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Self-extinguishment of cross-laminated timber

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ABSTRACT

Cross-laminated timber, or CLT, is receiving attention for its potential application in tall building structures. As a combustible material, one of the main 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 the structure's fire resistance rating, it is uncertain whether the structure will be totally consumed in the event of a complete burnout. If the structure would continue to burn, this could result in collapse of the building. Alternatively, the fire could decay by self-extinguishment.

Self-extinguishment of CLT was investigated with a theoretical model that describes the conditions under which it could be achieved. Two series of experiments were conducted to quantify these conditions. It was concluded that there is a potential for self-extinguishment of CLT if fall-off of charred layers is prevented by applying sufficiently thick lamellae, if the heat flux on the CLT during smouldering is below 5–6 kW/m^2, and if the airflow over the surface during smouldering is limited to a speed of 0.5 m/s. An exploration towards design implementation is presented.

1. Introduction

Architects and engineers are witnessing an increased interest in timber. Although wood has been a construction material for a long time, particularly in low-rise applications, it is now 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. The renewable nature and low embodied energy make wood a sustainable alternative to steel and concrete [1].

At the forefront has been the use of cross-laminated timber (CLT). CLT is an engineered wood panel product. A panel is composed of a number of layers, each consisting of side-by-side placed solid-sawn timber boards, which are sometimes edge-glued to create single-layer panels. These layers are stacked crosswise, typically at 90° angles, and adhesively bonded to create a solid panel (Fig. 1). One panel consists typically of an odd number of layers, symmetrical around the mid-layer. Polyurethane, melamine, and phenolic based adhesives are used, with polyurethane being the most popular in Europe [4].

Due to continuous bonding, a composite action between the layers is achieved and the panel has an improved dimensional stability. Large dimension can be realised and the crosswise orientation of the layers generates favourable mechanical properties. The panels can be relatively long and wide and are used as load-carrying plates and slabs. Furthermore, CLT allows for a high degree of off-site prefabrication and rapid construction.

2. Problem description

Timber being 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. While architects and developers are asking for more wood to be exposed, various research initiatives and design guidance documents have identified issues that will need to be addressed to warrant the safety of these tall buildings with exposed timber [5–8].

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

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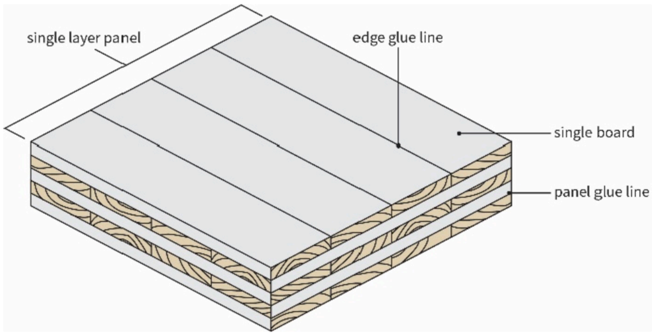

Fig. 1. Schematic representation of cross-laminated timber.

tall timber structures therefore is: will the exposed timber structure extinguish or continue to burn?

2.1. Exposed CLT during burnout

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 and fire protection can be achieved by charring of these members, e.g. heavy timber frame construction with columns and beams; or the amount of timber is multitude but fully protected by encapsulation, e.g. light timber frame construction.

However, an unprotected CLT structure consisting of walls and floors results in a large amount of exposed timber. 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 envisioned use of timber in tall building. With regards to structural fire safety, many building codes set out a functional statement and require that a building can be evacuated and searched during a reasonable amount of time in the event of a fire without the danger of collapse [9]. The building code then provides a set of performance requirements that allow compliance with the functional statement to be demonstrated. For structural fire safety, these performance requirements are fire resistance requirements for structural members. The required fire resistance is expressed in minutes of increasing levels depending on function, height, and fire load of the building.

It is generally recognised that these levels of increasing fire resistance are related to increased risk in buildings. Risk can be defined as the product of the probability that a hazard will be realised and the consequences of that hazard [10]. Consequences can be quantified, for example as the number of fatalities or injuries, or in terms of failure cost. Terwel [11] provides a definition of structural safety which incorporates risk. His definition can be adapted for structural fire safety: structural fire safety can be defined as the absence of unacceptable risk associated with failure of (part of) a structure as result of a fire.

The international fire safety community recognises the high complexity of fire safety for tall buildings. It can be argued that for increasingly tall buildings, the severity of the consequences of structural failure increases. According to the definition of risk, when the severity of the consequences increases, so does the risk if no measures are taken to lower the probability. This implies a lower (and potentially unacceptable) level of safety. However, building codes specifically require an equal level of safety for tall buildings as intended for lower buildings. It could be argued this implies an equal level of risk.

Therefore, in order to obtain that desired level of safety, building codes compensate for the more severe consequences with a higher level of reliability of the fire safety measures. This higher level or reliability is often achieved by specifying a higher fire resistance rating. The fire might not last longer, but the higher rating increases the probability of the structure to withstand its effects. For a tall building this practically means the structure is likely to withstand the burnout of all the combustible material present. Furthermore the risk to occupants and firefighters is reduced, because they have more time to evacuate, and perform search and rescue and firefighting operations.

However, the probability of structural failure for a structure that exposes large amounts of timber cannot be decreased by increasing the fire resistance alone. Increasing its fire resistance would rely on charring. However, the timber structure could continue burning and eventually collapse. Irrespective of the fire resistance rating, the level of safety intended by the code might not be achieved.

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 [12]. The design in consequence class 3 requires a high degree of insight into the structural (fire) behaviour [13]. 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 during a compartment burnout could be self-extinguishment. Self-extinguishment would occur if all combustible contents in the compartment have been consumed and the timber structure is still able to maintain its load-carrying strength or provide adequate compartmentation [5]. 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, or to protect the testing facilities.

This research aims to increase insight into the behaviour of unprotected CLT in a compartment burnout by 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. This means it is assumed that sprinklers are not present (or have failed) and that firefighters are unable to fight the fire. The main research question is: "Under what conditions is there a potential for self-extinguishment of cross-laminated timber?"

3. Theory

In order to qualify the conditions for self-extinguishment, a theoretical model is formulated first that describes 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. [14]. Observations indicated that CLT can be expected to burn in flaming combustion 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. When this initial fire starts to decay, flaming combustion of the CLT can be expected to decay along with it.

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 was reported to "delaminate" and charred layers fell off. Fall-off of char occurred when the adhesive between the lamella of the CLT lost 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 by McGregor suggest that if a potential for self-extinguishment exists, it will only be reached when the CLT does not exhibit char fall off and the fire can enter a smouldering phase. This idea was reinforced by the work of Medina Hevia [15], who conducted three tests on partially unprotected CLT rooms (respectively 63%, 58%, and 79% of the CLT surfaces protected). The first two tests did not self-extinguish. However, the first test did show a decay phase after room contents were consumed. The fire re-ignited causing a "second flashover" due to burning of the second layer of the CLT because of reported "ply delamination". The final test with only one CLT wall unprotected did self-extinguish and performed similarly to the fully protected room test conducted by McGregor.

3.2. The influence of char fall-off

The influence fall-off of charred layers of CLT and the performance of the adhesive on the burning behaviour of CLT has been investigated by Frangi et al. [16]. CLT using polyurethane (PU) and melamine urea formaldehyde (MUF) based adhesives were investigated.

It was found that CLT with the tested MUF-based adhesive did not exhibit char fall-off in an unfavourable horizontal configuration with standard fire exposure from below. However, MUF is not a common adhesive for CLT in Europe due to health consideration with regards to formaldehyde emission. The most common alternative is PU.

The PU based adhesives investigated were prone to char fall-off when the CLT was tested in a horizontal configuration with a standard fire exposure from below. The charred lamella fell off; exposing the next uncharred layer, resulting in a sudden increase of the burning and charring rates. Falling of the char occurred after a layer was completely charred, i.e. when the 300 °C isotherm (a measure for the charring front) reached the adhesive. The influence of the thickness of lamellae was also investigated. It was found that less lamellae but greater individual lamella thickness decreases the amount of layers that can fall-off, while increasing the time before it occurs.

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

3.3. Smouldering

If the CLT can reach a smouldering phase, the fire still needs to extinguish. Ohlemiller [17–19] investigated smouldering wood and found that it does not smoulder along its surface unless supplemented by a radiant flux of approximately 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. [20] and Swann et al. [21] found that a radiative flux of approximately 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 [22] 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 [23] 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 could be provided by mutual cross-radiation between CLT surfaces and other hot surfaces, e.g. due to flaming or smouldering of room contents, etc. If this heat flux drops below a certain threshold value, the smouldering CLT can be expected to self-extinguish. Furthermore, it can be assumed that smouldering is more likely to be sustained with a forced oxygen supply to the reaction zone.

3.4. The route to self-extinguishment

The observations discussed above can be used to formulate a model that describes self-extinguishment of a compartment fire with an exposed CLT structure.

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. This is accompanied by a decrease of the CLT's contribution to the fire, instigating its transformation from flaming combustion to smouldering combustion.

Subsequently, the smouldering CLT can self-extinguish if a sufficiently low heat flux is present and if the airflow over the surface is favourable. However, fall-off of charred lamellae can interfere with these transitions by sustaining flaming combustion or reverting the smouldering CLT back to flaming combustion. As a result, the CLT might not self-extinguish but continue to burn. In a real fire, this could result in collapse of the structure.

Alternatively, char fall-off may be prevented if lamellae are sufficiently thick and the charring front does not reach the adhesive. As a result, the transformations from flaming to smouldering combustion and finally to self-extinguishment may occur within the thickness of the first lamella.

This model of self-extinguishment, as described above, is depicted in Fig. 2. Two series of experiments were conducted to calibrate the model and to quantify the conditions under which the transformations from flaming to smouldering combustion and from smouldering to self-extinguishment occur.

4. Material and methods

This paragraph presents the material used and methods applied for the two series of experiments.

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 (Fig. 3). This two-step exposure represents the heat flux unprotected CLT receives in a room fire, based on results by McGregor et al. [14], assuming no fall-off of charred lamellae occurs.

The first heat flux of 75 kW/m^2 simulated the fully developed fire, corresponding to the flux emitted by a charred surface with emissivity of 0.8 and a temperature of approximately 860 °C (this temperature was verified after testing and was found to correspond well with measured surface

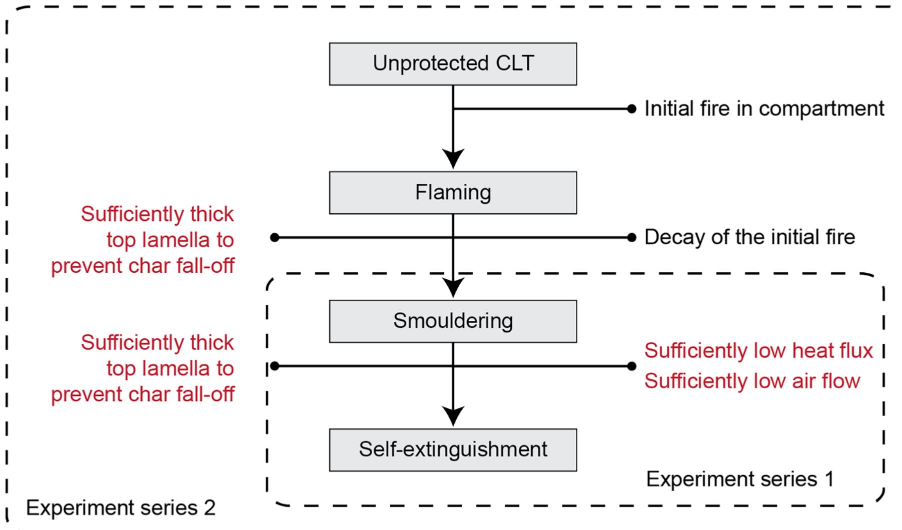

Fig. 2. Model of self-extinguishment of CLT.

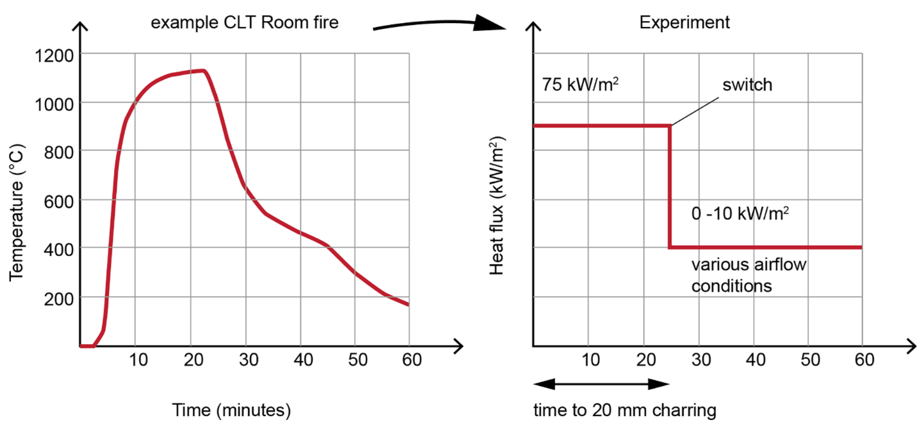

Fig. 3. Approach of the first series of experiments.

temperatures of the CLT during flaming combustion) and was within the range of the capacity of the available equipment (see next paragraph).

When the samples were charred 20 mm, they were switched to a variable second heat flux between 0 and 10 kW/m^2. This switch represented the decay of the fire due to burning of the room contents, while the second heat flux simulates the subsequent cross-radiation of smouldering CLT surfaces and other hot surfaces. A heat flux exposure of 10 kW/m^2 corresponds to the heat flux emitted by a charred surface with emissivity of 0.8 and a temperature of approximately 410 °C.

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

4.1.2. *Equipment*

An ISO 5660-1 certified cone calorimeter (Fig. 4) 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 lamellae in a horizontally configuration to prevent fall-off of char under the influence of gravity.

A separate cone heater was used to impose the low heat flux. A fast transition between the heat flux exposures (of approximately 10 s) was possible by switching the sample from one device to the other. Because the separate cone heater does not provide heat release rate or weight measurements, samples were simultaneously placed on a scale to measure the mass to provide an indication of self-extinguishment.

In the experiments with an additional air flow a domestic fan was used at a certain distance corresponding to the desired wind speed. The imposed air speed was measured with a portable airspeed measuring device just in front of the location of the sample surface before the experiment would commence. Gas temperatures were not measured during these experiments.

4.1.3. *Samples*

Samples were cut to sizes of 100 by 100 mm and 50 mm thick from 100 mm thick CLT plates (Fig. 5). The virgin CLT plates were built-up of five cross-wise oriented 20 mm thick lamellae, made of spruce, grade C24, and glued with a PU adhesive for face and finger jointing and an emulsion polymer isocyanate glue for edge joints.

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 horizontal channels were drilled, using a 1.6 mm drill diameter, from two sides of the samples at distances of 10, 20, 30 and 40 mm from the top surface, to accommodate thermocouples.

Type K mantle thermocouples (Nickel-Chromium/Nickel-Alumel wire pair with a steel mantle and isolated with magnesia powder) of 1 mm diameter were used. The channels were not sealed. To decrease any additional weight due to the thermocouples, the wires were connected to a supporting structure close to the sample. To avoid the wires influence the measurements due to their bending stiffness, the wires were attached as hinges to the supporting structure. To avoid uplift of the sample due to the heavy "back-span", the back-span was connected

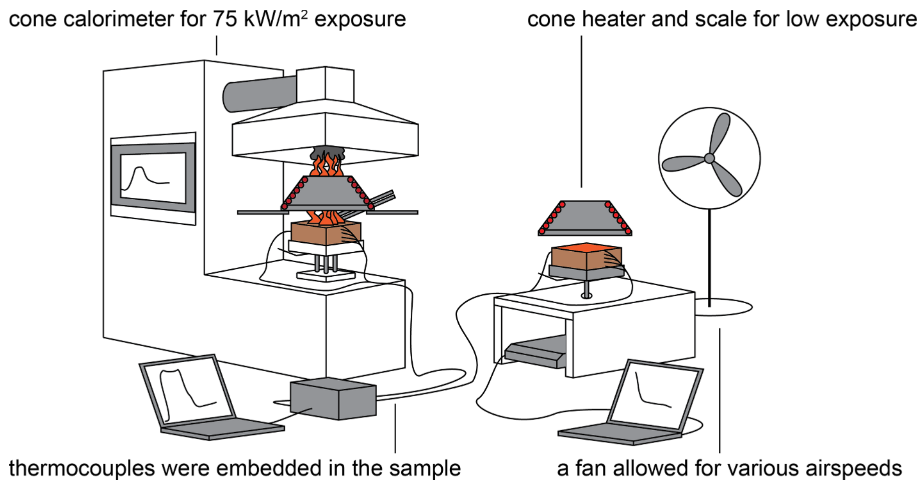

Fig. 4. Test setup of the first series of experiments.

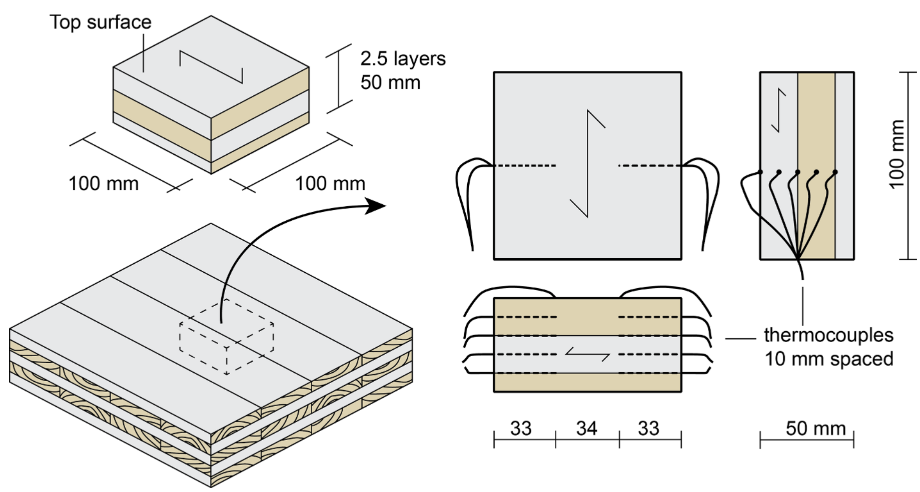

Fig. 5. Sample for the first series of experiments.

to the supporting structure. Two thermocouples were also installed in contact with the top surface. The thermocouples measured temperature data at their tips. This provided a temperature profile through the samples, which allowed for the determination of the location of the charring front (indicated by the 300 °C isotherm) and the derivation of charring rates. The temperatures in the samples also provided an additional indication (next to mass loss) on whether samples had extinguished.

Finally, the samples were weighed and the underside and edges were wrapped in aluminium foil to reduce the effect of sideward heating.

4.1.4. Procedure

The procedure presented in Table 1 was followed in each individual experiment.

Next to the direct measurements, the cone calorimeter provided indirect measurements: the heat release rate, derived from the oxygen consumption calculation, in kW/m^2, and the effective heat of combustion, derived from the heat release and mass loss rate, in kJ/kg.

4.2. Second series of experiments

The second series of experiments investigated the complete model of self-extinguishment, including the influence of fall-off of charred lamellae.

4.2.1. Approach

The approach was to subject small CLT compartments to a simple propane fire with a constant heat release rate of 41 kW and a decay phase (Fig. 6). This propane fire simulated the burning of an initial fire in a room, excluding the burning of CLT. The CLT became involved in the fire and once it was charred 20 mm, the initial fire was stopped, representing the depletion of the initial fire load.

The CLT was expected to either transform from flaming to smouldering combustion, or remain in flaming combustion as a result of fall-off of charred lamellae. If the fire did transform to smouldering combustion the CLT might transform back to flaming combustion as a result of fall-off of charred lamellae, continue smouldering if the heat flux received was high enough, or self-extinguish if the heat flux was sufficiently low. The influence of airflow was not investigated.

The heat flux received by the CLT after cessation of the propane fire would be provided by mutual cross-radiation between the exposed CLT surfaces. Various heat fluxes were created by varying the amount of exposed CLT compared to non-combustible surface. The CLT was orientated vertically as walls, such that fall-off of charred lamellae could occur.

The idea that a sufficient thick lamella can assist in achieving self-extinguishment was investigated in one experiment by increasing the thickness of the top lamella from 20 mm to 40 mm.

4.2.2. Equipment

The initial fire was created by a square propane burner bed with seven rows of five burners, each with a capacity of 26 kW (Fig. 7).

Table 1
Procedure and measurements of the first series experiments.

Step	Description	Direct measurements
1	The cone calorimeter and the separate cone were calibrated with Schmidt-Boelter Heat Flux Sensor 25 mm below the heaters. Calibration of the exhaust gas analyser was done by the cone computer. In the experiments with an additional airflow, an air speed measurement device was used to calibrate the air speed at the location of the specimen.	
2	A CLT sample was placed on the cone calorimeter load cell with the top surface 25 mm below the cone heater. At the start of the experiment the shutters opened, exposing the sample to a 75 kW/m^2 heat flux. The automatic igniter provided piloted ignition.	**Cone calorimeter** - the sample weight (g) - mass loss rate (g/s) - concentrations of exhaust gases **Thermocouples** - temperatures at 10 locations in the sample (°C)
3	After a certain time 20 mm of the CLT was charred. A char layer of 20 mm represents a steady thickness that can be expected to develop in a fully developed fire, while leaving sufficient material uncharred of the specimen to disregard disturbances and edge effects.	
4	When both thermocouples at 20 mm depth exceeded 300 °C the charring front was considered to have penetrated this depth. The sample was removed from the cone calorimeter and placed on the scale under the separate cone, during a switch of approximately 10 s.	
5	The sample was then exposed to the second heat flux between 0 and 10 kW/m^2. In some experiments an additional airflow was led over the sample surface.	**Separate scale** - the sample weight (g) **Thermocouples** - temperatures at 10 locations in the sample (°C)
6	The experiment was stopped if the sample was considered to be extinguished or burned through. The following criteria were used: **Extinguished**: the samples were considered to be extinguished when the thermocouple temperatures were all near or below 200 °C, i.e. no volatiles (gaseous fuel vapours) were produced and no wood was decomposed into char. This also meant the 300 °C isotherm no longer propagated through the material. Another indication was a stop of mass loss, i.e. a stabilising mass and a zero mass loss rate. **Burned through**: the sample was considered to be burned through if the 300 °C isotherm had reached both thermocouples at 40 mm depth. At that moment there is only 10 mm of uncharred CLT left. Any further testing would no longer be representative. Another indication was the continuation of mass loss, i.e. a mass which does not stabilise at a certain value and a non-zero mass loss rate.	
7	Once an experiment was completed, the 3 data sets (cone data, thermocouple data, and scale data) were combined.	

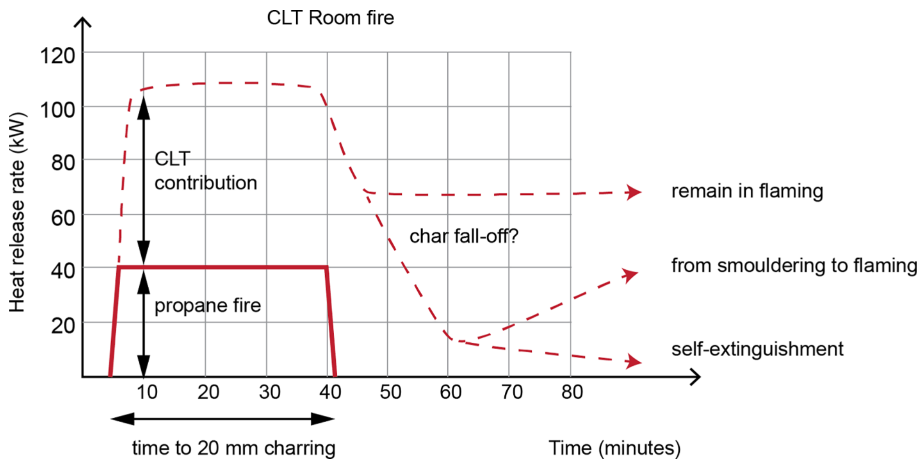

Fig. 6. Approach of the second series of experiments.

Compartments were placed on top of this bed so that the burners were level with the compartment floor. This required perforation of the floor with holes slightly bigger than the propane burner heads. A mass flow controller allowed the propane to be regulated to deliver the desired heat release rate. A propane torch was used for ignition of the burner bed.

In order to evaluate the severity of the fire and assess whether self-extinguishment had occurred, the complete testing setup was paced inside an NEN-EN 13823 certified SBI (single burning item) test setup. Smoke and gases were extracted and analysed by an oxygen consumption calorimeter that determined the heat release rate.

A Schmidt-Boelter heat flux sensor (with a calibrated range of 0–100 kW/m^2 and an accuracy of < 0.2 kW/m^2) was placed in the middle of the opening of the small CLT compartment.

4.2.3. Samples

The samples were small “rooms” or “compartments” 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 (PROMATECT-H board, made from calcium silicates, cement, and aggregates and with a density of approximately 870 kg/m^3). Back- and side walls were either CLT or also non-combustible board. Four configurations were tested in fife experiments, the configuration with 2 CLT side walls and 20 mm thick lamella was tested twice (Fig. 8).

The same CLT and method of conditioning were applied as in the first series of experiments. To accommodate thermocouples, five channels were drilled from the cold-side to a depth of 20, 30, 40, 50, and 60 mm from the fire-side surface. The same thermocouple type was used as explained for the first series of experiments. A set of five thermocouples 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 a temperature profile through the CLT cross-section, which allowed for the determination of charring rates and could provide an indication of self-extinguishment. Thermocouples were also installed in the middle of the rooms at 400 and 200 mm heights, to obtain the gas temperature inside the boxes.

Joints and channels were sealed with a non-combustible fire-resistant glue based on aluminium silicates and sodium silicates to avoid unwanted spreading of the fire. Because of the small size of the

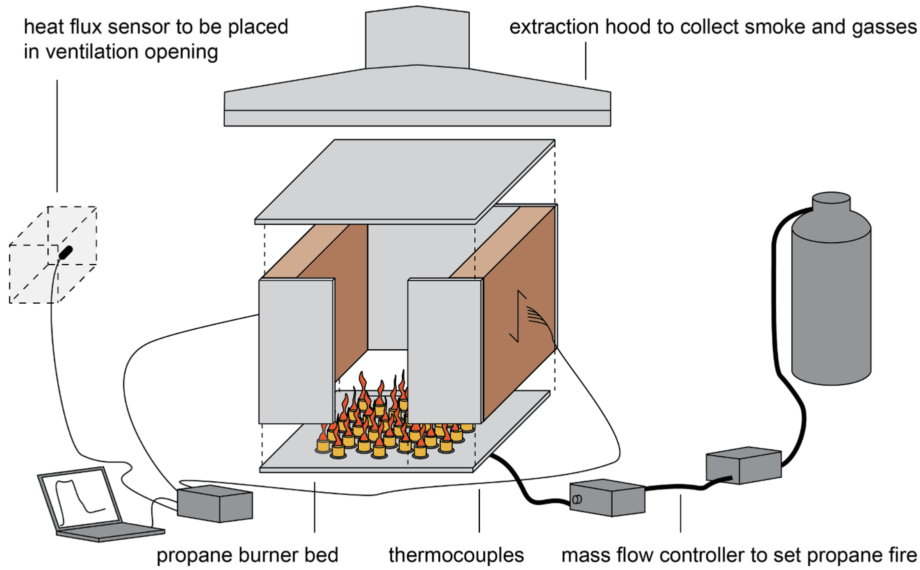

Fig. 7. Test setup of the second series of experiments.

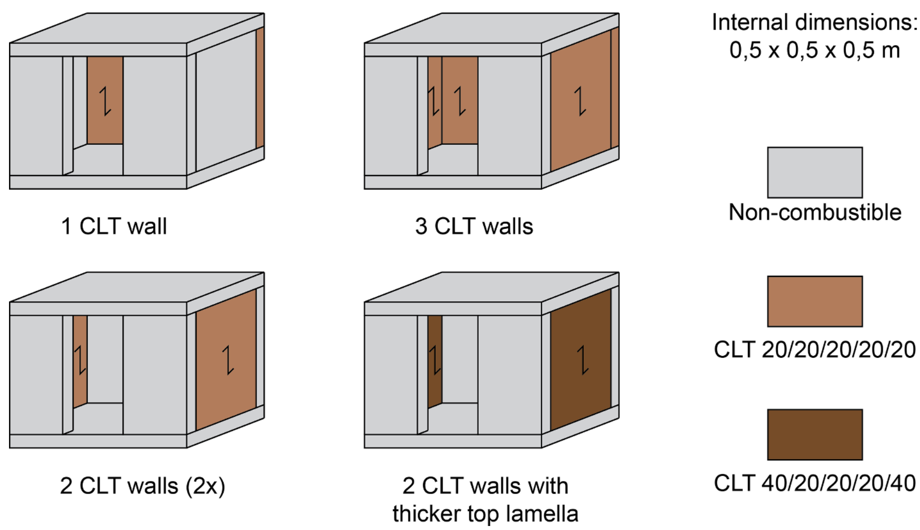

Fig. 8. Samples for the second series of experiments.

thermocouples compared to the samples, and the fact that the thermocouples were installed from the cold side, no influence of the thermocouples on the results was expected. The compartments were weighted on a scale both before and after testing.

4.2.4. Procedure

The procedure presented in Table 2 was followed in each individual experiment.

4.3. Overview of experiments

An overview of all experiments in is given in Tables 3 and 4.

5. Results and discussion

This paragraph presents and discusses the most relevant results of two series of experiments. A comprehensive presentation of results and analyses can be found in the corresponding full report [24].

5.1. First series of experiments

In the first series of experiments, during the initial 75 kW/m^2 heat flux exposure, all CLT samples became involved in flaming combustion within 10 s. 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 s: on average 0.18 g/s and 237 kW/m^2 respectively. This early peak can be attributed to the absence of char at the start of an experiment.

Due to the thermal degradation, a char layer developed, which was reflected in a decreasing mass loss rate and heat release rate after the initial peak. This suggests the char layer protected the wood underneath by decreasing the flow of heat to the thermal degradation zone, slowing

Table 2
Procedure and measurements of the second series experiments.

Step	Description	Direct measurements
1	At the start of the experiment the propane burners were ignited with a torch. The heat flux sensor was placed in the opening of the compartment and the propane flow was increased to the flow corresponding to a heat release rate of 41 kW for the initial fire.	**SBI oxygen consumption calorimeter** - concentrations of exhaust gases, for oxygen consumption calculation **Thermocouples** - temperatures at various depths in the sample, and at two locations in the room (°C) **Schmidt-Boelter sensor** - incident heat flux in the middle of the opening (kW/m^2)
2	The propane fire in the compartment burned and the CLT became involved in flaming combustion, contributing to the fire.	
3	After a certain time 20 mm of the CLT would be charred, representing a steady thickness that can be expected to develop in a fully developed fire, while leaving sufficient material uncharred in the specimen to disregard disturbances and edge effects.	
4	When all thermocouples at 20 mm depth exceeded 300 °C the charring front was considered to have penetrated this depth. Subsequently, the propane flow was reduced to 0% and the initial fire decayed.	
5	Without the initial fire, depending on the conditions in the compartment, the CLT would remain in flaming combustion, transform to smouldering combustion, or transform first to smouldering combustion but back again to flaming combustion.	
6	The experiment was stopped if the sample was considered to be extinguished or burned through. The following criteria were used: **Extinguished**: the CLT walls were considered to be extinguished when the thermocouple temperatures were all near or below 200 °C, i.e. no volatiles were produced and no wood was decomposed into char. This also meant the 300 °C isotherm no longer propagated through the material. Another indication was the heat release rate, which should be, or be near, 0 kW when the CLT has extinguished. **Burned through**: the sample was considered to be burned through if the 300 °C isotherm had reached all thermocouples at 60 mm from the fire-side surface. At that moment the charring front had already progressed through 60% of the CLT thickness; more than half of the structural section is consumed and structural failure can be expected in a real building. Another indication was the heat release rate, which remained positive when the CLT continues to burn.	
7	Once an experiment was completed, the 2 data sets (SBI oxygen consumption calorimeter and thermocouple data) were combined.	

Next to the direct measurements, the SBI provided an indirect measurement: the heat release rate, derived from the oxygen consumption calculation.

Table 3
Overview of first series of experiments.

Experiments	Second heat flux	Additional airflow
1.1 and 1.2	0 kW/m^2	–
1.3 and 1.4	5 kW/m^2	–
1.5 and 1.6	10 kW/m^2	–
1.7 and 1.8	8 kW/m^2	–
1.9 and 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
1.13 and 1.14	75 kW/m^2	–
1.15 and 1.16	75 kW/m^2 *	–

*no thermocouples were present.

Table 4
Overview of second series of experiments.

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

Note that the first series of experiments was expanded with experiments 1.13 and 1.14 where the 75 kW/m^2 heat flux exposure was continued to investigate the performance at a constant high heat flux, as well as with experiments 1.15 and 1.16 where, in addition, the thermocouples were omitted to investigate their possible influence on the results.

down the production of volatiles. Typically, the mass loss and heat release rates stabilised after 5 min at approximately 0.05 g/s and 73 kW/m^2 respectively.

On average the temperatures at 20 mm depth exceeded 300 °C after 20 min and 40 s, indicating the charring front had reached this depth. The samples were switched to a lower flux in the range of 0–10 kW/m^2. Visible flaming ceased within 1 min and the CLT smouldered. The sample either burned-through or self-extinguished, depending on the level of imposed heat flux and whether an additional airflow was present. Table 5 presents an overview of the results in terms of whether self-extinguishment occurred.

5.1.1. *Heat flux as condition for self-extinguishment*

Samples extinguished at a heat flux of 0 or 5 kW/m^2. 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 eventually burned-through. Samples exposed to 6 kW/m^2 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 (Fig. 9).

This observation 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 5–6 kW/m^2.

These results can be compared to those obtained in experiments conducted by Bartlett [25] on 85 × 85 × 100 m thick softwood CLT samples. These samples were investigated under a constant heat flux between 14 kW/m^2 to 35 kW/m^2 and two-phase tests with a heat flux from 40 kW/m^2 for 30 min and then dropping to 15 kW/m^2 to 31 kW/m^2. Extinguishment of flames was investigated. The outcome of the experiments was that for a heat flux lower than 31 kW/m^2 the flames extinguished. This is in line with the results in this paper, because for all the experiments for the second phase (with a maximum of 10 kW/m^2) visible flaming ceased within 1 min. However, the difference with the results here is that extinguishment was defined in this paper as whether the smouldering would stop as well. It turned out that a much lower level of heat flux is critical in that case, namely 6 kW/m^2.

5.1.2. *Air flow as 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

Table 5
Self-extinguishment and burning-through in the experiments.

Experiment	0 kW/m²		5 kW/m²		10 kW/m²		8 kW/m²		6 kW/m²		6 kW/m²	
											0,5 m/s	1,0 m/s
	1	2	3	4	5	6	7	8	9	10	11	12
extinguished	yes	yes	yes	yes	–	–	–	–	yes	yes	yes	–
burned-through	–	–	–	–	yes	yes	yes	yes	–	–	–	yes

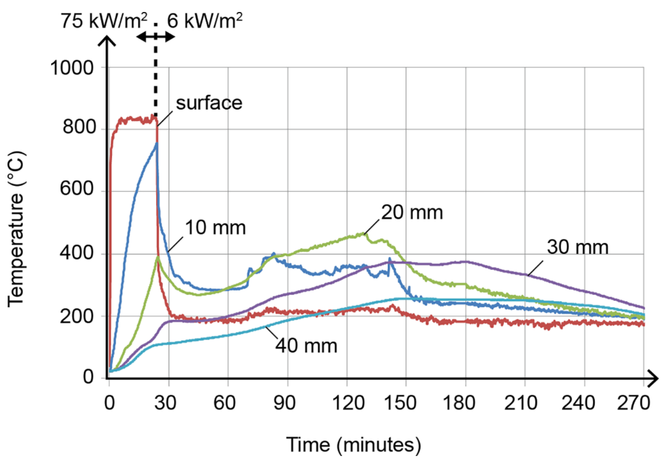

Fig. 9. Average thermocouple temperatures at various depths in experiment 1.9 during the 75 kW/m² and the 6 kW/m² exposure.

additional airflow speed of 0.5 m/s resulted in self-extinguishment more quickly than without an additional airflow, while an additional airflow of speed 1.0 m/s resulted in more intense smouldering and a faster burn-through.

Based on this limited amount of observations, it seems 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. It can reasonably be assumed that at a heat flux of < 6 kW/m², an airflow with a speed limited to 0.5 m/s results in self-extinguishment. Because only one experiment was conducted per airflow, it would be recommended to verify these conclusions.

An overview of the conditions to transform smouldering CLT to self-extinguishment is given in Table 6. Certain combinations of heat flux and airflow have been investigated in the experiments, but others require further research. It can reasonably be expected that an airflow with speed 0.5 m/s, will also result in self-extinguishment at heat fluxes lower than 6 kW/m²; and that an airflow with speed 1.0 m/s will also result in burning-through at heat fluxes higher than 6 kW/m². However, it is currently unknown if self-extinguishment would occur in combinations of lower heat fluxes with higher air flow speeds and vice versa.

5.1.3. Charring rates

Charring rates were obtained using the location of the 300 °C isotherm. The 300 °C isotherm was estimated to have reached a certain depth (10 mm, 20 mm, and so on) when the average of both thermocouples at that depth indicated a temperature of 300 °C. The average charring rate for the layers of 10 mm of material between these sets of thermocouples could then be determined using the time at which the 300 °C isotherm reached those depths. Charring rates varied as the smoulder front propagated through the material.

The average charring rate during 75 kW/m² heat flux exposure was 1.67 mm/min for the first 10 mm and 0.78 mm/min for the second 10 mm. In experiments 1.13 and 1.14, where the samples were not switched, charring rates of 0.78 mm/min and 0.67 mm/min were obtained for the third and fourth 10 mm respectively.

Charring rates for the lower exposures were found to depend on the level of heat flux and any additional airflow. For a 0 and 5 kW/m² heat flux, no charring rates were obtained, because these samples extinguished. For the 6 kW/m² heat flux 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 kW/m² and 8 kW/m² heat flux 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. This increase between the third and fourth layer could be the result of edge effects. Samples became thin near the end of the experiments. As a result, there is less wood below the reaction zone. The smoulder speed could increases because the losses to the deeper layers of wood decrease. Furthermore, this effect could also be the result of an increase of insulation due the growing residual ash and char layer. The smoulder speed could increase because the losses to the surfaces decrease.

In the experiments with an additional airflow, no charring rates were recorded at a speed of 0.5 m/s, while charring rates of 0.48 mm/min and 0.56 mm/min for the third and fourth 10 mm of CLT were obtained at a speed of 1.0 m/s.

5.1.4. Fall-off of char

Visual inspection of the samples also showed in the experiments using a 0 kW/m² second heat flux exposure the char had propagated just beyond 20 mm depth. This observation indicated that loss of bonding occurred when the whole 20 mm thick lamella was charred and the PU adhesive reached a temperature of 300 °C.

This did not result in fall-off, because the layer would lie on top of the sample due to the horizontal orientation. In some experiments, an increase in mass loss rate and heat release rate was observed just before the samples were switched, i.e. the moment the 300 °C isotherm penetrated to 20 mm depth and thus the PU adhesive layer. This might be a result of loss of bonding and the layers coming apart slightly, resulting in a change in burning behaviour. However, this phenomenon was not further investigated.

5.1.5. Smouldering mechanisms and temperature profiles

The distribution of temperatures through the CLT provided insight into how the samples smouldered. Fig. 10 depicts temperature profiles

Table 6
Conditions for self-extinguishment and burning-through.

Heat flux Add. air flow	< 6 kW/m²	6 kW/m²	> 6 kW/m²	
none	Self-extinguishes	Self-extinguishes after some smouldering	Burns-through	Based on experiments
0,5 m/s	Expected to self-extinguish	Self-extinguishes	Unknown	Further research required
1,0 m/s	Unknown	Burns trough	Expected to burn through	

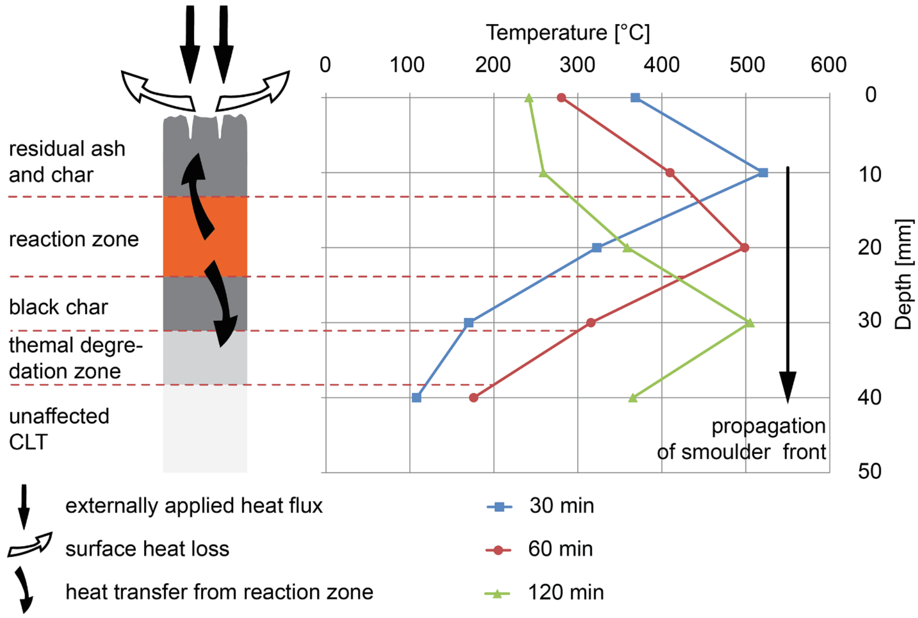

Fig. 10. Temperature profiles in experiment 1.6.

during one of the experiments using a 10 kW/m^2 heat flux 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, and eventually decreased below 400 °C, but only once thermocouples lost contact with the surface. The surface temperature is important, because in a real fire, the heat flux received by other surfaces depends partially on the surface temperature of the smouldering CLT. For the purpose of estimating this heat flux, this surface temperature 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 higher: 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.

Investigation of the temperature profiles also suggested an additional airflow had two effects. When the experiment with an additional air flow of speed 0.5 m/s was compared to those without it, it was observed that temperatures in the CLT were approximately 100 °C lower. Furthermore, peak temperatures were sustained for a shorter period of time. These observations suggest a cooling effect might occur due to the additional air flow. However, despite this cooling effect, similar mass loss rates were obtained and the samples lost approximately the same percentage of mass. This suggests that a forced oxygen supply due to the additional airflow might (partially) counteract this cooling by speeding up the smoulder reaction. Nevertheless the net effect of the 0.5 m/s speed air flow was a quicker self-extinguishment.

In the experiment with an additional air flow of 1.0 m/s it was again observed that the temperature at the surface was approximately 100 °C lower. However temperatures in deeper layers were actually more than 100 °C higher. Furthermore, the sample burned-through more quickly, and a high mass loss rate and charring rate were obtained. These observations suggest that a forced oxygen supply might overcome the cooling effect at an additional air flow of speed 1.0 m/s. While the surface is cooled, deeper layers reach higher temperatures because the smouldering reaction speeds up due to forced oxygen supply. This results in more heat being generated, a higher mass loss rate, and a faster propagation of the smouldering zones and the charring front. As a net result, the effect of the 1.0 m/s speed air flow resulted in a rapid burn-through.

These two mechanisms; additional surface cooling and additional heat generated due to an increased reaction speed, seem to compete in slowing down and speeding up the smouldering and the net result appears to depend on the speed of the additional airflow.

5.1.6. *Continued 75 kW/m^2 exposure*

In the four experiments where the samples were not switched to a second lower heat flux (experiments 1.13 to 1.16), the samples continued burning in flaming combustion under the 75 kW/m^2 heat flux exposure. The mass loss rate and heat release typically decreased slightly during continuation of the 75 kW/m^2 heat flux exposure to < 0.050 g/s and < 70 kW/m^2 respectively. This decrease could be attributed to the continued build-up of a protective char and ash layer.

All four experiments showed an increase in the mass loss rate and heat release at approximately 40 min, which dropped again toward the end of the experiments at 50 min. During this period, burning was observed along the sample edges, which could indicate the samples had become thin and all sides became involved in flaming. This would temporary increase the mass loss rate and heat release until almost all fuel was consumed.

Two of these additional experiments, 1.15 and 1.16, were conducted without thermocouples to investigate the influence of the thermocouples on the measurements. The samples without thermocouples lost slightly more mass than the samples with thermocouples (29% mass lost compared to 31% mass lost on average after 1240s of testing). This difference was established during the first 5–15 min of testing, possible due to some stiffness of the thermocouples wires. Subsequently, the mass graphs were parallel; indicating this influence of the thermocouples on the mass loss remained limited. The results also indicated the amount of fluctuation of the mass loss rate increased when thermocouples were present. However the average mass loss rate over a longer period of time was not significantly affected by the thermocouples. The heat release rate was not affected by the thermocouples.

5.2. Second series of experiments

In the second series of experiments, after ignition of the propane fire, the CLT walls of the compartments became involved in flaming combustion within 2 min. The heat release rate of the propane fire was 164 kW/m² floor area, but the total heat release rate rose rapidly to an average of 354 kW/m² due to involvement of the CLT in the fire. On average, the CLT contributed 90 kW/m² CLT surface area during burning of the propane fire. An overview of the heat release rates during burning of the propane fire is provided in Table 7.

Contrary to the first series of experiments, the heat release rate and mass loss rate did not peak early. This is likely due to the fact that the CLT was not instantly exposed to a high heat flux (as was the case with the cone calorimeter). Temperatures in the compartments rose rapidly to 900 °C, followed by a more gradual increase to 1000–1170 °C.

The heat release rate results can be compared with larger scale tests that have been performed with exposed CLT by McGregor [14] and Medina Hevia [15]. McGregor found that the CLT in a fully exposed compartment approximately doubled the heat release. Medina Hevia found that the contribution of CLT can be negligible if one of the room walls is unprotected. The results reported in Table 7 show bigger increases of the heat release rate compared to those reported in these two sets of experiments. This could be due to differences in the initial "design" fire used, or due to issues related to scale. However, all results point to a significant increase of heat release rate during flaming combustion in the case of multiple exposed walls, and a relatively minor increase of heat release rate with only one wall exposed.

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 that small pieces of char were breaking off locally, not that fall-off of completely charred lamellae occurred. The amount of fall-off was minor compared to when charring had progressed further into the CLT to reach the first adhesive layer.

When thermocouples showed temperatures at 20 mm depth exceeded 300 °C, indicating the charring front had reached the first layer of adhesive, the propane flow was stopped and the initial fire decayed. The subsequent behaviour of the compartments is depicted in Fig. 11. Fall-off of charred lamellae played a major role.

5.2.1. Compartments that burned through

In compartment 2.2 with three CLT walls, fall-off of charred layers of CLT exposed new wood to the fire. This occurred when temperatures in the compartment were declining, but were still relatively high, in the range of 700–900 °C; as was the measured heat flux in the middle of the opening: > 70 kW/m².

It should be noted here that heat flux on the CLT was not measured directly: only the heat flux in the middle of the opening was measured using a Schmidt-Boelter heat flux sensor. These measurements were used to make a crude estimate of the heat flux on the CLT, to allow comparison with the first series of experiments. Assuming pure radiative heat transfer, based on the measured heat flux in the opening and the configuration factors of the compartment, a CLT surface temperature was estimated, neglecting other surfaces. This was then used to

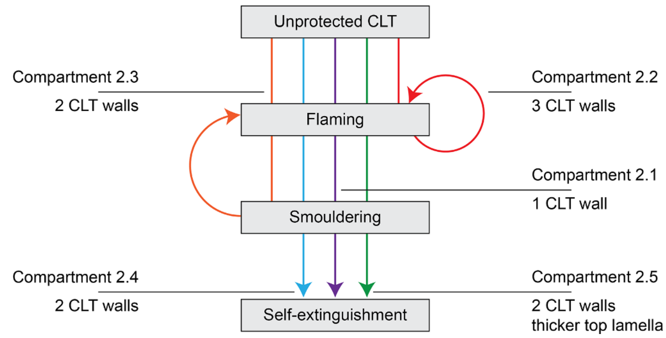

Fig. 11. Results of second series of experiments.

estimate the flux on the CLT wall. This method is explained in more detail in paragraph 6.3.2.

It must be noted that in reality there is a convective component as well as a radiant component to the heat flux. A Schmidt-Boelter gauge is designed to measure radiation-dominated heating scenarios, but it is sensitive to local convection. The estimation of heat flux on the CLT should therefore be viewed with caution. Further research could more accurately assess the total thermal exposure as a combination of radiant and convective components in both the fully developed fire and the smouldering fire phases. Nevertheless, these shortcomings were accepted. Estimated values for the CLT, using the approach outlined above, will be reported in parenthesis after the reported values of measured heat flux in the middle of the compartment opening. For example, for compartment 2.2, the measured heat flux in the middle of the opening at the time of fall-off was > 70 kW/m² (or estimated to be approximately > 49 kW/m² at the middle of the CLT side walls and > 43 kW/m² at the middle of the CLT back wall).

Because temperatures were still high in compartment 2.2 when char fall-off occurred, the newly exposed wood immediately became involved in flaming combustion. As a result, flaming combustion was sustained, which resulted in further fall-off of charred lamellae, which again provided more fuel for the flaming combustion. A smouldering phase was never reached and the compartment remained in flaming combustion (Fig. 12). Inspection of the CLT after the experiment showed the fall-off of subsequent layers (Fig. 13).

In compartment 2.3 with two side walls, the fire transformed from flaming to smouldering combustion when gas temperatures were in the range of 400–500 °C and the measured heat flux was 30 kW/m² (or estimated to be 12 kW/m² on the middle of the CLT side walls). However, fall-off of char 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 gas temperatures had dropped to 250–350 °C and the measured heat flux was 20 kW/m² (or estimated to be 8 kW/m² on the middle of the CLT side walls).

5.2.2. Compartments that extinguished

In compartment 2.1 with one CLT wall, the fire transformed from flaming to smouldering combustion when gas temperatures were

Table 7
Heat release rates during burning of the propane fire.

Experiment	Configuration	Propane [kW] (/m² floor)	Avg. total [kW] (/m² floor)[a]	CLT contribution [kW] (/m² CLT)	Increase
2.1	1 back wall	62 (248)[b]	78 (312)	16 (64)	26–39%
		41 (164)	57 (228)	16 (64)	
2.2	1 back-, 2 side walls	41 (164)	110 (440)	69 (92)	168%
2.3	2 side walls	41(164)	102 (408)	61 (122)	149%
2.4	2 side walls	41(164)	95 (380)	54 (108)	132%
2.5	2 side walls +	41(164)	79 (316)	38 (76)	93%

[a] Average over period from flashover (gas temperatures in compartment > 600 °C) until start of decay of initial fire.
[b] During the first 12 min of experiment 2.1, the initial fire HRR was 62 kW, but was then adjusted.

Fig. 12. Compartment 2.2 with three CLT walls remained in flaming combustion due to fall-off of charred lamellae after the initial fire was stopped.

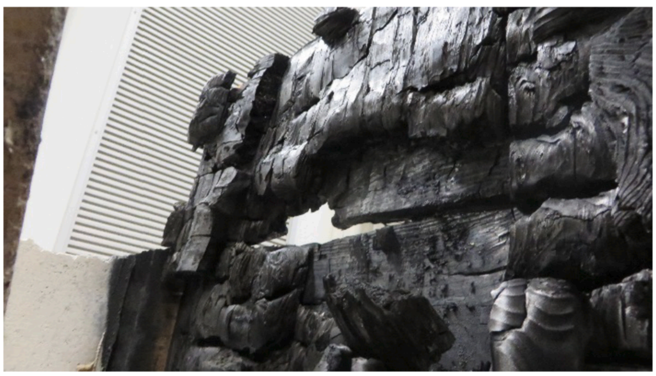

Fig. 13. Up to 5 different levels of char fall-off can be observed.

approximately 400 °C and the heat flux measured in the middle of the opening was 30 kW/m^2 (or estimated to be 12 kW/m^2 on the middle of the CLT back wall). Fall-off occurred during smouldering when gas temperatures were relatively low, < 225 °C, as was the heat flux < 9 kW/m^2 (or estimated to be < 3.5 kW/m^2 on the middle of the CLT wall). Fall-off did not result in a transformation from smouldering combustion back to flaming. The smouldering decreased in intensity and the CLT was considered self-extinguished after approximately 80 min from the start of the experiment.

In compartment 2.4 with the same configuration as compartment 2.3, the fire was able to transform from flaming to smouldering when gas temperatures were in the range of 450–600 °C and the heat flux measured was approximately 30 kW/m^2 (or estimated to be 12 kW/m^2 on the middle of the CLT side walls). During smouldering of the CLT fall-off of charred lamellae occurred when gas temperatures were < 250 °C, and when the measured heat flux was < 10 kW/m^2 (or estimated to be < 4 kW/m^2 on the middle of the CLT side walls). Some local flaming occurred, but this did not result in a second flash-over. The smouldering decreased in intensity and the CLT was considered self-extinguished after approximately 140 min from the start of the experiment.

In the experiment with compartment 2.5, a setup with two CLT side walls and an increased thickness of the top lamella of 40 mm instead of 20 mm, the fire transformed from flaming to smouldering combustion within minutes of the propane fire being stopped. Gas temperatures were in the range 400–550 °C and the heat flux measured was approximately 30 kW/m^2 (or estimated to be 12 kW/m^2 on the middle of the CLT side walls). No fall-off of charred layers of CLT was observed (Fig. 14). The smouldering quickly decreased in intensity and the CLT was considered self-extinguished after approximately 70 min from the start of the experiment. Inspection of the sample after the test showed the charring front had penetrated just past a depth of 20 mm.

Fig. 14. No fall-off of charred lamellae had occurred.

5.2.3. Char fall-off condition for self-extinguishment

The experiments showed that the conditions in the compartment have an influence on the effect of fall-off of charred lamellae. An overview of the conditions in the compartments is provided in Table 8.

The effect of fall-off of charred lamellae is illustrated in Fig. 15. It shows the development of the gas temperatures in the experiments and the moments of char fall-off.

In experiment 2.2 flaming was sustained because compartment conditions were sufficiently “hot” when fall-off occurred. The newly exposed wood was subject to high gas temperatures and heat flux, resulting in the release of more combustible gases that burned in flaming combustion.

In experiment 2.3, fall-off occurred when the gas temperature was in the range of 250–350 °C and the heat flux measured was approximately 20 kW/m^2 (or estimated to be 8 kW/m^2 on the middle of the CLT walls). 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 fall-off of charred lamellae of other surfaces more likely. When even more pieces of char fell off, this resulted in a “chain reaction” and a second flash over.

In experiments 2.1 and 2.4 fall-off did not result in sustained flaming. Compartment conditions were sufficiently “cool” by the time fall-off occurred. Insufficient combustible gases were released when new wood became exposed or some local flaming occurred but was insufficient to start in a chain reaction. The conditions at which fall-off was “safe” were found to be gas temperatures of < 250 °C and a measured heat flux of < 10 kW/m^2 (or estimated to be < 4 kW/m^2 on the middle of the CLT wall(s)).

These results show that fall-off of charred lamellae and its effects are unpredictable. Experiments 2.3 and 2.4 had the same configurations, but showed completely different outcomes; one exhibited self-extinguishment whereas the other burned-through after a second flashover. Therefore, relying on compartment conditions to sufficiently cool down to allow for “safe” fall-off seems risky.

Alternatively, as shown in experiment 2.5, an increased thickness of the lamellae can prevent fall-off of char. The charring front did not reach the adhesive and no fall-off occurred: the panel would behave as if of solid timber. The fire transformed from flaming to smouldering combustion and could then make the transition to self-extinguishment if the conditions of heat flux and air flow (as investigated in the first series of experiments) were favourable. This was indeed the result in experiment 2.5 where the configuration with two CLT walls opposite each other resulted in an estimated heat flux on the CLT during smouldering below the threshold value of 5–6 kW/m^2.

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 9 shows the energy released by the propane fire and by the CLT. In the experiments where the compartments

Table 8
Overview of conditions in the compartments.

	Flaming → smouldering	Conditions during transformation	Fall-off of charred lamellae?	Conditions during char fall-off	Smouldering → extinguished
2.1	Yes, 5 min after decay[a]	HRR: 10 kW Room T: 400 °C Flux[b]: 30 (12) kW/m^2	Yes, during smoulder Did not result in (local) flaming	HRR: 6 kW Room T: < 225 °C Flux[b]: < 9 (3.5) kW/m^2	Yes
2.2	No	–	Yes, during flaming Fire remained in flaming	HRR: > 32 kW Room T: 700–900 °C Flux[b]: > 70 (43) kW/m^2	No
2.3	Yes, 26 min after decay	HRR: 10 kW Room T: 400–500 °C Flux[b]: 30 (12) kW/m^2	Yes, during smouldering Fire transformed back to flaming	HRR: 10 kW Room T: 250–350 °C Flux[b]: 20 (8) kW/m^2	No
2.4	Yes, 13 min after decay	HRR: 15 kW Room T: 450–600 °C Flux[b]: 30 (12) kW/m^2	Yes, during smouldering No transformation back to flaming	HRR: < 5 kW Room T: < 250 °C Flux[b]: < 10 (4) kW/m^2	Yes
2.5	Yes, 5 min after decay	HRR: 10 kW Room T: 400–550 °C Flux[b]: 30 (12) kW/m^2	No fall-off during flaming and smouldering	–	Yes

[a] Decay = decay of propane fire.
[b] Flux = measured heat flux in the opening (estimated heat flux on the middle of the CLT walls).

did not self-extinguish, the CLT contributed significantly to the fire. For example, this contribution was 412 MJ/m^2 exposed CLT area in the experiment with three CLT walls, 401% of the propane fire load in that experiment. 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 fall-off occurred; 142 MJ/m^2 CLT area. Note that these values were obtained under specific conditions of the experiments, with a high ratio of CLT to floor area.

Fig. 16 illustrates the contribution of the CLT to the fire in the experiments with two CLT walls where burn-through (2.3) and self-extinguishment (2.5) occurred. It can be observed that exposed CLT can significantly increase the total energy released, as well as the duration of the fire. Both the total energy released and the duration are increased even further when fall-off results in prolonged flaming.

5.2.5. 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 are expressed as an average for each layer of 10 mm material.

Charring of the first 20 mm of CLT 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 [26]. This was 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.

The charring speed 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, for example from approximately 0.36 mm/min to 2.4 mm/min between adjacent 10 mm layers. This observation was attributed to the wood being exposed suddenly due to fall-off, followed by periods of relative steady burning. The average charring rate in these experiments was 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 was attributed to the fact that char fall-off increased the overall charring rate.

These results can be compared with results by McGregor [14]: 0.63 mm/min and 0,85 mm/min; and with results by Medina Hevia [15]: 0.69, 0.88, and 0.71 mm/min. These tests had varying amounts of unprotected CLT, but the charring rates were similar and correspond with the average of 0.77 mm/min found in the experiments conducted in this work. The charring rates were typically higher than the value of 0.65 mm/min prescribed by Eurocode. Char fall-off and radiation between burning walls were mentioned as potential causes.

6. Towards design implementation

This paragraph provides a first exploration for a method to assess potential self-extinguishment in the design of a CLT building. It must be stressed that this is a suggestion only, based on results from a limited amount of experiments, performed under specific conditions, and with a limited scale. Sufficient proof is still missing and the assessment method

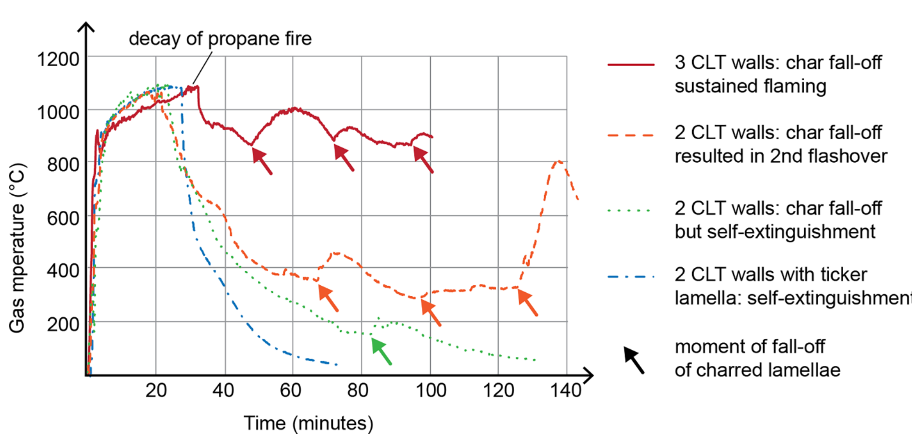

Fig. 15. Gas temperatures in the middle of the compartments at 400 mm height during four experiments.

Table 9
Energy released in the second series of experiments.

Experiment	Setup	Propane [MJ] (/m^2 floor)	Total [MJ] (/m^2 floor)	CLT contribution [MJ] (/m^2 CLT)	Increase
2.1	1 back wall	112 (448)	169 (676)	57 (228)	51%
2.2	1 back-, 2 side walls	77 (308)	386 (1544)	309 (412)	401%
2.3	2 side walls	55 (220)	240 (960)	185 (370)	336%
2.4	2 side walls	62 (248)	183 (732)	121 (242)	195%
2.5	2 side walls +	63 (252)	134 (536)	71 (142)	113%

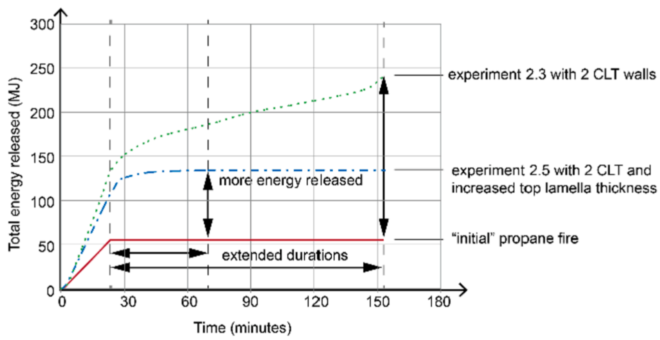

Fig. 16. Total energy released.

would require more research and validation before it could be applied in practice. Scale-up of the experiments would be especially valuable, because the physical conclusions of this paper cannot be ported directly to a larger scale without further testing, in part due to scaling issues, ventilation conditions, and more complex fire behaviour of large compartments.

6.1. Assessment method

The assessment method could consists of two steps (Fig. 17). The first step is to ensure the CLT can transform from flaming to smouldering combustion, by preventing fall-off of charred lamellae by means of a sufficiently thick lamellae. The second step is to ensure the smouldering CLT is able to make the transition to self-extinguishment, depending on the conditions of heat flux and airflow.

6.2. Step 1 - determination of minimal lamella thickness

To determine a minimum lamella thickness to prevent fall-off of char, a finite charring depth needs to be calculated. This requires a design fire with a decay phase and the ability to take into account the contribution of CLT to the fire. The standard fire does not meet these requirements. Alternatively, the parametric natural fire can be used. This design fire, as described in Eurocode 1992-1-2 annex A [26] decays and is dependent on input regarding the fire load, ventilation conditions, and boundary conditions of the compartment. This method is based on the research of Hadvig [27] and confirmed by Olesen and Hansen [28], Olesen and König [29], and König and Walleij [30]. The method is presented in textbooks, for example by Buchanan [31].

The Eurocode approach and the approach as presented by Buchanan differ. In Eurocode, the method is expanded by taking into account the thermal adsorption of the boundaries. Furthermore, the Eurocode applies a factor 1.5 to the initial char time. These changes might be the result of a wish to incorporate the boundary conditions and introduce additional safety. The assessment method presented here uses the original formulas and was found to match reasonably well with the results of experiment 2.5 where self-extinguishment occurred [24]. Further research would be recommended to explore differences between the methods. Furthermore, the parametric fire is limited to relative small compartments. Expansion of this model for larger compartment would be recommended, or another model might be developed for larger compartments. The approach of step 1 is depicted in Fig. 18.

Using the parametric fire equations, one could take into account the ventilation conditions by means of the opening factor the initial fuel load of the room contents. For the initial fuel load, Eurocode 1991-1-2 appendix E [32] offers values for various functions. A contribution of the CLT would need to be assumed and would depend on the development and duration of the initial fire as well as the CLT contribution itself, i.e. for a high fuel load of the initial fire, the contribution of the CLT should also be assumed high. Further research could provide guidance.

Based on the opening factor and fuel load, the parametric charring rate could be calculated. The average charring rate of 0.77 mm/min found in the experiments conducted in this work could be used, but might be too high because it includes the influence of char fall-off, which this design method aims to prevent (see paragraph 5.2.5). A charring of 0.65 mm/min as prescribed by Eurocode might be more suitable. Further verification is needed.

Due to the decay phase of the parametric fire, the charring rate decreases to zero and a finite charring depth can be determined. Based on the charring depth, the total amount of burned CLT in kg can be estimated. This can be multiplied with the effective heat of combustion and checked against the assumption of CLT contribution to the fuel load. After some iterations, an estimation of the final charring depth could be achieved. A design rule could then be constructed to ensure the lamella thickness of the first layer of CLT is larger than the calculated charring depth, in order to prevent fall-off of charred lamellae. Additional thickness could be added to improve reliability.

6.3. Step 2 - determination of critical lamella thickness

Assuming fall-off of char is prevented and the CLT reaches a smouldering phase, the second step in a potential assessment method is to ensure the smouldering CLT can make the transition to self-extinguishment.

6.3.1. Airflow condition

The airflow was found to have influence on the smouldering of the CLT and the potential to self-extinguish. However the investigation of the air flow was limited to two air speeds at a 6 kW/m^2 heat flux exposure. An additional air flow of 0.5 m/s resulted in quick self-extinguishment, while an additional air flow of 1.0 m/s resulted in a quick burn-through. It is recommended to investigate more speeds in combination with a range of heat fluxes and relate these to conditions in real compartments, with and without opening in the facade. For now, the condition of air flow is not taken into account in this assessment method.

6.3.2. Heat flux condition

Secondly, the heat flux on the smouldering CLT should be determined. Based on the geometry and orientation of the compartment, a radiant heat flux on the CLT during smouldering could be calculated. This heat flux will be (cross-) radiation between the smouldering CLT surfaces and radiation received from other hot surfaces in a room, e.g. due to burning or smouldering of room contents, etc.

The energy emitted by the smouldering CLT can be based on the estimation of the CLT surface temperature of 400 °C, as found in the first series of experiments. The emissivity of char can be taken as 0.8, as suggested by Eurocode 1995-1-2 [26] for wood surfaces. The configuration factor takes into account the geometrical relationship between

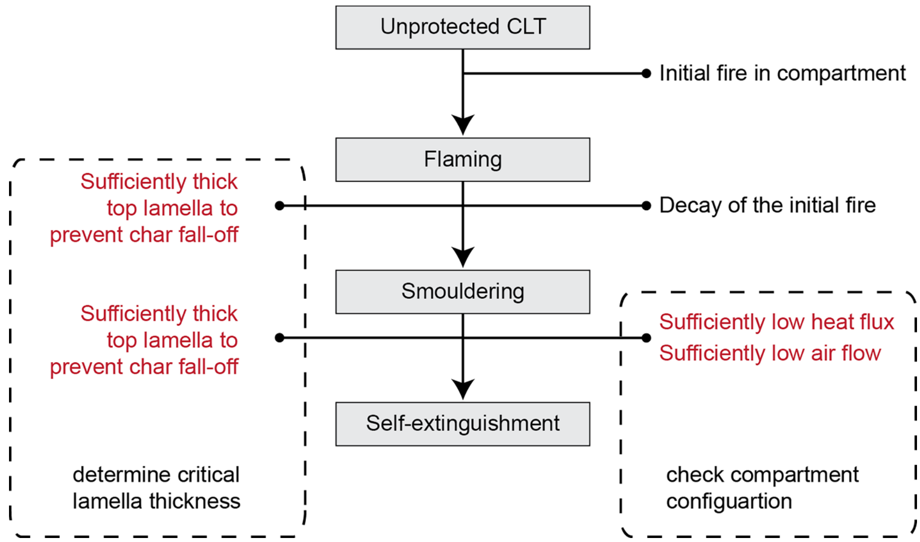

Fig. 17. Proposal for an assessment method for self-extinguishment of CLT structures.

the emitter and the receiver. It is important to consider the CLT with the most unfavourable configuration with regards to other hot surfaces. Eurocode 1991-1-2 appendix G [32] and Drysdale [33] provide calculation methods for the configuration factor, and refer to values for common shapes and geometries in literature. Other hot surfaces will also have to be taken into account in a similar way by estimating the energy transferred from them to the CLT.

By adding up the energy emitted by various sources, the radiative heat flux on the CLT with the most unfavourable configuration can be calculated and compared to the threshold heat flux of 5–6 kW/m^2. A conservative approach would be to ensure the resulting heat flux on the CLT is limited to ≤ 5 kW/m^2. It must be noted that in reality there is a convective component as well as a radiant component to the heat flux. Further research could more accurately assess the total thermal exposure as a combination of radiant and convective components in both the fully developed fire and the smouldering fire phases.

It should also be noted that a "steady state" heat flux check on the CLT with the most unfavourable configuration, might be too conservative, because it does not account for the interactive nature of smouldering surfaces in the compartment. For example, it might be possible for one area of CLT to receive a heat flux of 10 kW/m^2 and keep smouldering, while another receives 5 kW/m^2 and self-extinguishes. Because sustained smouldering is dependent on the externally applied heat flux, the extinguishment of the latter section will influence the heat flux on the first section. The flux on the first section might drop from 10 kW/m^2 to 5 kW/m^2, which would result in self-extinguishment as well.

These interactions make it difficult to assess a compartment solely in a steady state. Further research would be recommended on this interactive nature and the implications on the assessment method.

7. 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. It must be noted that these are based on a limited number of experiments, conducted under specific conditions. Unloaded specimen were used and

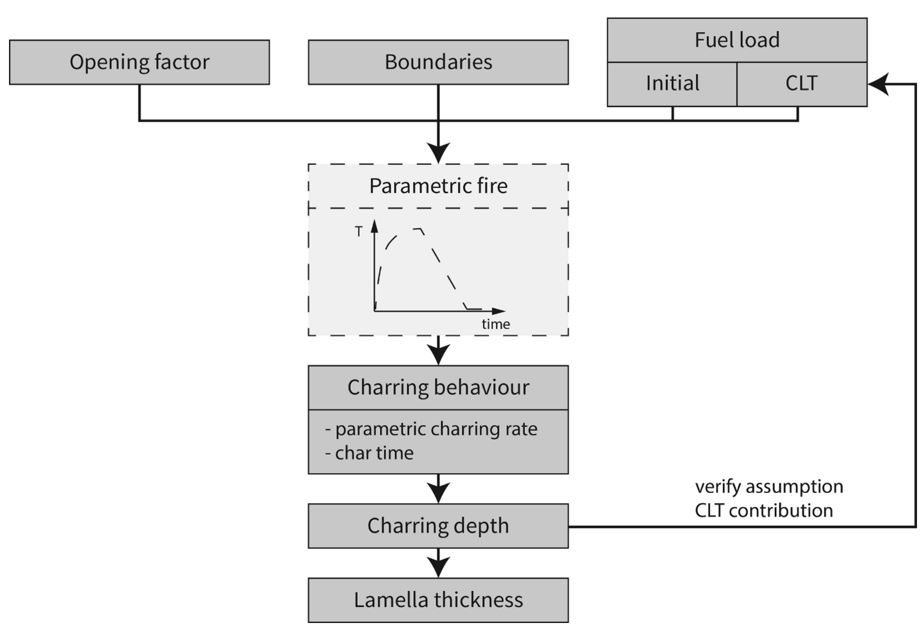

Fig. 18. Determination of a lamella thickness based on the parametric charring behaviour.

choices were made regarding fire load, ventilation conditions, CLT build-up, adhesive, wood species, configuration, and scale. These conditions can influence both the fire development and structural response. Furthermore, even seemingly identical conditions can lead to different results. It is important to consider the conclusions within this experimental range.

7.1. Conclusions

A challenge for the construction of tall buildings with an exposed timber 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 exposed 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 is a transition from smouldering to self-extinguishment. In order to make the transitions from flaming to smouldering combustion and subsequently to self-extinguishment, a number of conditions need to be satisfied.

There is a potential for self-extinguishment of smouldering CLT if the heat flux received by the CLT is below 5–6 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.

Fall-off of charred lamellae of CLT can sustain flaming combustion or revert smouldering combustion back to flaming combustion. This prevents the CLT from reaching a smoulder phase from which it can self-extinguish. 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 fall-off result in prolonged flaming.

7.2. Recommendations and further research

To verify the conclusions of this work and assess the applicability for real structures, further research is recommended on a larger scale, on loaded specimen, and with variations of fire load, ventilation conditions, CLT build-up, adhesive, wood species, and compartment configuration. A good overview of experiments is presented by Brandon et al. [34].

In a real 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 of cross-radiation between smouldering CLT surfaces. This cross-radiation is interactive by nature and should be further investigated. Furthermore, in reality there is a convective component as well as a radiant component to the heat flux. Further research could more accurately assess the total thermal exposure as a combination of radiant and convective components in both the fully developed fire and the smouldering fire phases.

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.

Fall-off of charred lamellae of the CLT due to loss of bonding of the polyurethane adhesive at elevated temperatures might be prevented by (the 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 fall-off of charred lamellae would no longer be required.

Even if fall-off of charred lamellae is prevented, flaming might be sustained by a sufficiently high heat flux, even after the initial fire had decayed. This was not investigated, but would need to be addressed and added to the model of self-extinguishment.

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 should 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 fall-off of charred lamellae on the charring rate. Results could be compared with values in design guidance.

An explicit method for assessing 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. A potential design implication was explored, but would require further research and validation before it could be applied in practice.

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