a compartment, as well as the duration of the fire. These are increased even further when delamination and fall-off result in prolonged flaming.

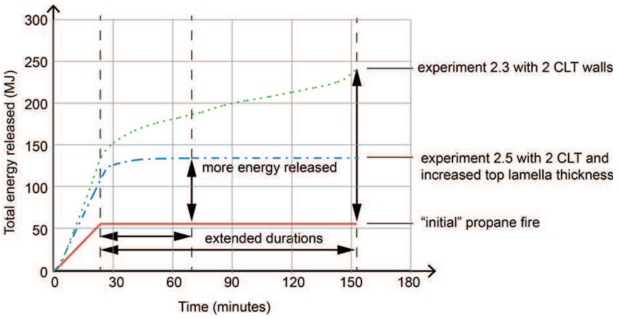

***Figure 12:** Total energy released*

5.2.5 Charring rates

Charing of the first 20 mm was fairly constant for all compartments, with an average 0.76 mm/min. This average is higher than that provided by Eurocode 5 for solid timber and glulam of 0.65 mm/min [16]. This is attributed to the relatively intense propane fire compared to the standard fire, and to the contribution of the CLT to the fire during charring of the first 20 mm of CLT.
Charring of the deeper layers varied greatly. For the compartment that self-extinguished, no charring rates were obtained for the deeper layers. In the experiments where burn-through occurred a wide range of charring rates were obtained, with the average being 0.77 mm/min. Again, this average charring rate is higher than provided by Eurocode, even though the propane fire was not burning at this stage. This is attributed to the fact that delamination increased the overall charring rate.

6 CONCLUSIONS AND RECOMMENDATIONS

Two series of experiments were conducted to investigate the conditions under which CLT can self-extinguish. From the analysis a number of conclusions and recommendations can be drawn. These are based on a limited number of experiments, conducted under specific conditions. Unloaded specimen were used and choices were made regarding fire load, ventilation conditions, CLT build-up, adhesive, wood species, configuration, and scale. These can influence the fire and structural response. Furthermore, even seemingly identical conditions can lead to different results. It is important to consider the conclusions within this experimental range.

6.1 CONCLUSIONS

A challenge for the construction of tall timber buildings with an exposed structure is the fundamental tenet of tall building fire safety design that the structure shall withstand the burnout of all the combustible material present. A key question for the fire safe design of tall timber structures therefore is: will the timber structure extinguish or continue to burn?

Self-extinguishment of CLT follows a number of phases. Under the influence of an initial fire due to burning of room contents, the exposed CLT becomes involved in flaming combustion. Once the room contents have been largely consumed and the initial fire decays, the CLT contribution is expected to decrease as well, transforming from flaming to smouldering combustion. Finally, there will be a transition from smouldering to self-extinguishment.

There is a potential for self-extinguishment of smouldering CLT if: the heat flux received by the CLT is below 5 to 6 kW/m^2; and the airflow over the surface is limited to a speed of 0,5 m/s at heat flux exposures below 6 kW/m^2.

Delamination and fall-off of charred lamellae of CLT can sustain flaming combustion or revert smouldering back to flaming combustion. This prevents the CLT from reaching a smoulder phase from which it could self-extinguish. Delamination and fall-off can be prevented by an increased thickness of the top lamella ensuring the charring front does not reach the polyurethane adhesive, which would result in loss of bonding.

Exposed CLT increases the heat release rate and the total energy released, and extends the duration of a fire. These are further increased when delamination and fall-off result in prolonged flaming.

6.2 RECOMMENDATIONS

To verify conclusions and assess the applicability for real structures, further research is recommended on a larger scale, on loaded specimen, and with variations of the conditions mentioned above.

An explicit method for determining self-extinguishment is currently not part of fire safety considerations for timber buildings. Pending further research, self-extinguishment might be considered as part of a total fire safety concept for timber buildings.
In a real tall building, active measures, such as sprinkler activation and fire brigade intervention, can be expected.

It would be recommended to investigate self-extinguishment as part of a total fire safety strategy.

The heat flux received by the CLT consists partly on cross-radiation between smouldering CLT surfaces. This cross-radiation is interactive by nature and should be further investigated.

The influence of the airflow on the transition from smouldering to self-extinguishment was investigated to a limited degree. It would be recommended to further investigate a range of airspeeds in combination with a range of heat fluxes. Results should be compared with actual values that can be expected in real compartments and buildings, with and without openings in the façade.

Delamination and fall-off due to loss of bonding of the polyurethane adhesive at elevated temperatures might be prevented by (development of) other types of glue. As a result, the CLT might perform as a solid slab of wood and the application of a certain lamella thickness to prevent delamination would no longer be required.

Exposed CLT can significantly increase the severity of a fire. It is recommended to investigate the influence on the development of fires. Results could be compared to a standard fire and implications with regards to the fire resistance of members could be discussed.

Charring rates in experiments where CLT contributed to the fire were typically higher than suggested by Eurocode 5. It is recommended to further investigate the influence of the CLT contribution to the fire and of delamination and fall-off on the charring rate. Results could be compared with values in design guidance.

Even if delamination is prevented, flaming might be sustained by a sufficiently high heat flux. This was not investigated, but would need to be addressed and added to the model of self-extinguishment.

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