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RISTKIHTPUITKONSTRUKTSIOONIDE KÄITUMINE TEGELIKUS TULEKAHJUS

BEHAVIOUR OF CLT STRUCTURES IN NATURAL FIRES

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1. INTRODUCTION

Wood is inarguably one of the oldest building materials known to mankind and has been around for thousands of years. Unlike steel and concrete, wood is a sustainable material [1]. As a result of engineers and architects discovering methods for using concrete and steel to build high-rise structures and extensive fires happening in large apartment blocks consisting mainly of wooden houses, the popularity of wood being used as a building material decreased substantially in the late 19th century [2]. Nowadays, timber is once again seeing increase in popularity due to a relatively new building material – cross-laminated timber (CLT) – offering solutions for usage of timber in medium- and high-rise building's constructions. CLT, consisting of timber boards, is still a combustible material, therefore challenges regarding fire safety remain. Cross-laminated timber and "typical" timber behave differently in fire because of the non-fire proof adhesive used for bonding CLT layers. This allows CLT to decompose when high temperatures are reached. As a relatively new material, CLT design regarding fire safety is not described in Eurocode 5 [3], therefore tests need to be conducted.

To analyse the behaviour of CLT in fire, a full-scale compartment fire test was conducted in Väike-Maarja on November 1st, 2017. The author of this thesis was present at the test site to help install thermocouples and other instruments, as well as to solve various problems. The test house was designed as an office building compartment. Based on the collected data, three theses were to be written, analysing different façade materials, joints, penetrations and cross-laminated timber in case of fire. The main goal was to demonstrate the effect of self-extinguishment.

In case of fire, there are two possibilities for CLT to react. The first possibility is that CLT, as a combustible material, will contribute to fire load and the fire in compartment fill burn until all fuel has run out. The second one is a passive protection mechanism - the timber will self-extinguish due to fuel running out in the compartment. This way timber will maintain its load-bearing capacity. Self-extinguishment is easier to achieve by using passive protection measures along with active ones – for example fire-brigade intervention or sprinkler activation [1]. The test house did not have sprinkles and was focused on passive protection mechanisms. The self-extinguishment is probable to happen if it is possible to avoid the fall-off of char layer caused by adhesives losing its bonding capacities at high temperatures. Keeping that in mind, the composition of CLT was modified to keep the fire in the first layer of CLT for as long as possible.

The thesis is divided into three parts. The first part describes the test house and gives quick assessments to different aspects that were analysed from the fire safety point of view. The second part is an introduction to CLT – how CLT is produced and how the CLT used in test differed from typical CLT. The third part is an analysis of CLT in the actual tests.

2. TEST DESCRIPTION

The test description was co-written with Mihkel Karuse and Liisa Luhar.

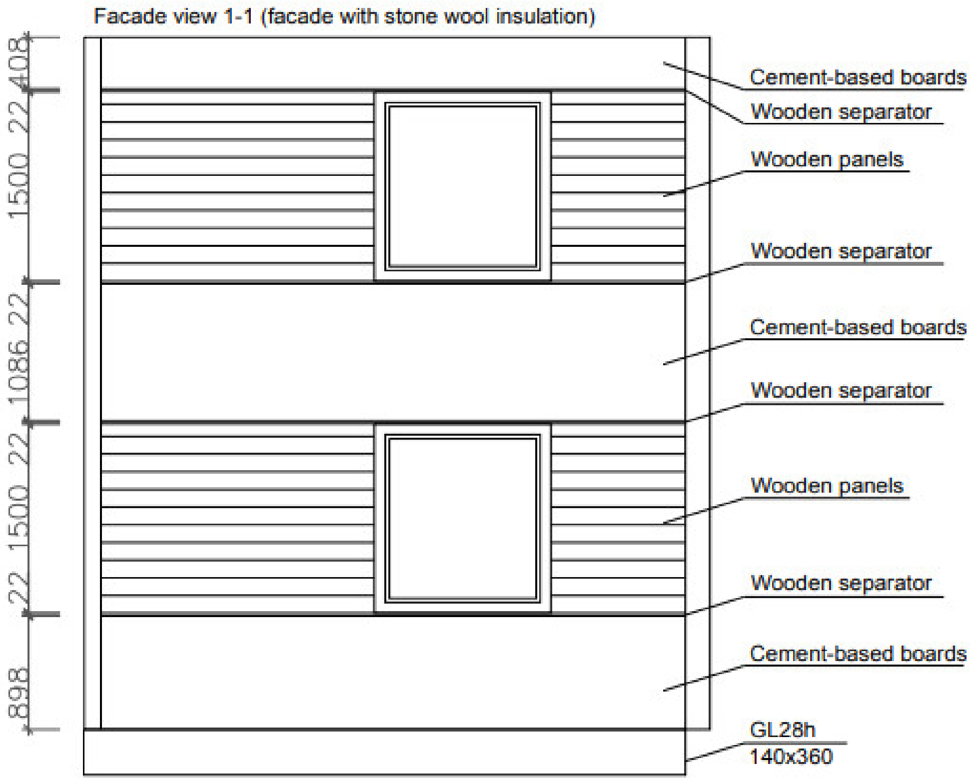
2.1. General

The aim of the compartment fire test was firstly to demonstrate the self-extinguishment of cross-laminated timber (CLT) and secondly to measure the fire spread through the joints and on the facade.

To conduct the fire test, a two-storey house was built on the test polygon of the Estonian Academy of Security Sciences in Väike-Maarja. All the walls, load-bearing or not, also the floor, intermediate ceiling and roof were made of cross-laminated timber produced by Peetri Puit. The design of the test house was to illustrate a part of an apartment building. On the inside of both floors, two out of four walls were covered with two layers of gypsum board. The remaining two walls were uncovered CLT exposed to fire. The ceiling was covered with three layers of gypsum board on both floors. The floor was covered with stone wool with cement boards on top of it. On both floors there were two windows (1400x1500 mm) and one door (950x2100 mm).

Table 2.1 Characteristics of the test house

	Height [m]	**Width [m]**	**Thickness [mm]**	**Quantity [pcs]**	**Area [m²]**	**Volume [m³]**	**Weight [t]**
CLT							
Walls	6	3,5+4,5	130	2	96	12,5	5
Floors	3,5	4,5	130	3	47,3	6,1	2,5
				Total CLT	143,3	18,6	7,5
Gypsum							
Lower floor	2,5	3,5	15	2x2	17,5(35)	0,52	
	3	3,5	15	1x2	10,5(21)	0,32	
Upper floor	2,5	3,5	15	2x2	17,5(35)	0,52	
	3	3,5	15	1x2	10,5(21)	0,32	
				Total gypsum	112	1,7	1,5
Façade							
Walls	6	3,7	12	1	22	0,27	
	6	4,7	12	1	28	0,34	
			Total facade		50	0,61	1,2
			Total weight				10,2



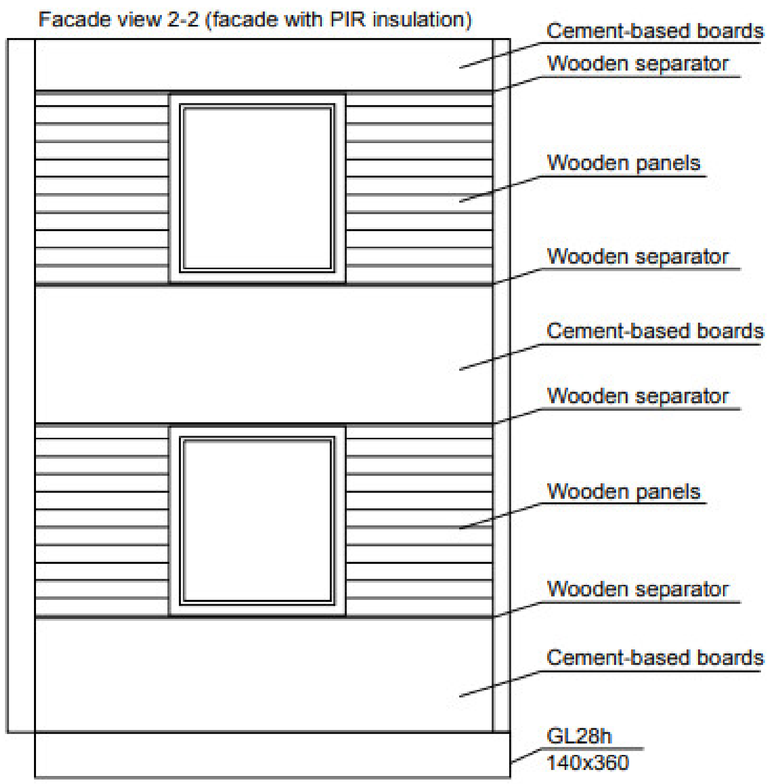


Figure 2.1 Facade views of the test house.

The test house was designed with special attention to fire safety. The CLT layers on the fire side were made thicker than usual. The gypsum boards used were fire rated. The boards were with a thickness of 15,4 mm and fixed with smaller spacing of screws than usual (centre to centre 300 mm).

On the outside, two out of four walls were covered with different insulation materials and facade cladding. The wall depicted as “facade view 1-1” on Figure 2.1 used stone wool insulation with a thickness of 150 mm. The wall shown as “facade view 2-2” on Figure 2.1 used a PIR insulation with a thickness of 160mm. The two remaining walls were left uncovered. Horizontal fire stops of stone wool were added to the cavities behind the facade cladding to stop the fire spread. The cladding was made of wooden boards (which were not impregnated or painted fireproof) and cement-based boards. The battens for wooden boards were painted with fire resistant paint. To help stop the fire spread on the facades, horizontal protruding boards were used as fire stops.

The fire was ignited on the lower floor. After the ignition, the door was closed and covered with fire-rated gypsum board. According to the scenario, once the fire load from furniture had combusted, the CLT would not contribute to fire, but would change from flaming to smouldering, the heat release would drop and eventually the CLT would self-extinguish. If the CLT should fail to extinguish on the first lamella, the char layer would fall off and expose a new, pre-heated thinner lamella to fire. In that case, a new flashover would occur and the self-extinguishing would be unlikely. In case of fire reaching the upper floor or the unexposed side of walls without facade boards, it was to be extinguished. If the windows were not broken because of fire, they were to be broken manually.

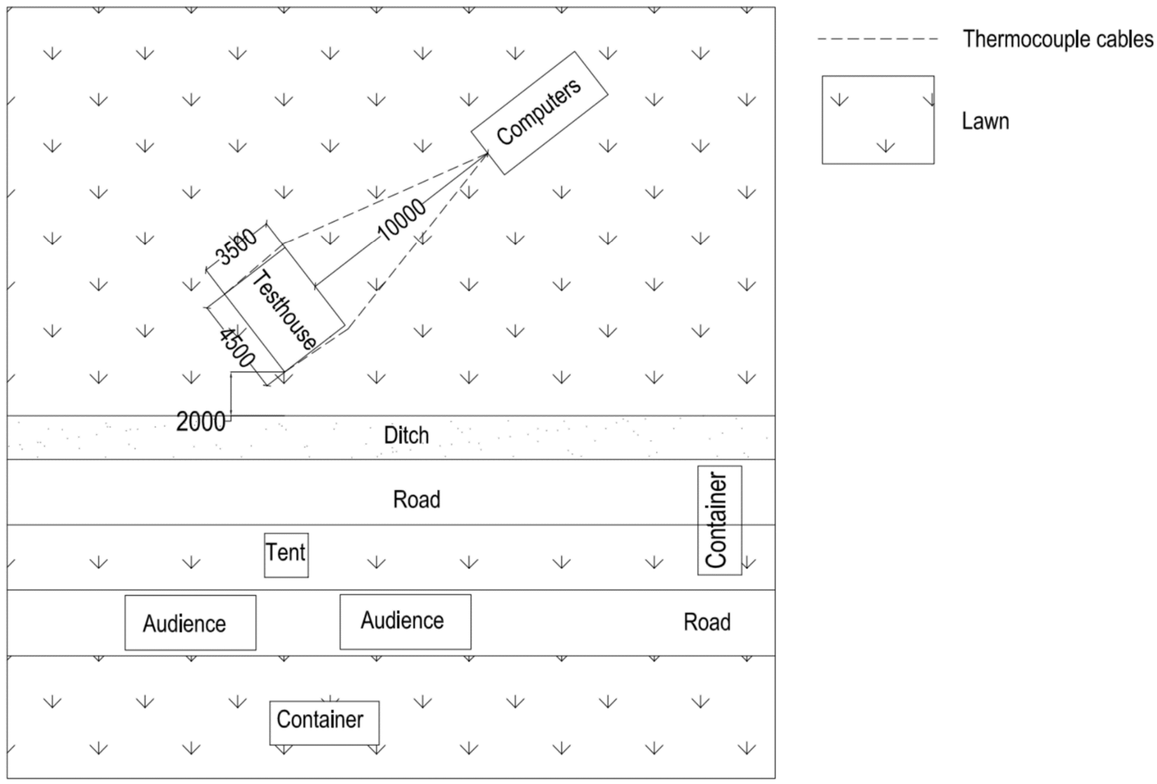


Figure 2.2 Site plan

2.1.1. Instrumentation

The following measurement instruments were used in the test in Väike-Maarja:

Data logger - FLUKE 2638A HYDRA SERIES III DATA ACQUISITION UNIT

Load cell - VETEK VZ266AH

Load cell logger - HBM MGC plus (program - Catman Version 4.5)

Thermocamera – FLIR T420

Oxygen Analyser - M&C PMA 10

Table 2.2. Load cell sensors

Load cell sensors	
Company:	Load Indicator AB, Sweden
Load cell type:	AB50
Nominal capacity:	50kN
Nominal output sensitivity (N.O.):	2,0 +/- 0,1% mV/V
Linearity deviation:	<+/- 0,1% of N.O.
Permissible temperature range:	-30 … +70 Degrees of Celsius
Protection marking:	IP65

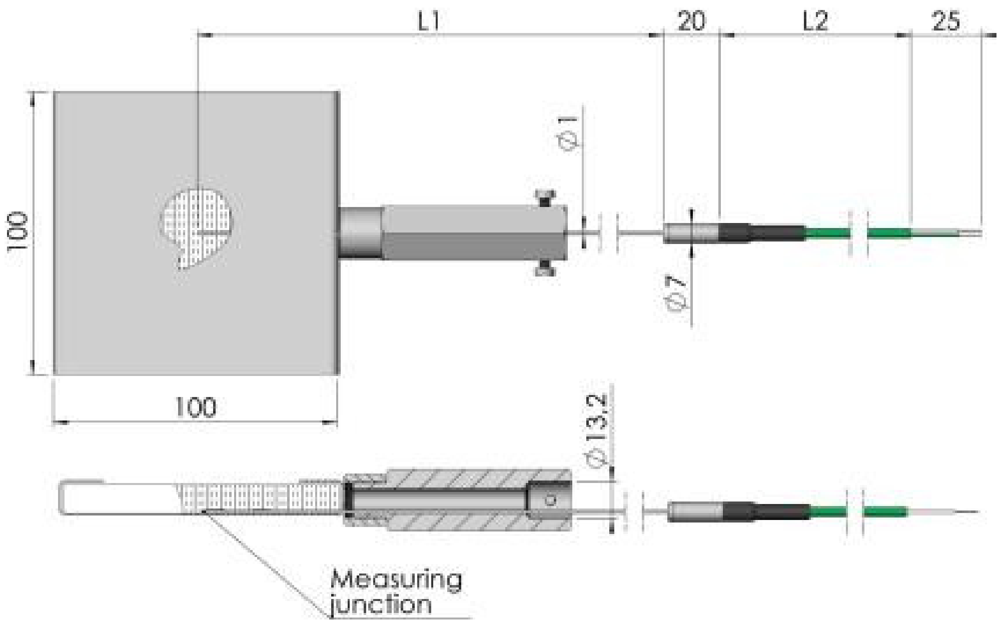


Figure 2.3 Plate thermometers. Image: Pentronic.se

Figure 2.4 PC-loggers (Intab).

Regarding temperature measurements, it is to be noted that the measured temperatures are relative. However, at the time of the test, the ambient temperature was about 0 °C, which means that the measured temperatures are also absolute in this case.

2.2. Physically based fire curve

The test hypothesis and set up was made according to physically based fire, or parametric fire curve, which states that the load-bearing function of a building should be maintained during the entire duration of the fire including the cooling phase, or a specified required time [3]. This concept provides a simple design to approximate a post-flashover compartment fire [4]. A flashover is a rapid transition from a localized fire to the involvement of all exposed surfaces of combustible materials within an enclosure, and it occurs somewhat commonly in small and medium enclosures [5]. Flashover happens when the hot gases reach a temperature high enough for them to combust, in turn involving all the other combustibles of the compartment into the fire. The general criteria for gas temperature is 500 °C to 600 °C in the upper layer of gases [5]. The curve accounts for the fuel load, compartment size, thermal properties of the walls and ceilings and ventilation conditions [4]. The physically based fire curves are valid for compartments with up to 500m^2 of floor area, with no openings in the roof and for a maximum compartment height of 4m. It is also assumed that the designed fire load of the compartment is completely burnt [6]. Such a fire curve shows an exponential growth of temperature within the compartment, which, after reaching the maximal temperature and flashover, starts a linear cooling phase until reaching a residual, usually the ambient temperature, shown on Figure 2.5 [7].

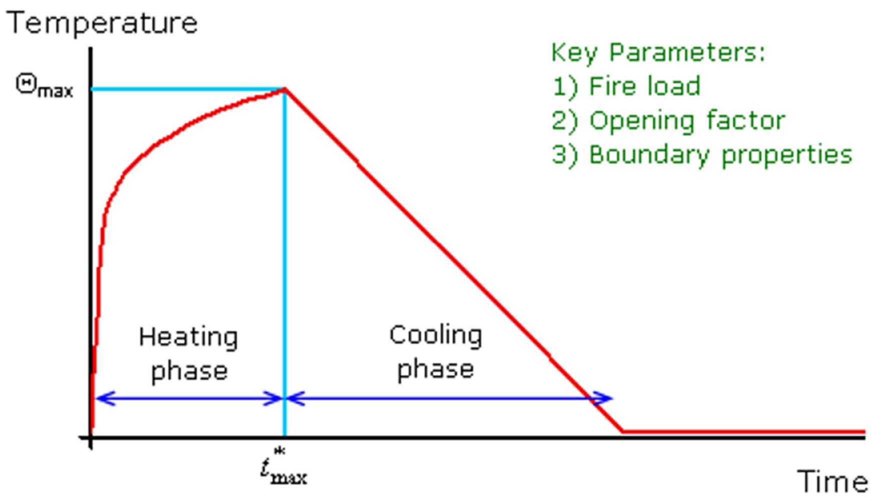


Figure 2.5 Standard physically based fire curve, Θ_{max} – maximum temperature, t^{*}_{max} – fire duration [7].

2.3. Fire load

The fire load inside the room was designed to be 600 MJ/m^2 – the regular burn load from items and furniture of an average office space. Real furniture was chosen and preferred instead of a crib of wood. As both options were considered, the usage of real items was decided due to having a closer resemblance to a realistic situation and to also divide the burn load inside the room, instead of it being concentrated in one point of the room.

Furniture and different other items such as books and clothes were chosen in mind to represent a situation that would simulate the interior of an office space. The items included a corner couch, large writing table, two bookshelves including books, a chest of drawers and some clothes. Curtains were also placed in front of the 2 windows to help the windows reach a higher temperature faster and break quicker. The windows were expected to break early for the fire to have more oxygen and reach flashover.

Fire burn load was calculated using values from the Estonian standard EVS 812-7:2008, appendix B [8], which lists different materials’ burn loads per weight unit. The used table is presented in Table 2.3:

Table 2.3 Burn loads of different materials according to EVS 812-7:2008, appendix B.

Material	Burn load per kilogram [MJ/kg]
MDF (acrylic plate)	27
Asphalt	40
Epoxy resin	34
Cork	31-35
Rubber	21
Linoleum	21
Melamine resin	19
Leather	20
Paper, cardboard	16-18
Paraffin	47
Polyester resin	30
Polyethylene	47
Polystyrene	42
Polyurethane	24
Polyvinyl chloride	18
Wood	17-20
Hay	17
Fat	40
Clothes	17-23
Silk	17-21
Celluloid	19
Cellulose	15
EPS	32
Polyurethane foam	25-29
Grain	17
Wool	23

The table does not display values for either plywood nor HDF, but after discussing this on site, it was decided to use the values of wood and MDF respectively.

All the furniture that was acquired was deconstructed to individual materials and weighed on site using a hanging scale, after which the items used in the room were chosen to reach a burn load of exactly 600 MJ/m^2. The furniture was then reconstructed. The used items and their representative values and calculations are presented in Table 2.4 and the values for calculation are from the table above. It is to be noted that the specific density of polyurethane foam inside the couch and office chair was calculated on-site using a sample piece of polyurethane from inside a couch. The density was calculated to be $\rho = 43{,}65\,\frac{\mathrm{kg}}{\mathrm{m}^3}$.

Table 2.4 Fire load used in the compartment test.

	Material	**Weight [kg]**	**Burning load [MJ/kg]**	**Total load [MJ/kg]**
1	MDF	22,3	27	602,1
2	MDF	5,5	27	148,5
3	MDF	5,5	27	148,5
4	Wood	7,8	18	140,4
5	MDF	33,1	27	893,7
6	MDF	47,7	27	1287,9
7	MDF	31,4	27	847,8
8	MDF	28,1	27	758,7
9	MDF	28,1	27	758,7
10	MDF	26,5	27	715,5
11	HDF	3,3	27	89,1
13	Couch middle (1pcs)		-	
13.1	- Polyurethane foam	2,8	27	75,6
13.2	- Plywood	1,5	18	27,0
13.3	- MDF	18,8	27	507,6
14	Couch corner (2pcs)		-	
14.1	- Polyurethane foam	5,8	27	157,7
14.2	- Plywood	3,0	18	54,0
14.3	- MDF	54,9	27	1482,8
15	Books	22,1	18	397,8
16	Clothes	11,1	23	255,3
17	Office chair (polyurethane foam)	3,8	27	102,6
		363,2	-	**9451,3**
	Room area "A"	15,75m^2		
	Needed burning load to achieve 600MJ/m^2	9450	**Current burning load [MJ/m^2]**	**600**

*Polyurethane density $\rho = 43{,}65 kg/m^3$ (calculated from a piece of foam from inside the couch)

2.4. Opening factor

Opening factor represents the amount of ventilation depending on the area of openings in the compartment walls, on the height of these openings and on the total area of the enclosure surfaces [6].

The wood surfaces inside the house were partly uncovered. This means that part of the bearing structure was completely open to the fire in its untreated form. Compartment fire tests with exposed wood surfaces have been tested only a few times before. In Väike-Maarja fire test the opening factor was the biggest it has ever been compared to other fire tests with exposed surfaces. This means that the percentage of exposed wood surfaces was bigger than in the tests conducted before. The purpose of largely exposed timber surfaces and bigger opening factor in this test was to demonstrate the effectiveness of timber frames in a fire situation where the building is supposed to meet the highest requirements of fire safety, therefore, the opening factor was based on an average classroom of a new high school in Viimsi currently being built, which uses a lot of CLT elements, including load-bearing.

Calculation of the opening factor

Opening factor is calculated:

$$O = \frac{A_v \times \sqrt{h_{eq}}}{A_t} \tag{2.1}$$

Where O Opening factor, $m^{1/2}$,

A_v Total area of vertical openings on all walls, m^2,

h_{eq} Weighted average of window heights on all walls, m,

A_t Total area of enclosure (walls, ceiling and floor, including openings), m^2.

Table 2.5 Test house measurements for opening factor

Measurements of the room **a x b x h / m**	**Measurements of one window*** **c x d / m**	**Floor area** m^2	**Wall area** m^2	**Ceiling area** m^2	**Total area** m^2
3,5 x 4,5 x 2,7	1,4 x 1,5	15,75	40	15,75	71,5

*Test house had two windows sized 1,4m x 1,5m

Table 2.6 Calculations for opening factor

A_v m^2	A_t m^2	h_{eq} **m**	**O** $m^{1/2}$
4,2	71,5	1,5	0,072

2.5. Cross-Laminated Timber

As the main goal of the fire test was to demonstrate the self-extinguishment of cross-laminated timber, the wall and floor elements of CLT were designed with increased fire resistance in mind. The layers of CLT were made thicker than usual, ranging from 20 to 40mm (40, 30, 20, 20, 20), 40mm being the fire side. The cross-section of the CLT panel is shown on Figure 2.6.

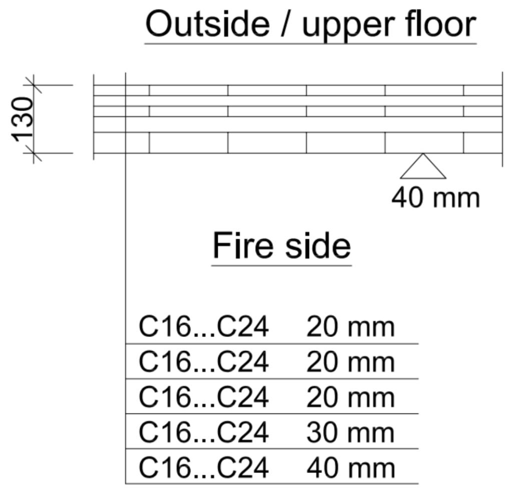


Figure 2.6 CLT panel cross-section

The thicker the layer on the fire side, the more time it takes for this layer to char. Therefore, using thicker cross section would minimize the chance of char layer falling off, therefore leading to self-extinguishment. In case of char layer falling off, the exposed layer would char at higher rate. Taking into consideration that the exposed layer is also notably thinner than the layer originally on fire side, the self-extinguishment is hardly unlikely to happen in second layer.

In the actual test the self-extinguishment did not take place. The first layer of cross-laminated timber fell off and even though there was still a slight chance of self-extinguishment in the second layer, it was decided to extinguish the fire manually. The calculations for the test were made with assumptions that the windows are opened during the whole test. In the actual test, the windows were closed at the beginning, but were broken manually to improve the oxygen flow, thus letting the fire develop properly.

2.6. Joints and penetrations

2.6.1. Joints

The conducted experiment also set out to show how correctly designed joints can be very fire-resistant and contain the fire in a real situation. The CLT panels' continuation joints were designed to be overlapping, with an overlap of 100mm, fastened by self-tapping screws spaced 150mm apart, see Figure 2.7.

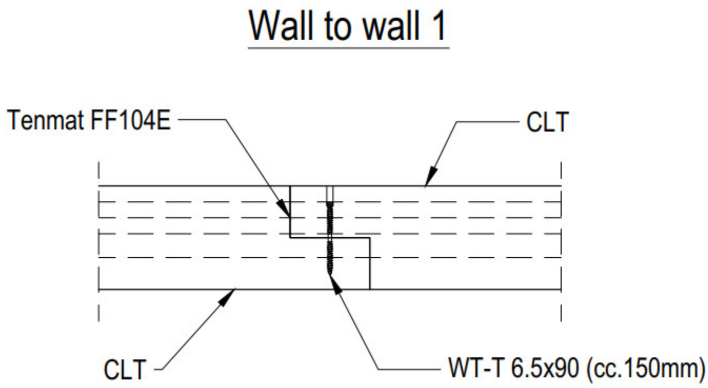


Figure 2.7 CLT+CLT overlapping joint

Overlapping joints were used for the connection of two elements of the same type – wall to wall and floor to floor (roof to roof).

The corners of the house had a wall to wall connection where one wall crossed on top of the other and the two walls were connected by self-tapping screws with a spacing of 200mm, see Figure 2.8.

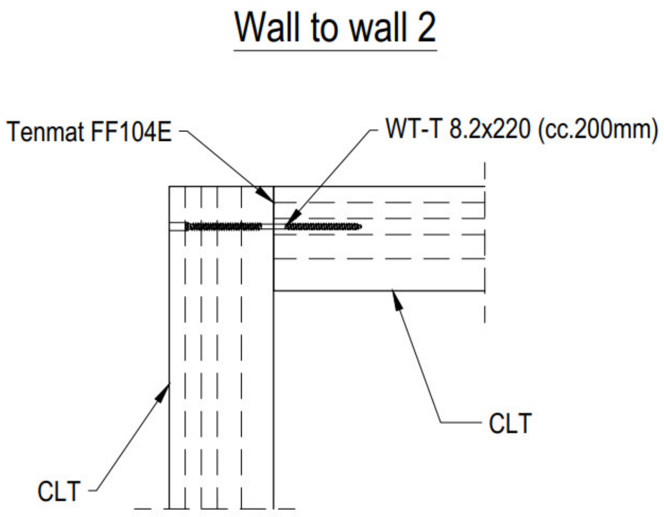


Figure 2.8 CLT + CLT corner joint

Two joint principles were tested for the attachment of floors panels to wall panel.

The first of these is designed in such a way that the floor/ceiling is placed between two wall panels and connected with 2 self-tapping screws per cross-section with an approximately equal distance between screws, see Figure 2.9. This type of joint is to be used when designing lower and smaller buildings. All types of wood have a small resistance to perpendicular compression. When compressed perpendicular to the grain of the wood, timber quickly loses its strength capabilities and is to be regarded as having reached its ultimate limit state. This limits the usage of such a joint to smaller scale buildings, simply because the floors timber would receive perpendicular compression forces far above its tolerance. Problems would also occur in the serviceability limit state, because the deformations would be too big and cause unwanted deflections for the building.

The second joint solution was with a continuous wall panel, see Figure 2.10. The floor should be connected to the wall panels with special clamps, brackets or corners of some sort that would be able to transfer the forces from the floor to the wall. The fastening system must also be fire resistant or thoroughly isolated from fire. Since the compression forces inside the wall are not transferred through the floor panel, there is no perpendicular compression and therefore the floor panel only needs to withstand internal forces created by that floors loads, enabling the use of this design in high, multi-storey buildings.

It is to be noted that this principle was used in two walls of the test house, however, these walls were not mechanically fastened to the wall panel, because the span of the room was small and the other two walls were already attached following the design principle of the first joint solution described above.

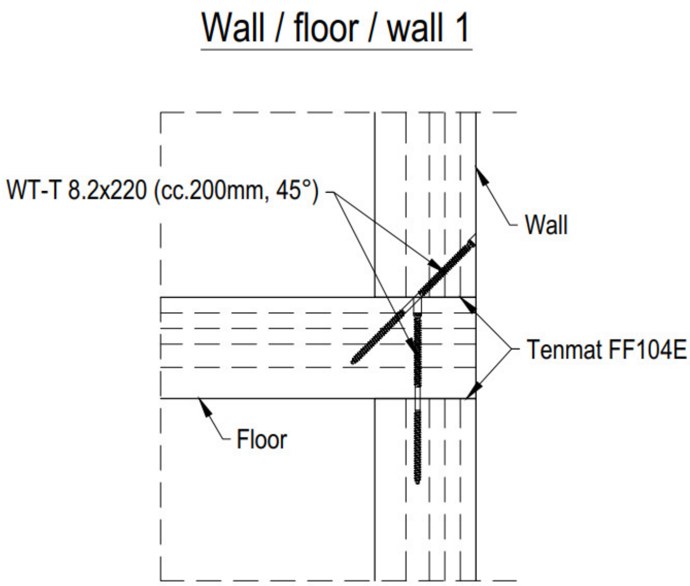


Figure 2.9 Wall-floor-wall joint to be used in smaller buildings

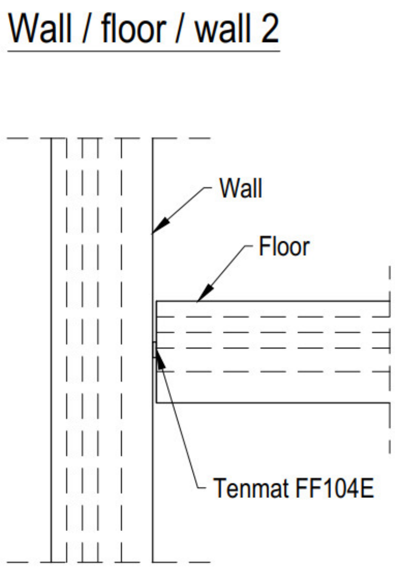


Figure 2.10 Wall-floor-wall joint for larger buildings

As seen from the schemes, an intumescent paper “Tenmat Firefly 104E”, dimensioned at 1,8 mm thick and 25 mm wide, was used to seal the joints. According to the manufacturer of FF104E, it is an intumescent paper which generates high expansion and expansion pressure when exposed to fire or heat (data-sheet downloadable from reference link). Therefore, by expanding, this product seals the joint and works according to the same principle as a fire-retardant paint on steel would (isolating it from fire). The paper is supposed to expand up to 100% of its original size and the material is said to start expanding when the temperature rises to 200 °C [9].

During the duration of the test, the CLT joints did not show any signs of failing. Even visual inspection after the test showed no flames or hot smoke to reach the upper floor as well as no fire penetration through the wall joints.

2.6.2. HVAC and other penetrations

HVAC systems' penetrations were also tested in this experiment. A non-mechanical fire damper, Protecta FR Damper, with a diameter of 100 mm, penetrated one of the walls. According to the technical sheet, it is used to fire proof ventilation ducts at their penetrations of fire rated constructions, i.e. fire walls and compartments, preventing the spread of smoke and flames. The product is made of steel, which is treated with an advanced heat expanding graphite. The graphite works as an intumescent material in case of fire and expands when exposed to heat, sealing off the whole damper [10]. The wall around the penetration hole was insulated from the fire with two layers of Protecta FR Board [11], a high-density stone wool plate with a thickness of 60 mm, which is coated with Protecta FR Coating. The coating provides additional fire protection by reducing the permeability of the stone wool core and prevents passage of hot gases. This reduces temperature rise on the other side, as well as lessens heat conduction [11]. The penetration was sealed using Protecta FR Acrylic, which is a sealant that cures under atmospheric conditions. The sealant works similarly to the intumescent paper used in the buildings joints. Thermal activation is to take place at 180 °C, after which the material expands and creates a durable intumescent char, which prevents the passage of fire and smoke for periods of up to 4 hours [12].

The same wall was also penetrated by metal tubes of a small diameter. These tubes were used to measure the rooms pressure. The tubes' penetrations were sealed using Protecta FR Putty Cord, which is a putty that is supplied in the form of non-setting cords. It is easily workable by hand and is designed especially for penetrations that are small or have no gaps. The putty was installed around the services, and due to its non-setting properties is supposed to provide a tight fit for a long time [13].

Thermocouple trees and cables penetrating the walls were sealed with Protecta FR Graphite. FR Graphite is a high specification formula designed to prevent fire, smoke and gas spread through openings in fire rated constructions. The sealant expands when it is subjected to fire and closes openings around penetrations when any combustible or low temperature melting materials have burnt away [14].

During the fire test, no smoke or fire was seen coming through the HVAC simulation system or any of the other penetrations. Also, the thermocouple trees and cables showed no fire or smoke damage on the upper floor or outside walls.

2.7. Doors and windows

Both floors also had windows and doors supplied by a local manufacturer Aru Grupp. The windows and doors, however, were different on both floors.

The lower floor used non-fireproof windows so that the windows would break due to fire, in turn enabling the fire to get larger amounts of oxygen and reach higher temperatures and eventually flashover. All the windows were equal in size with the dimensions being 1400x1500 mm. Windows and doors were all made with wooden frames. The door on the lower floor was fire rated as EI30, whereas the upper floor door had no fire rating. The doors had a dimension of 950x2100 mm.

The windows of the upper floor were fireproof windows, rated to EI30. The hypothesis was that these windows' first layer of glass would break, revealing the thin, completely transparent material that is between two layers of glazing, which becomes intumescent and protects the inner glass from breaking.

Figure 2.11 EI-30 window on the upper floor

Even though the fire brigade made some slight scratches on the glass on the lower floor for it to break more easily, in the actual test the windows did not break from the fire. The fire brigade broke the glass manually, thus letting the fire develop. The outer layer of the windows on the upper floor broke and the transparent protective material was revealed.

The fire did not access the door on the upper floor. On the lower floor though, the EI30 door held up surprisingly good. The inner board was charred, but no visible damage from fire was observed outside, so the fire did not reach the gypsum board that protected the door from the outside.

2.8. The timeline of the test

0:00:00 (hh:mm:ss) The fire is ignited on the lower floor. The sofa near the window and curtains is ignited, imitating a somewhat realistic beginning to the fire. After the ignition, the door is closed and covered with fire-rated gypsum board. The windows were also closed air tight.

Figure 2.12 The test house before the ignition

For approximately 20 minutes a small amount of smoke is coming out of the house but there are no flames visible from the outside

0:20:10 The fire brigade starts breaking the window on facade 1-1. This is done to provide more oxygen for the fire to not succumb and to speed up the process of reaching flashover. A small amount of grey smoke is blowing out of the window. The smoke alarm starts working as soon as the first window is broken.

0:20:58 The first window is completely broken on facade 1-1. More grey smoke comes out of the window. Smoke continues slowly blowing out of the window.

Figure 2.13 After breaking the first window the fire starts to develop

0:23:22 Flames are getting higher as seen from the window.

0:24:47 The second window of the lower floor (facade view 2-2) is also manually broken. Smoke continues blowing out of both windows.

0:27:02 The amount of smoke blowing from the windows is decreasing.

0:33:02 The amount of smoke coming out of the windows is gradually increasing. It is seen from the windows that the flames are burning higher inside the test house.

0:41:57 The first flames are reaching out of the window that was broken first. The fire stop above the window is slowly starting to burn.

0:46:32 The fire stop is completely burning; the flames are getting out of the window that was broken second.

Figure 2.14 Flames are reaching the facade of the upper floor

0:46:42 The first flashover occurs.

0:48:00 The firestop above the second window (facade 2-2) prevents the fire reaching the area on top of the window, which is the weakest spot of the facade when the house is on fire.

The same thing is not happening on facade 1-1. The facade area on top of the window is starting to get darker and the cement board is starting to lose its surface treatment material.

0:49:00 The wooden boards next to the windows on the lower floor are also on fire now. The lower fire stop and the wooden facade on the upper floor of facade 2-2 are burning.

0:50:00 The window on the upper floor of facade 1-1 is on fire but does not break

0:52:00 The cement board above the secondly broken window is starting to disintegrate.

Figure 2.15 Fire has spread to the facades

0:54:00 Pieces of the fire stops above the window on facade 1-1 are falling.

0:57:00 The same thing is happening on facade 2-2: PIR insulation starts falling.

0:58:00 The decay phase starts.

1:05:00 The fire starts fading. The CLT inside the building is burning. On the outside, the fire stops on the upper floor are burning. All the fire stops on lower floors' windows are burned. The cement-based board has not broken off, but the layer of paint is peeling.

Figure 2.16 The flames are subsiding

1:09:00 Exposed CLT walls are smouldering with no visible flames. The fire is dying. Upper floor has not been on fire throughout the whole test although the facade has small flames.

1:26:00 There is a small fire inside the room and on both facades but the CLT walls are not burning.

Figure 2.17 The CLT is smouldering

1:51:00 The charred layer of the CLT falls off and the second layer of CLT starts to burn with increased rate due to being preheated.

2:00:00 The second flashover occurs. The exposed second layer of CLT is now completely on fire.

Figure 2.18 The second layer of CLT is burning

2:16:00 It is decided that the compartment will not self-extinguish, and the fire is manually put out by the fire brigade.

3. PRODUCTION AND USAGE OF CLT

3.1. General

Cross-laminated timber, or CLT, is an engineered wood panel product that consists of an odd number (typically 3, 5 or 7) of layers. These layers are stacked crosswise at 90-degree angles. Layers with even numbers consist of longitudinal boards and layers with odd numbers have transverse boards. It is not recommended to use CLT in conditions that meet service class 3 [15]. Deformations caused by exposure to conditions meeting service class 3 are shown on Figure 3.1.

CLT panels can be widely used. For example, floors, walls, intermediate ceilings, roofs, balconies and bridges can all be built out of CLT. The building process is relatively fast because of the panels are big in size but lighter than e.g. concrete analogues. The panels are connected on site using screws, bolts and dowels. The maximum height of the panel is 3.5 m and maximum width is 15 m [15]. CLT is currently gaining popularity due to its increasing usage in high-rise buildings.

Because the layers are crosswise and bonded, the CLT panel has improved stiffness, splitting resistance, stability and high strength. The prefabrication is done off-site, which speeds up the on-site building process. Other advantages include good thermal insulation and air tightness [1]

The disadvantages of CLT include low damping ratio of CLT floors with regards to vibrations [1] and the price which, depending on the location, can be higher than e.g. concrete analogue.

As analysis have shown [1], the fire behavior of CLT is strongly dependent on the number and thickness of layers. Other significant factors regarding fire behavior are the position of the panel (vertical panels perform better than horizontal) and the type of adhesive used for connecting layers.

In case of the fire side lamella being thicker than 25 mm, the fall-off of charred layers becomes relevant if fire resistance of more than 60 minutes is necessary. If the fire lasts for 30 minutes or less, only the layer on the fire side will char [16].

Figure 3.1. Visible deformation of boards exposed to weather conditions. Photo is taken six months after the test

3.2. Production of CLT

The construction detail of a typical cross-laminated timber panel is shown on Figure 3.2. Each layer consists of parallel timber boards that are placed side-by-side. The strength class of boards is usually C24, but C16 and C18 are also used. The boards are kiln-dried to moisture content of about 12% to prevent cracking and dimensional variations. To achieve higher strength properties local growth characteristics are often cut out – this is referred to as trimming. The remaining boards are finger jointed to achieve desirable length [1].

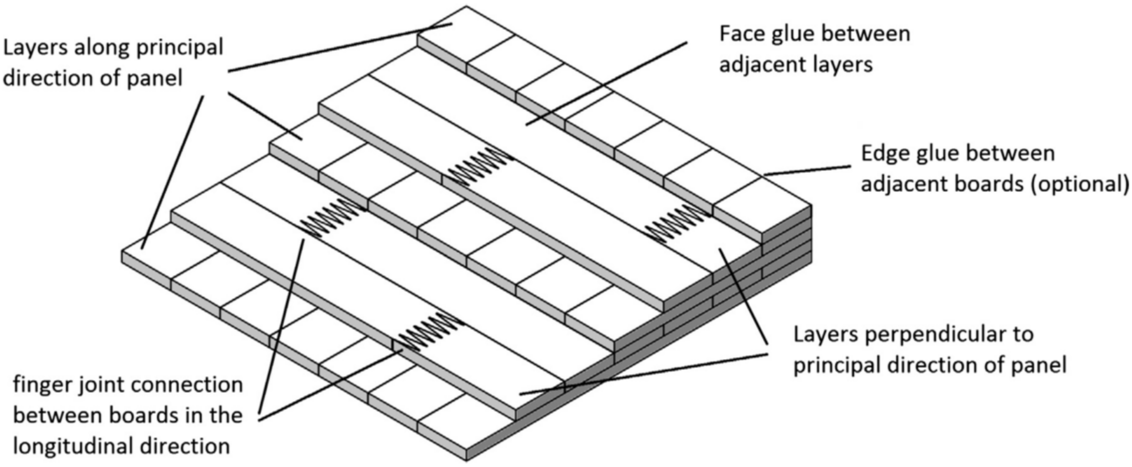


Figure 3.2 Construction detail of CLT [23]

The boards are then planed on four sides. This increases the gluing effectiveness and helps to keep the required thickness within tolerance. On Figure 3.3, a cross-laminated timber panel prior to machining is shown.

In some cases, the boards are bonded to one another using edge gluing. The adhesives are usually based on polyurethane. This reduces or eliminates the gaps between boards. This procedure mainly increases acoustic performance, fire performance and airtightness. It is also important if the outer surface of CLT is left visible and class A surface quality is needed.

The panel is created using surface bonding. This means that glue is applied on the layer of boards. This is done using a special glue application system that can move on rails, therefore work relatively fast and provide an even layer of glue. Once the adhesive is applied, the layers are bonded by pressing. This can be done using screws, brackets, nails, vacuum pressing or hydraulic pressing.

The assembled panels are usually planed to achieve the desired thickness and smoothness of the surface.

Figure 3.3. CLT panel prior to machining

The planed panel is then sent to computer numerical control (CNC) machine to cut out openings for doors, windows or building services with high precision. The CNC machining is also necessary to cut out joints for connecting the panels on site.

Depending on the final use of the panel, factory installation of additional layers is possible. These layers include gypsum board, vapor barrier, oriented strand board, cladding, acoustic panels, cement-based boards etc.

In theory, it would be possible to use fire retardant impregnation or paint, but due to high cost this option is not used.

3.3. CLT panels for the test

The cross-laminated timber panels used in the fire test were untypical for several reasons.

It was necessary to measure temperature between the layers of CLT. That meant installing as many thermocouples as possible off-site during manufacturing. This, however, was challenging because the panels needed to be cut in CNC machine after the thermocouples were installed. It was necessary to be extremely careful not to cut the wires. To make sure that all the installed thermocouples work, the electrical resistance of every thermocouple was measured before and after the pressing as presented in Table 3.1. Only one thermocouple was damaged during pressing.

To avoid the fall-off of char layer and to achieve self-extinguishment, the thickness of layers was changed. Usually the layers are symmetrical around the mid-layer. The test panel's layers were 20 mm, 20 mm, 20 mm, 30 mm and 40 mm thick with 40 mm being the fire side.

To avoid deformation caused by moisture, Peetri Puit usually makes small cuts along the boards used in CLT. To make the panel as air tight as possible and to avoid stack effect, it was decided not to use the cuts. Prior to CNC machining, in order to protect the cables from cutting, they were put away in a void (see Figure 3.4). Once the CNC was done, a hole was drilled for leading the cables to the outer side of the panel. The hole was then filled with fire resistant PU foam (see Figure 3.5). Additional boards were installed to close the voids.

Figure 3.4. Thermocouples were put away before CNC machining

Figure 3.5. Finished CLT panel

Table 3.1 Electrical resistance of thermocouples

Panel	Thermo-couple	Electrical resistance prior to pressing (Ω)	Electrical resistance after pressing (Ω)
P-3	CC1	35	33.1
	CC2	35.7	32.3
	CC3	34.7	35.1
	CD1	86.6	87.1
P-4	CA1	41.7	37.2
	CA2	43.3	38.5
	CA3	44.6	43.2
	CB1	85.1	86.1
P-5	CH1	91.8	92.7
	CH2	90.2	88.5
	CH3	81.1	91.1
	CG1	45.3	43.4
	CG2	37.7	37.1
	CG3	40.3	40
P-6	CE1	37.1	35.4
	CE2	41.6	38.2
	CE3	40.1	38.8
	CF1	92.7	91.9
	CF2	92	92.2
	CF3	94.2	FAILURE
S-2	WA1	61.2	59.8
	WA2	60.9	59.9
	WA3	59.8	60.2
	WE1	122.7	123.1
	WE2	120.3	120.3
	WE3	117.2	115.8
S-3	WB1	65	64.1
	WB2	65.4	64.5
	WB3	61.5	61.6
	WF1	124.3	125
	WF2	128.3	126.5
	WF3	127.4	125.4
S-5	WC1	66.7	66.3
S-6	WD1	68.1	68.5
S-7	WG1	66.8	64.2
	WG2	59.6	57.1
	WG3	58.5	61.4
S-8	WH1	65.2	68

Panel	Thermo-couple	Electrical resistance prior to pressing (Ω)	Electrical resistance after pressing (Ω)
S8	WH2	63.4	63.7
	WH3	64.6	65.1

4. BEHAVIOUR OF CLT IN THE ACTUAL TEST

4.1. Building weight

During the fire test, the weight of the building was measured.

The weight of the floor was measured separately using five load cells – four in the corners and one in the centre of the floor. As shown in Figure 4.1, the measured floor weight decreased 3 kilonewtons which is slightly different from the weight of the furniture used for fire load [Table 2.4]. The reason for the small difference between those numbers is that there were some items among the furniture that did not burn, e.g. steel furniture legs. The weight of the floor started to decrease after the flashover. After the second flashover, the weight of the floor started increasing due to the charred layer of CLT falling off

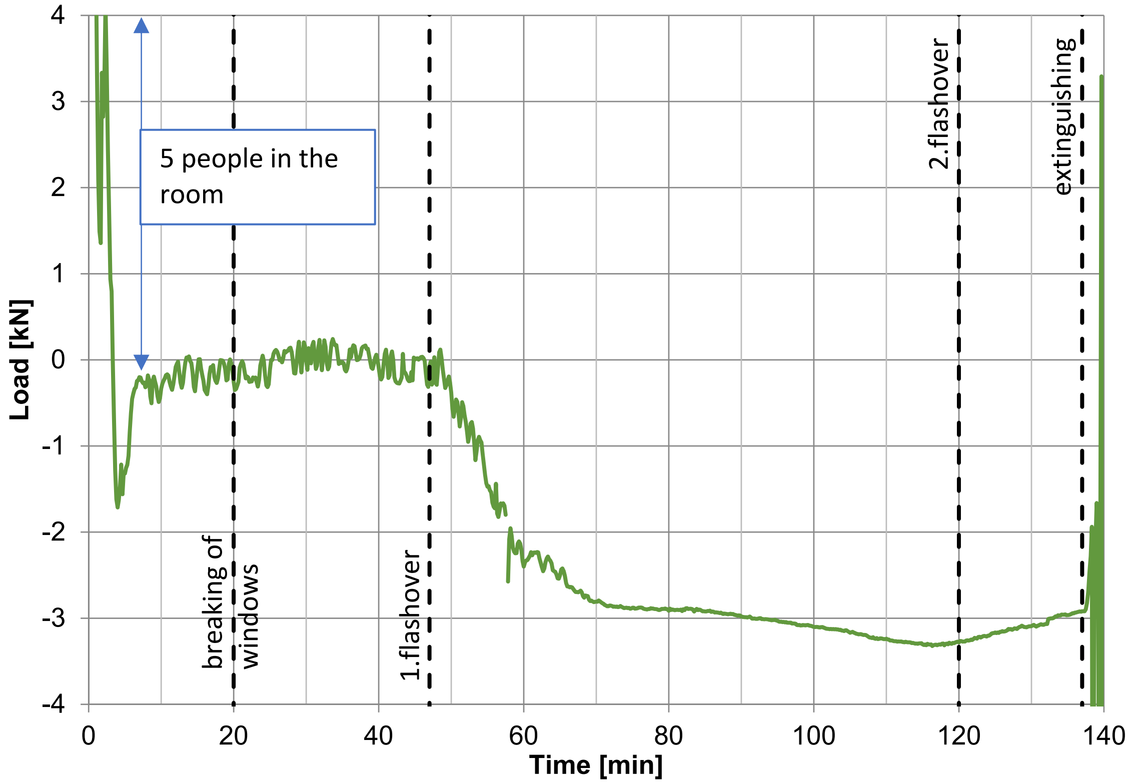


Figure 4.1. Floor weight

To measure the weight changes of the whole building, load cells were installed in every corner of the walls. The measurements are presented in Figure 4.2. These measurements do no reflect the weight of the floor, but the weight of the walls and the ceilings. The local extrema in the graph are caused by visitations to the upper floor for inspection. After the second flashover, as the weight of the floor increased, the weight of the whole building decreased.

The contribution of CLT to the change of the weight of the whole building was calculated to be

$$G_{CLT} = A * t * \rho = [2 * (2{,}5 * 4{,}5) - 1{,}4 * 1{,}5] * 0{,}04 * 4{,}2 = 3{,}4\ kN \quad (4.2)$$

Where $A - Area\ of\ exposed\ CLT\ walls,\ m^2$

$t - Thickness\ of\ the\ first\ layer, m$

$\rho - self - weight\ of\ timber,\ kN/m^3$

It is estimated that 21% of the weight of the gypsum board is chemically combined water [17]. As the temperature in gypsum boards reach 100 ^{o}C, the water starts to evaporate. The total area of the gypsum boards is presented in Table 4.1 below.

Table 4.1 Total area of the gypsum boards

	Wall/ Ceiling		**Openings**		**Layers**	**Area**
	a [m]	**b [m]**	**a [m]**	**b [m]**		**[m^2]**
Wall 1	2.5	3.5	1.4	1.5	2	13.3
Wall 2	2.5	3.5	0.95	2.1	2	13.51
Ceiling	4.5	3.5			3	47.25
						74.06

The contribution of water evaporating from the gypsum boards is calculated:

$$G_{Gypsum} = A * \frac{21}{100} * m_w = 74{,}06 * \frac{21}{100} * \frac{12{,}1}{100} = 1{,}9\ kN \qquad (4.3)$$

Where $A - area\ of\ gypsum\ boards,\ see$ Table 4.1

$$m_w = 12{,}1\frac{kg}{m^2} - \text{weight per 1 m}^2 \text{ of Gyproc GKF 15 gypsum board [18]}$$

The total weight change from CLT falling off and water evaporating from the gypsum boards:

$$G = G_{CLT} + G_{Gypsum} = 3{,}4 + 1{,}9 = 5{,}3\ kN \qquad (4.4)$$

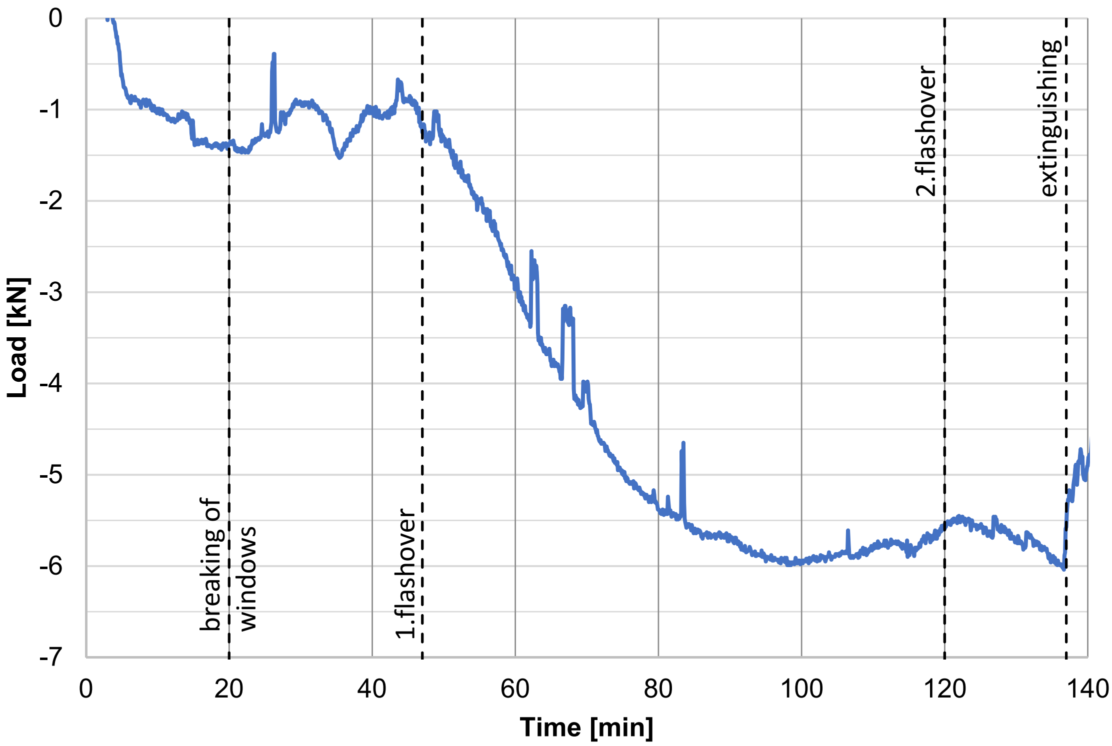


Figure 4.2. Measured weight of the building

4.2. CLT structures exposed and unexposed to fire

4.2.1. CLT walls exposed to fire

Thermocouples WA1…WA3 and WB1…WB3 were placed between layers of exposed cross-laminated timber (Figure 4.5 and Figure 4.6). As shown in Figure 4.7 and Figure 4.8, temperatures behind the first layer of CLT exceeded 300 °C for both cases. The first layer of CLT fell off on both walls and the second layer of CLT started to burn. However, at no point did the temperatures rise above 300 °C behind the second layer. This indicates that the delamination of the second layer was highly unlikely. The charring of the second layer was measured to be approximately 20 mm after the test as shown in Figure 4.3.

Figure 4.3. Measurements after test showed that approximately 20 mm of the second layer was charred

According to data from plate thermometers PT2 and PT3, the gas temperature reached 300 ^{o}C on 36th minute (see Figures 4.7 and 4.8).

For WA1, the fall-off of char layer took place on 118th minute. However, the temperature reached 300 degrees already on 111th minute, which means that the glue held up unexpectedly well (Figure 4.7 and 4.9)

The highest temperature recorded for WB1 was 280 degrees before fall-off of char layer on the 116th minute. This means that on this wall, for some reason, the glue did not hold up as well (Figure 4.8 and 4.10).

Charring rate for WA1 is calculated to be

$$\beta_{WA1} = \frac{d_{char}}{t} = \frac{40}{111-36} = 0{,}53\ \frac{mm}{min} \tag{4.5}$$

Where	β	Rate of charring	[mm/min]
	d_{char}	Charring depth	[mm]
	t	Time of fire exposure	[min]

Charring rate for WB1 is calculated to be

$$\beta_{WB1} = \frac{d_{char}}{t} = \frac{40}{116-36} = 0{,}50\frac{mm}{min} \tag{4.6}$$

According to Peetri Puit’s webpage [15] , the charring rate for CLT panels with gaps between boards up to 2mm, the charring rate is 0,65 mm/min. On both walls that were directly exposed to fire, the charring rate in our test was slower than the value declared by the company. However, the charring rate from Peetri Puit’s webpage is calculated under the conditions of standard fire.

To illustrate the difference between charring in standard fire and in the actual test, the charring of the CLT is calculated according to the charring rate in standard fire. As the time period with a constant charring rate (t_0) in our test exceeds 40 minutes, it is not possible to calculate charring in physical fire for our test using Eurocode 5 [19]. The first lamella would be charred after 60 minutes, burning at 0.65 mm/min. The first 25 mm of the second layer would burn twice as fast at 0.13 mm/min because of the pre-heating. The last 5 mm of the second layer would burn at 0.65 mm/min and after 88 minutes this layer would also fall off. The third layer would start to burn, again at twice the rate. It would take 135 minutes to completely burn the five-layer CLT wall (see Figure 4.4).

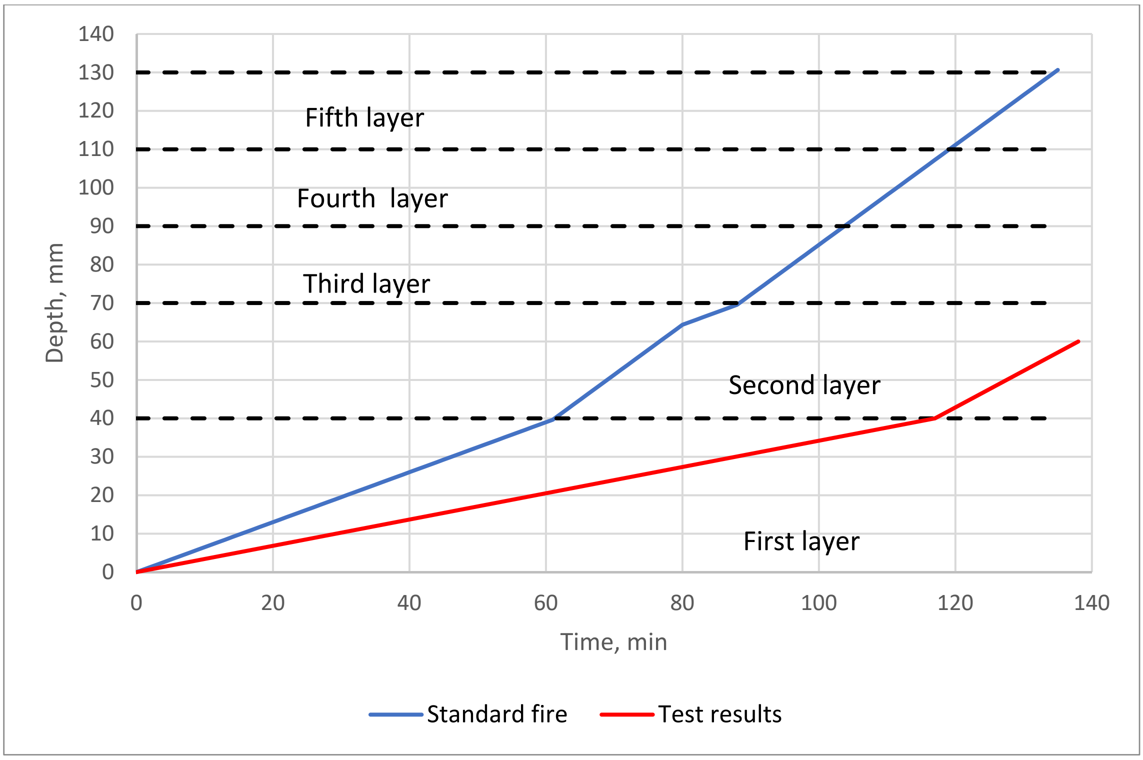


Figure 4.4. Charring in standard fire compared to charring in the test

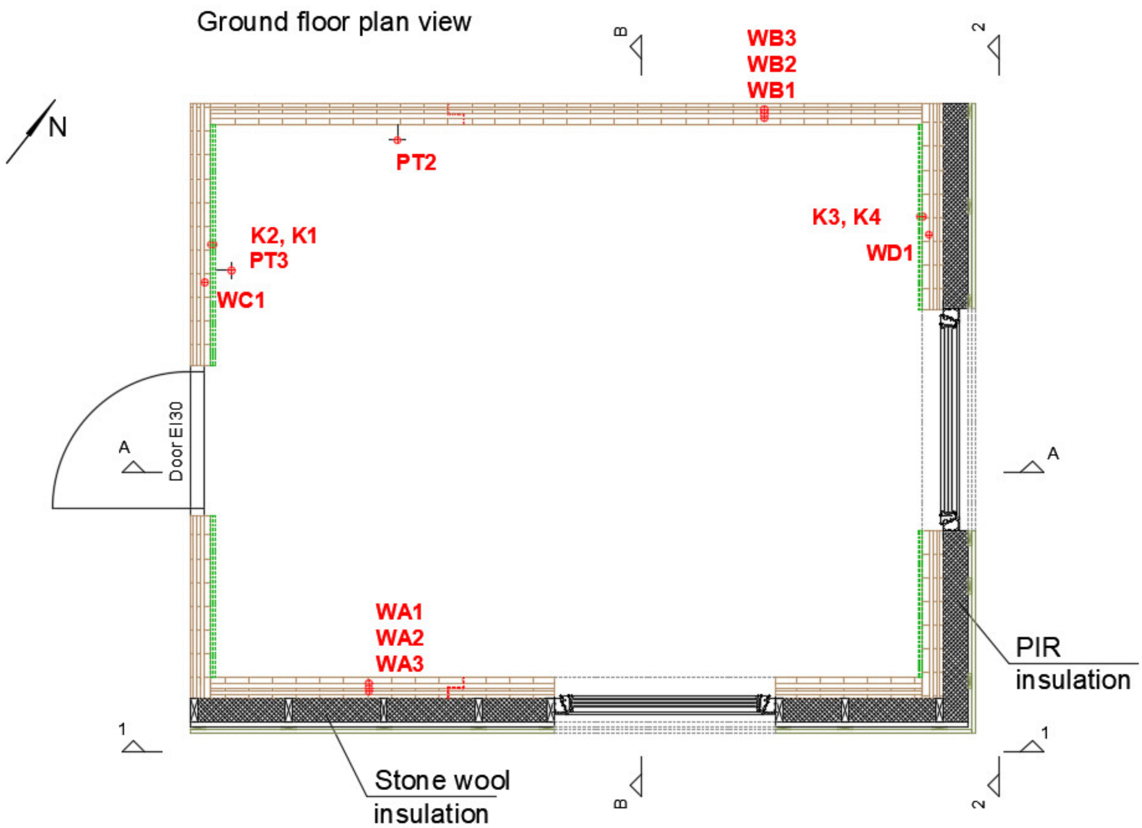


Figure 4.5 Location of CLT thermocouples and plate thermometers

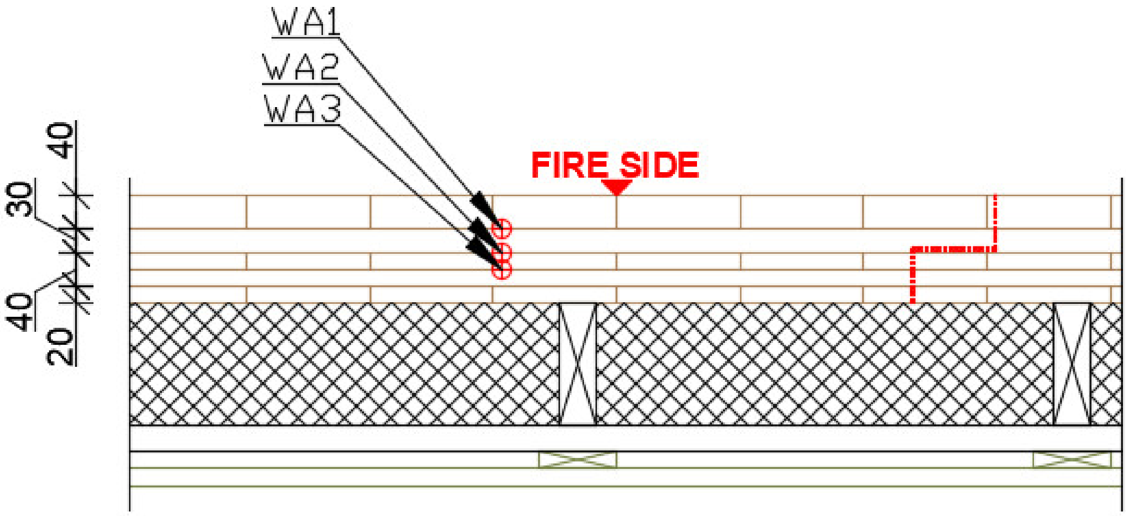


Figure 4.6. Location of thermocouples WA1...WA3. Horizontal section

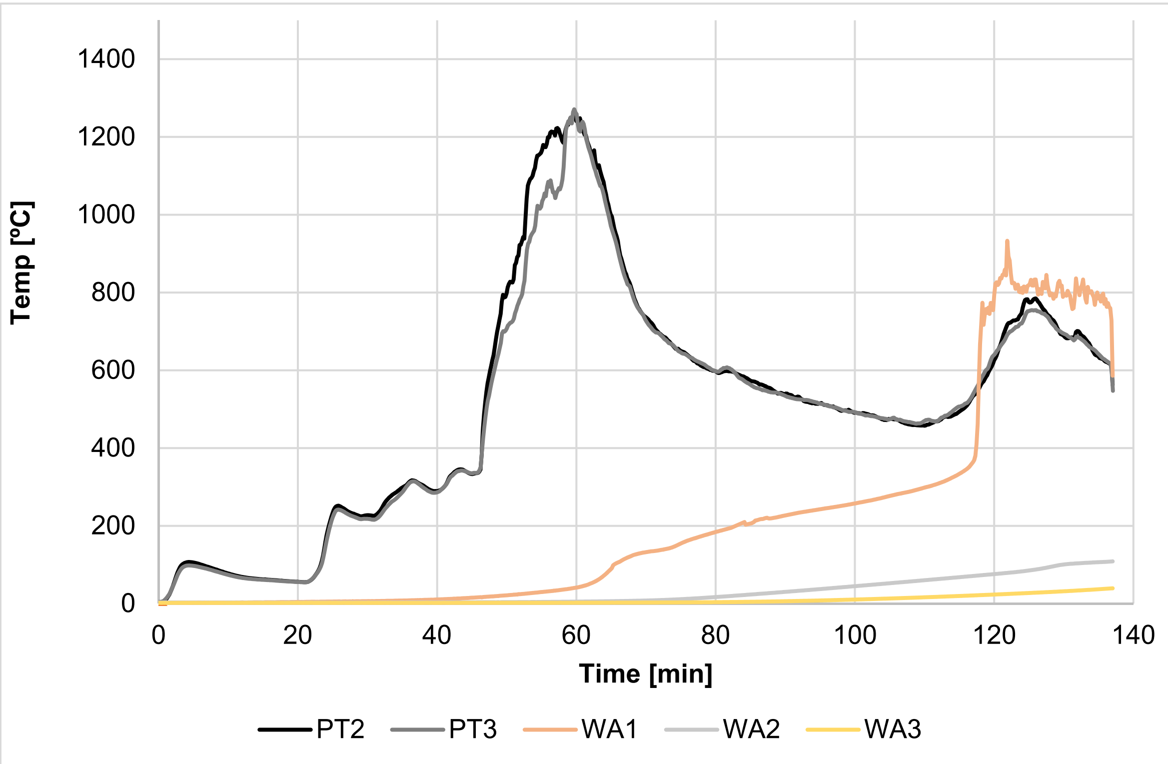


Figure 4.7 Temperatures for thermocouples WA1...WA3

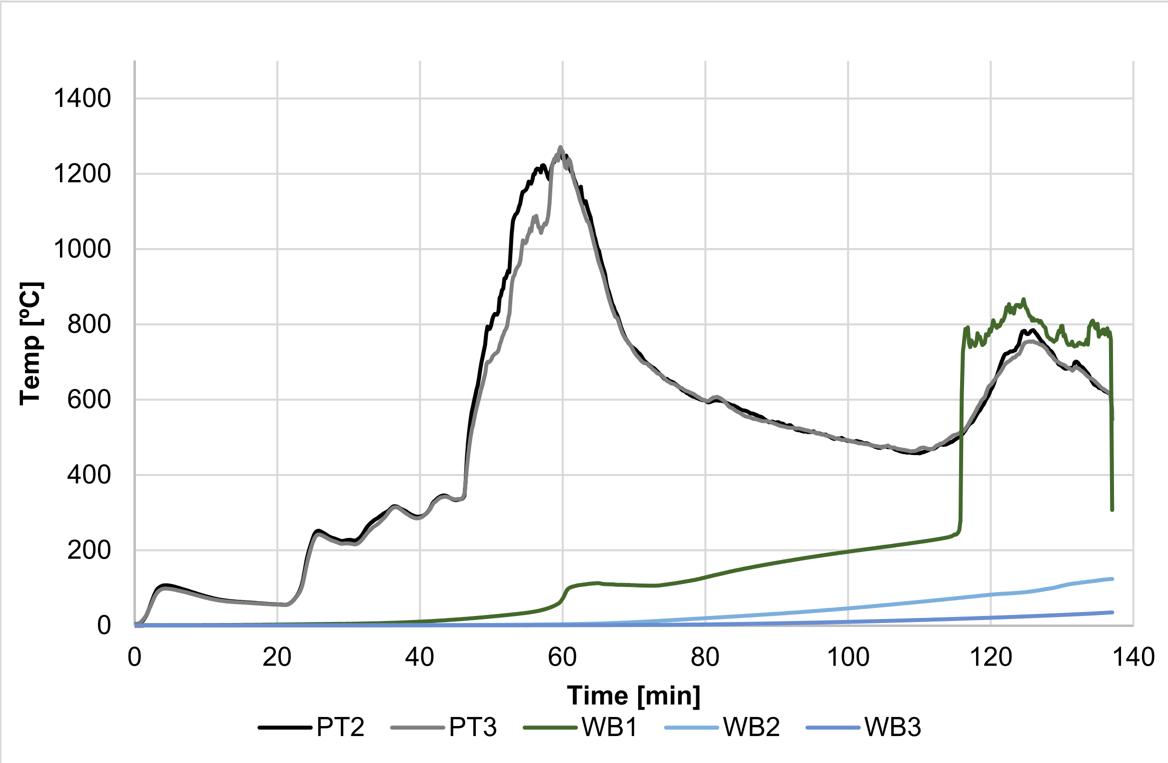


Figure 4.8. Temperature curve for thermocouples WB1...WB3 compared to plate thermometers

Figures 4.9 and 4.10 describe the temperature at characteristic points in the cross-sections. The temperature on the first layer of CLT reaches 300 °C on 36th minute. The fall-off occurs on 111th minute for WA. The highest temperature recorded prior to the fall-off was on 115th minute for WB, on 116th minute temperatures immediately following the fall-off are shown. The fire was extinguished on 138th minute, which marks the end of the test.

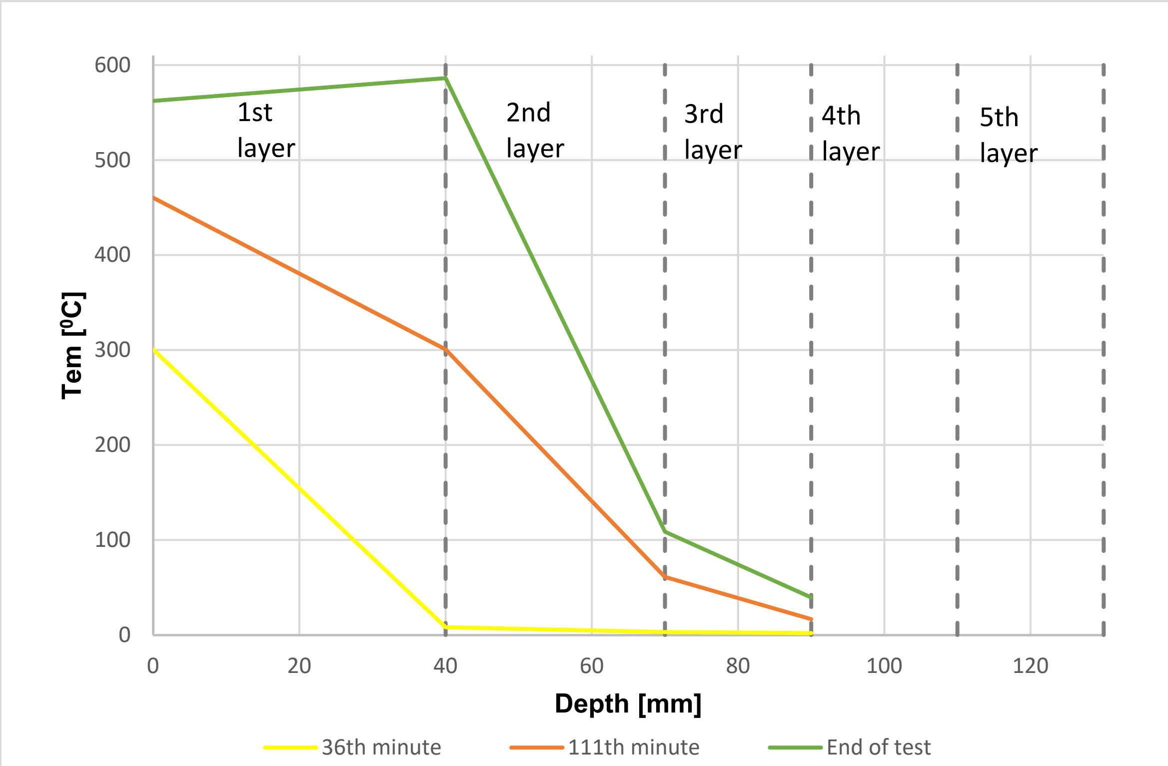


Figure 4.9. Characteristic temperatures in cross-section WA

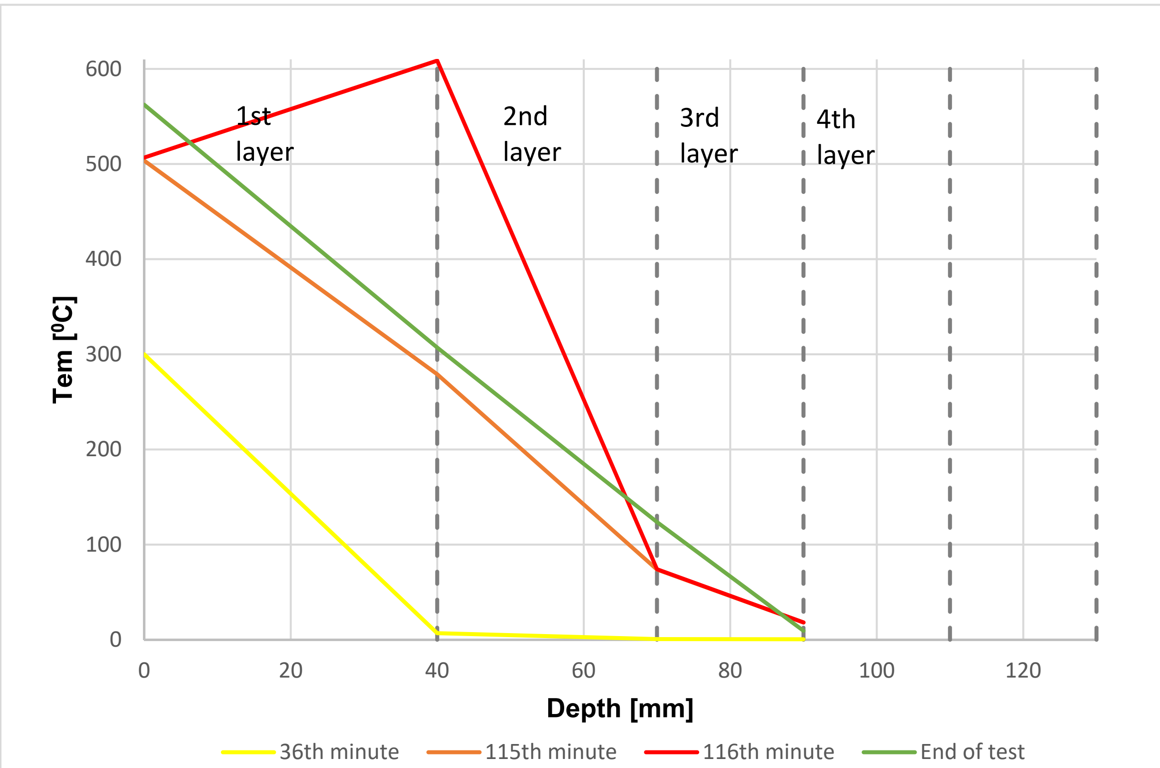


Figure 4.10. Characteristic temperatures in cross-section WB

4.2.2. CLT walls covered with gypsum board

Thermocouples WC1 and WD1 were located behind the first layer of CLT, which was covered with two layers of fire rated gypsum board. Temperature at these points did not rise above 67 °C. Considering the low temperature it is safe to assume that there was no charring behind the first layer of CLT at these locations.

Thermocouples K1 and K3 were placed behind the first layer of gypsum board. K2 and K4 were behind the second layer of gypsum board. The gypsum boards were fixed with screws with different length of 57 and 75 mm and spacing from centre to centre of 300 mm. The highest recorded temperature for K1 was 522 °C and for K3 548 °C. The highest temperature recorded on the first layer of CLT was 290 °C – nearly the temperature that is needed for timber to start charring (see Figure 4.13). As shown in Figure 4.12, minor charring occurred.

The fall-off times for 2-layer Gyproc fire-rated gypsum boards with stud spacing of 600 mm is 84.7 min **in standard fire** based on full scale fire test reports by SP Research Institution of Sweden [20]. The fire in test was extinguished on 138th minute. This 138-minute timeframe included two flashovers and cooling phases. During that time the gypsum boards did not fall off nor showed any signs of failure.

To compare the physically based fire with standard fire, charring behind the gypsum boards in standard fire was calculated. The charring is shown on the Figure 4.11. As there is no given equation in Eurocode 5 for failure time of two-layer type F gypsum boards, the equation from "Fire Safety in Timber Buildings" [21] is used. Other than the time of failure of the protection, values and formulas from Eurocode 5 are used [19].

The parameters needed for calculations are as follows:

$$t_f = 4 * h_{p,tot} - 40 = 4 * (2 * 15,4) - 40 = 83,2\ min \tag{4.7}$$

$$h_p = 15,4 + 0,8 * 15,4 = 27,7\ mm \tag{4.8}$$

$$t_{ch} = 2,8 * h_p - 14 = 63,6\ min \tag{4.9}$$

$$k_2 = 1 - 0,018 * h_p = 1 - 0,015 * 15,4 = 0,769 \tag{4.10}$$

$$d_{char,t=t_f} = \beta_0 * k_2 * \left(t_f - t_{ch}\right) = 0,65 * 0,769 * (83,2 - 63,6) = 9,8\ \mathrm{mm} \tag{4.11}$$

$$k_3 = 2 \tag{4.12}$$

Where t_f – time of failure of the protection, min

$h_{p,tot}$ – total thickness for gypsum boards, mm

h_p – thickness of gypsum boards, second layer is taken into account by 80 %, mm

t_{ch} - time of charring, min

k_2 – the insulation factor

k_3 – the post-protection factor

β_0 – the one-dimensional charring rate

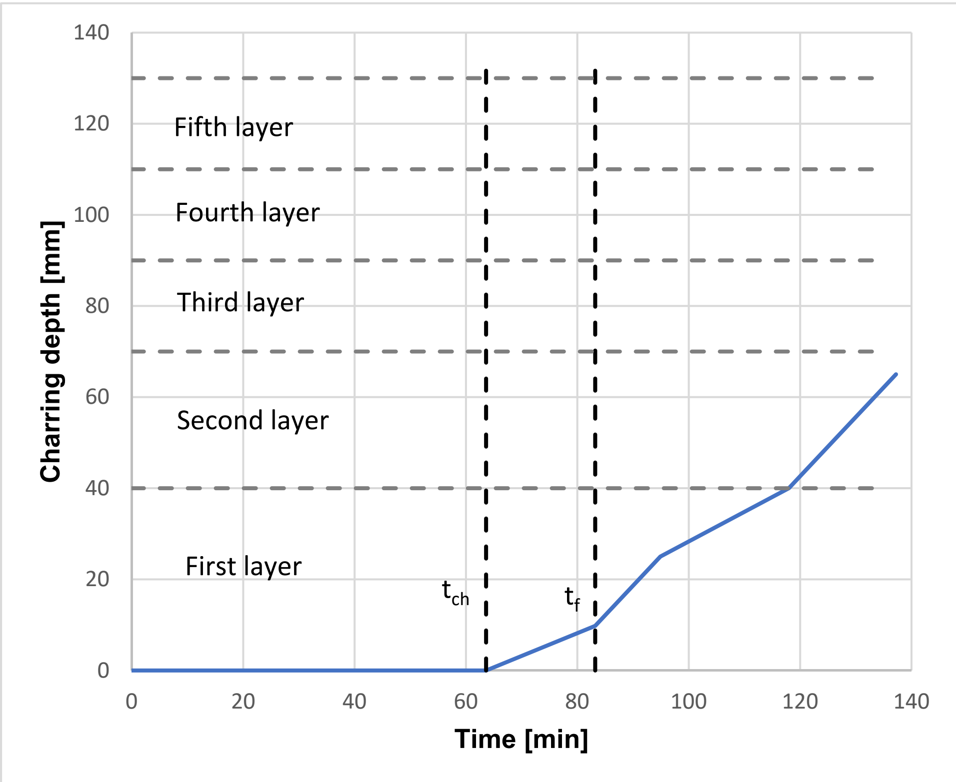


Figure 4.8. Charring behind two layers of type-F gypsum boards in standard fire

Figure 4.9. Location of K3 and K4

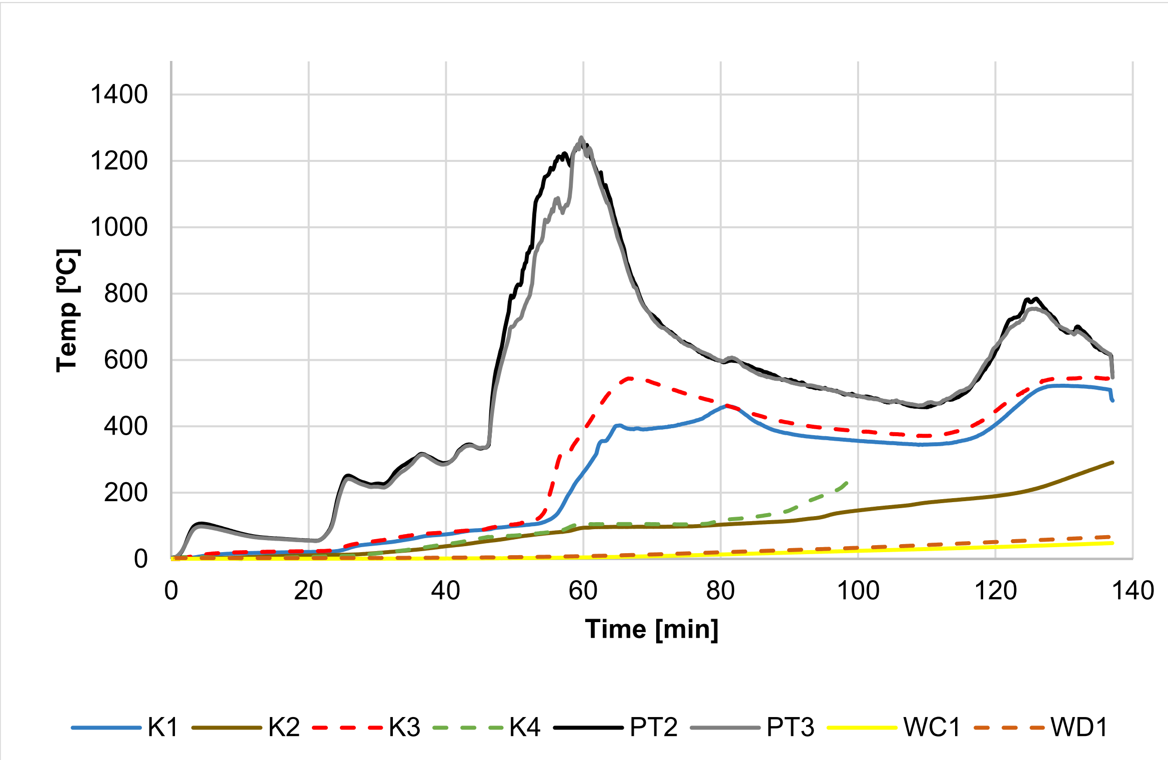


Figure 4.10 Temperature curve for thermocouples on walls covered with gypsum boards compared to plate thermometers

4.2.3. CLT ceiling

The CLT ceiling panel was covered with three layers of fire rated gypsum board. Thermocouples K5.1…K10 were placed behind every layer of gypsum board (see Figure 4.14). The gypsum boards were fastened the same way as the gypsum boards for walls using screws with spacing of 300 mm from centre to centre. During the fire, the gypsum boards did not fall off. The gypsum boards fell off during the fire brigade intervention (see Figure 4.16). The maximum temperature was 108 °C behind the third layer of gypsum board (so on the first layer of CLT) and 248 °C behind the second layer of gypsum board (see figure 4.15). There was no charring on CLT. This indicates that two layers of gypsum board would have been enough to avoid charring of cross-laminated timber.

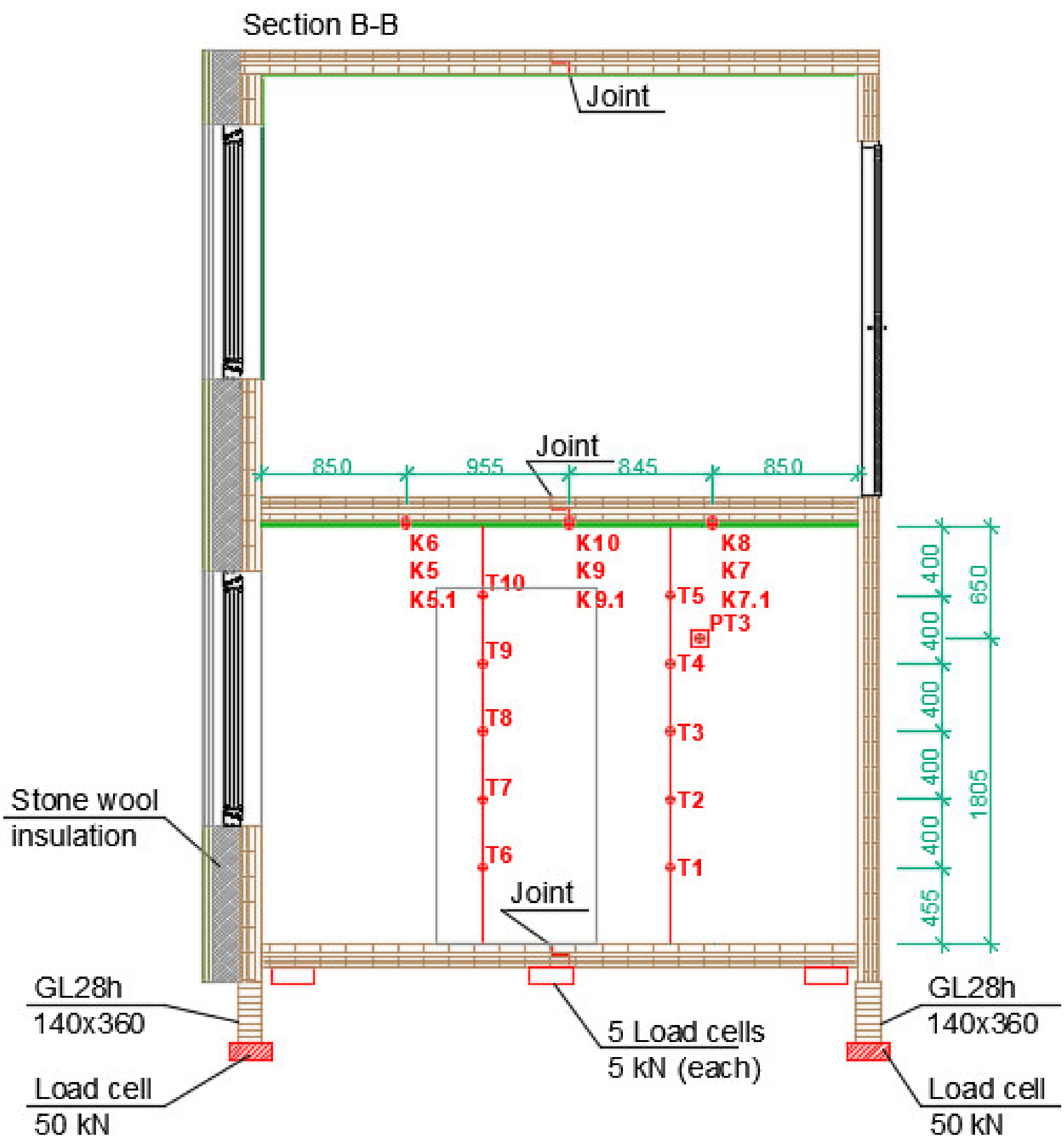


Figure 4.11. Ceiling thermocouples, thermocouple trees.

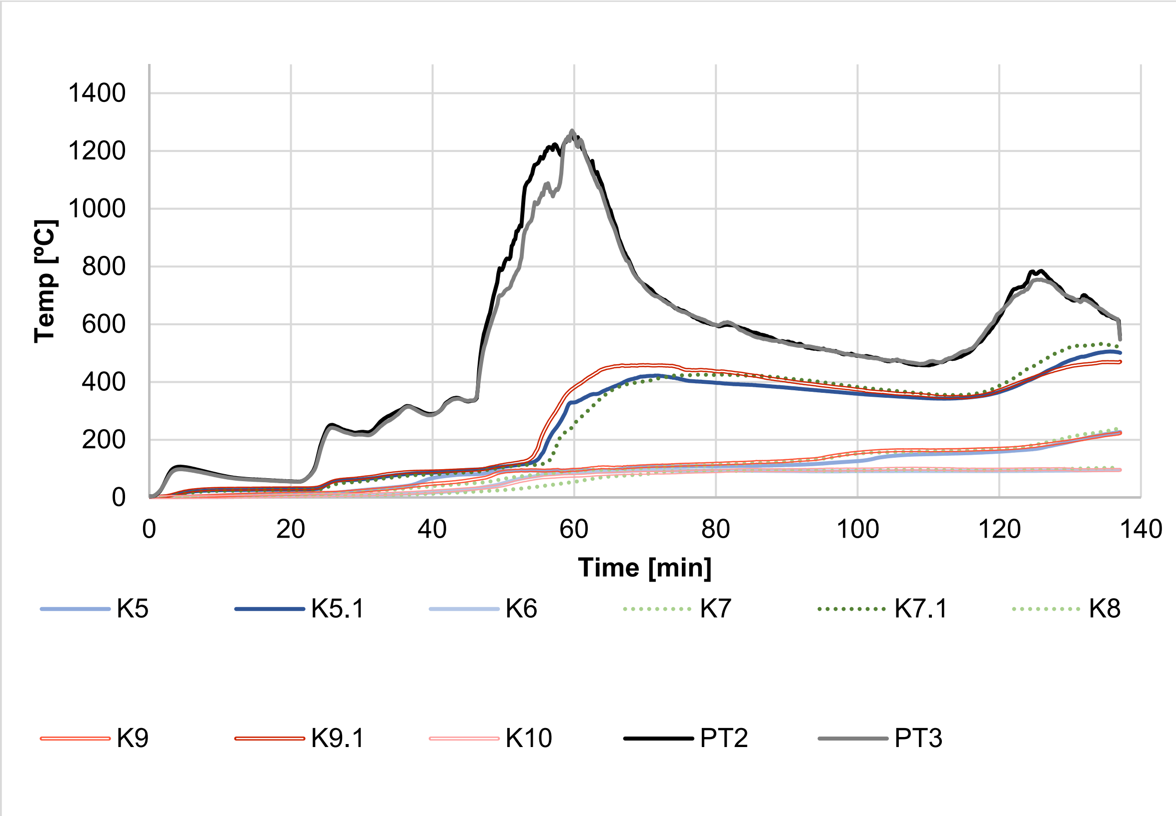


Figure 4.12. Ceiling gypsum thermocouples

Figure 4.13. The third layer of gypsum fell off during extinguishing

4.3. Test results compared to predictions and other tests

The predicted time-temperature graph and the actual measurements are quite different, as shown in Figure 4.17 and 4.18. The average temperature of thermocouple trees is the average value of thermocouples T1…T5 described in Figure 4.14 and 4.21. The first major difference is that in the predictions, it was presumed that the windows are open during the whole test. In the actual test, the windows were closed at first and broken on 21st minute. This, on one hand, shifted the temperature graph 21 minutes further. On the other hand, during the time when the windows were closed, the room temperature rose and the CLT panels were pre-heated prior to breaking the window and accessing a large amount of oxygen. This might be the reason why the peak temperatures were also higher than predicted, the self-extinguishment did not occur and the first layer of CLT fell off.

According to the prediction, the flashover was to occur on 4th minute. In the test, the flashover took place on 46th minute. The peak temperatures were reached on 62nd minute. The predicted rapid temperature growth did not occur, the causes could be the low outside temperature and used furniture's low reaction to fire. The fire was ignited on the sofa, so it remains possible that the sofa was affected by the low outside temperatures and humidity, so it did not burn as fast as hoped.

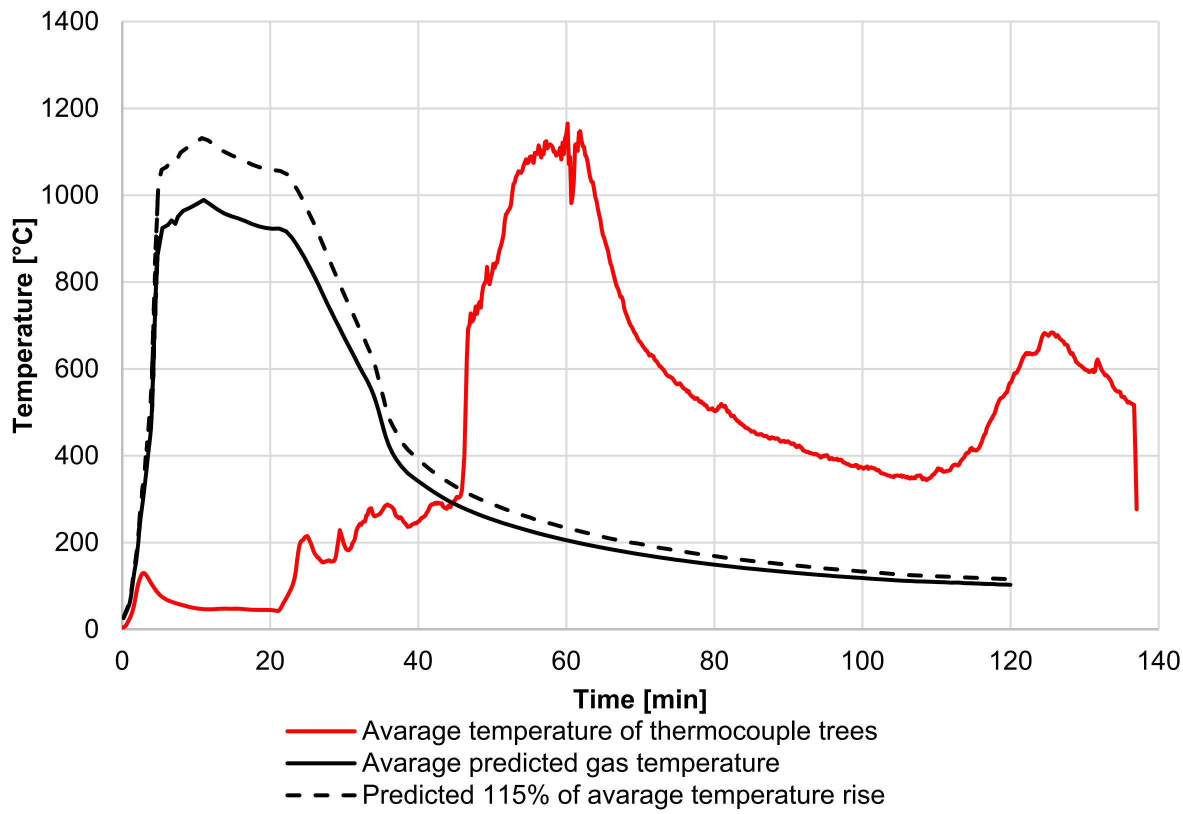


Figure 4.17. Test predictions [22] compared to results

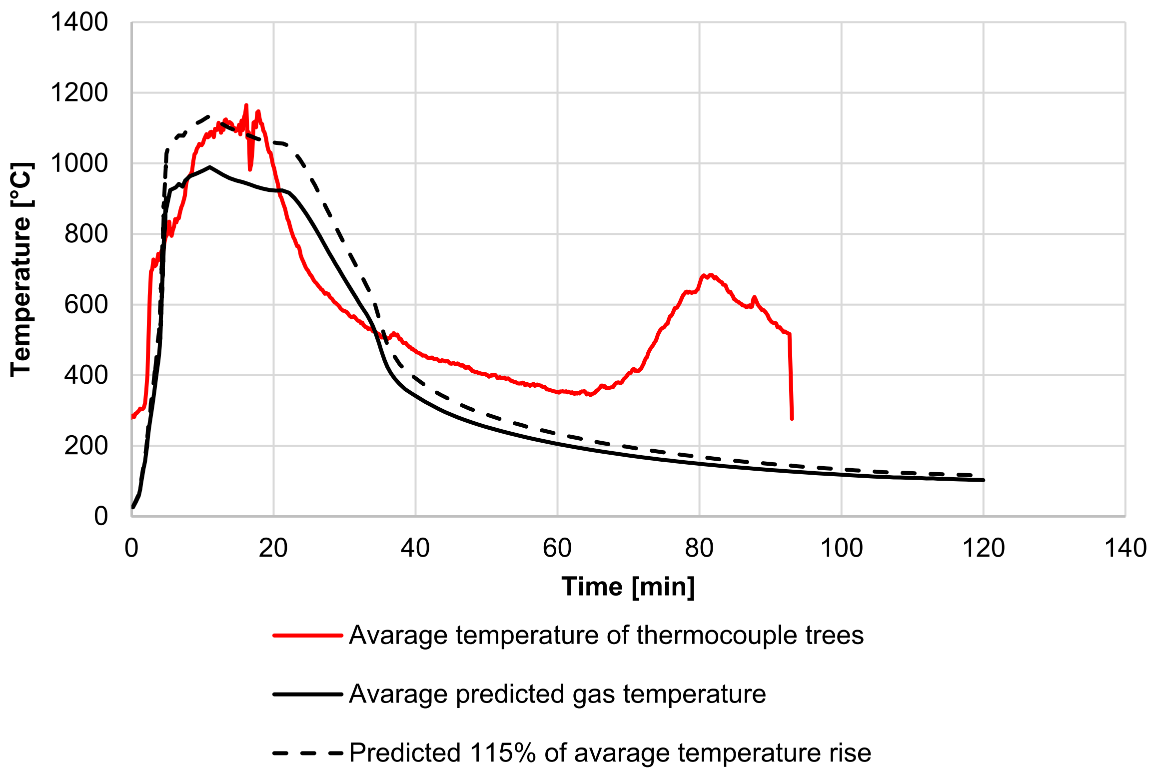


Figure 4.18 Test predictions compared to results. Time of the actual test is shifted by 45 minutes for better comparison

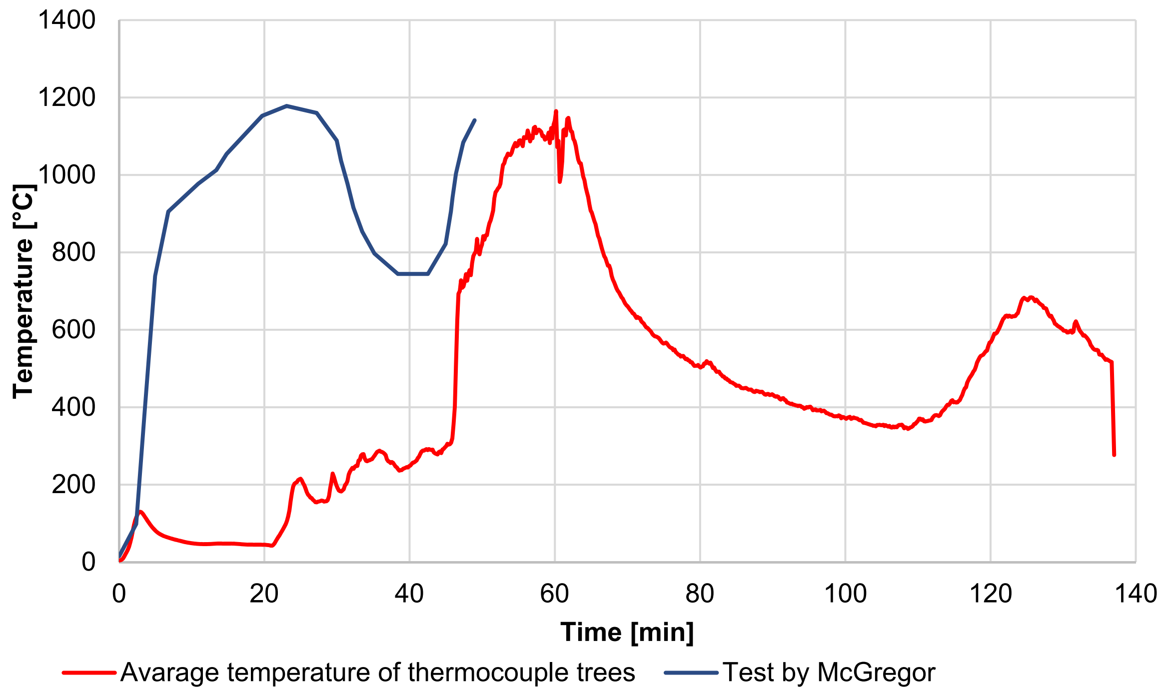


Figure 4.19. Fire test in Väike-Maarja compared to fire test by McGregor [21].

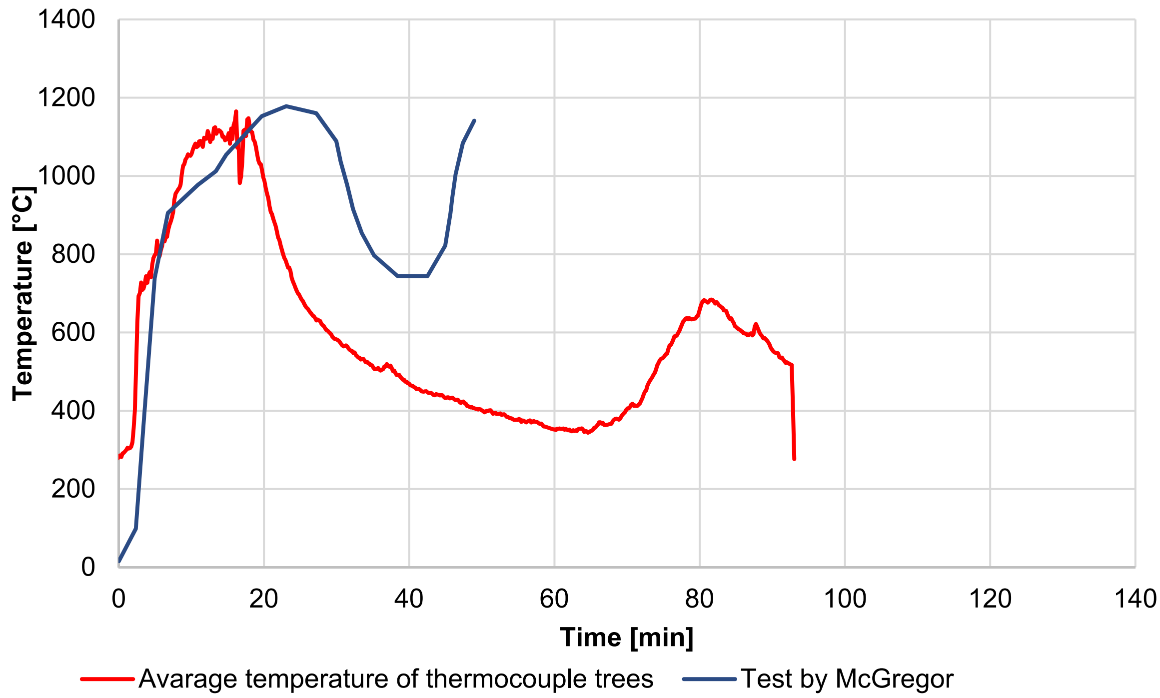


Figure 4.20. Fire test in Väike-Maarja compared to fire test by McGregor Time of Väike-Maarja test is shifted by 45 minutes for better comparison

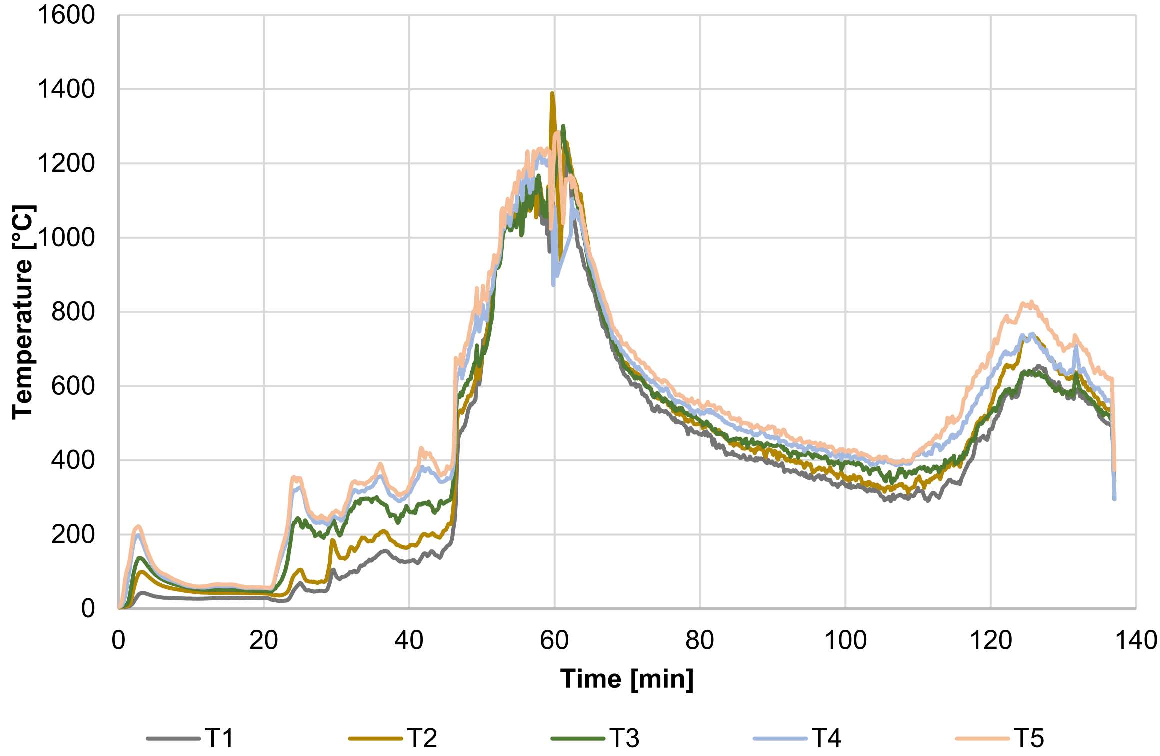


Figure 4.21. Room temperature, thermocouple trees

Compared to test performed by McGregor in 2013 [23] as shown in Figure 4.19 and 4.20, the second flashover in our test took significantly more time to occur. The test compartments and area of exposed CLT in both tests were equal in size. The fire load consisted of furniture in both tests. However, the test by McGregor featured only one opening sized 1100 x 2000 mm. Also, in McGregor's test, the CLT consisted 3 layers that were 35 mm thick. This causes the shorter cooling phase, the first layer chars and drops more quickly, therefore exposes the second layer of CLT which contributes strongly to heat release and leads to the second flashover.

4.4. On-site perpendicular thermocouples

In order to test the accuracy of on-site mounted perpendicular thermocouples, two of these were installed on-site. The PERP 60 was 60 mm from the outer layer of CLT, therefore it was located behind the second layer of CLT, which makes it comparable to thermocouple WB2 placed in the same wall. The PERP 90 was 90mm from the outer layer of CLT, so it can be compared to WB1 located behind the first CLT layer. Looking at the result shown on Figure 4.22, it is clear that the temperatures measured by these comparable thermocouples differ vastly. For example, on 110th minute, the temperature measured by PERP 90 was 131 °C and by WB1 221 °C. Temperature of 200 °C was measured on 102st minute by WB1 and on 121nd minute by PERP 90. The perpendicular thermocouples measure significantly lower temperatures. As it is a fact that the first layer of CLT fell off and the flashover occurred also in the second layer, the readouts of perpendicularly placed thermocouples are considered unreliable, especially for measuring charring rates.

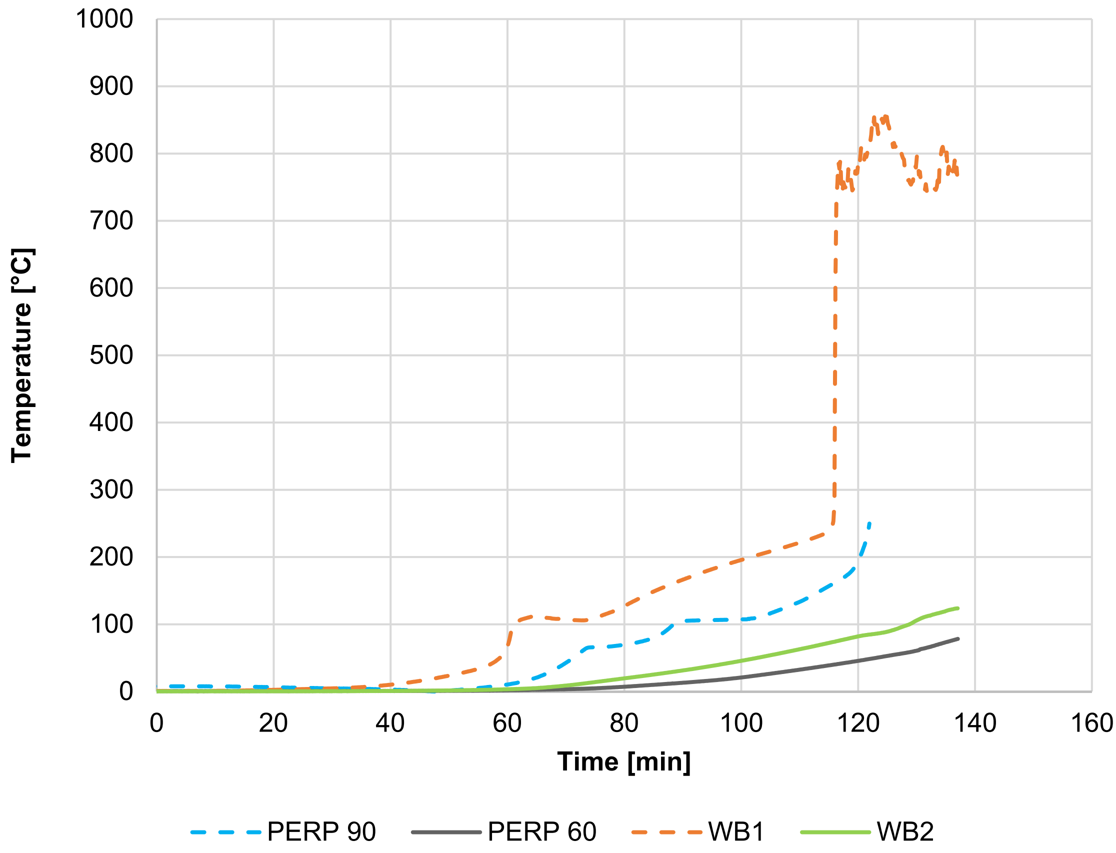


Figure 4.22. Perpendicular thermocouples

5. SUMMARY

The main purpose of the thesis was to analyse the behaviour of CLT structures in natural fires. The analysis is based on data collected from full-scale compartment fire test conducted in Väike-Maarja on November 1st, 2017, where the author of this thesis was present to install thermocouples and help with solving various problems.

Even though the test failed to demonstrate the self-extinguishment of cross-laminated timber, one of the main goals set for the test, it did not fail to illustrate the fact that it is possible to build timber constructions that are fire-safe. 93% of residents in Estonia have guaranteed access to fire brigade arrival in under 15 minutes [24]. In our case, if, for example, a neighbour sees the fire while flashover is taking place, there would be an hour and 13 minutes for fire brigade to intervene, before the second flashover will occur.

For CLT walls that were completely exposed to fire, it took 117 minutes on average for the char layer to fall off. However, for one wall, the fall-off of char layer occurred after temperatures at that point were higher than 300 °C, but on the second wall with exposed CLT, the fall-off took place before the temperatures reached 300 °C. This suggests that it is not possible to precisely predict whether the adhesive can keep layers bonded at critical temperatures.

In CLT walls that were covered with two layers of fire-rated gypsum board, the temperatures on the fire side of CLT reached nearly 300 °C and very minor charring occurred. This indicates that the two layers of gypsum was enough to avoid extensive damage to bearing constructions.

Three layers of fire-rated gypsum boards were used to cover the CLT ceiling panel. The highest measured temperature behind the second layer of gypsum was 248 °C. This indicates that two layers of gypsum would have been enough to avoid charring.

The results and predictions of the test were dissimilar. The flashover took considerably more time to occur and instead of self-extinguishing, the second flashover took place. For future tests I would like to propose having multiple predictions because of the varieties – e.g. windows can be closed or open, self-extinguish can happen in the first or second layer.

The perpendicularly placed thermocouples that were installed on-site measured temperatures that differed vastly from temperatures of thermocouples that were installed off-site.

Considering the outcome, 40 mm thick lamella on the fire side for CLT exposed to fire can be recommended given the opening factor is not greater than in the test.

6. KOKKUVÕTE

Käesoleva lõputöö eesmärgiks oli uurida ristkihtpuidu käitumist tegelikus tulekahjuks. Analüüsi aluseks olid Väike-Maarjas 1. novembril toimunud ruumtulekatses mõõdetud andmed.

Põhieesmärgiks seatud ristkihtpuidu isekustumist ei õnnestunud katses demonstreerida, kuid katset võib sellest hoolimata õnnestunuks lugeda. Katsetulemuste analüüsi põhjal saab tõdeda, et puidust on võimalik ehitada tuleohutuid hooneid. Eestis on 93% elanikkonnast tagatud tuletõrjeüksuse kohalejõudmine 15 minuti jooksul. Antud katse kontekstis, kui lahvatuse hetkel teavitatakse päästeametit tulekahjust, on päästemeeskonnal 1 tund ja 13 minutit aega sekkumiseks, enne kui teine lahvatus toimub.

Tulele avatud CLT seintel toimus tulepoolse lamelli ärakukkumine keskmiselt 117. minutil. Ühe seina puhul toimus lamelli kukkumine madalal ning teise puhul kõrgemal, kui 300 °C . Selle põhjal võib järeldada, et on võimatu ennustada täpset hetke, millal liim oma siduvad omadused kaotab ning lamell ära kukub.

Kahe tulekindla kipsplaadi kihiga kaetud CLT seintel ulatusid temperatuurid peaaegu 300 °C ristkihtpuidu pinnal. Paiguti oli võimalik katsejärgselt visuaalsel vaatusel näha ka vähest söestumist. Kahest kihist tulekindlast kipsplaadist piisas, et hoida ära tõsised vigastused kandvatele konstruktsioonidele.

Kolme tulekindla kipsplaadi kihiga kaetud CLT vahelael mõõdeti teise kipsikihi taga kõrgeimaks temperatuuriks 248 °C. Sellest temperatuurist lähtudes saab järeldada, et kahest kihist tulekindlast kipsist oleks piisanud CLT pinnal söestumise vältimiseks.

Katsetulemuste ja ennustuste vahel olid suured erinevused. Lahvatuseni jõudmiseks kulus katses tunduvalt rohkem aega, samuti ei saavutatud isekustumist. Tuleviku tarveks võiks kaaluda erinevate stsenaariumitega ennustusmudelite koostamist. Näiteks võiks vaadelda eraldiseisvana võimalusi, et aknad on avatud või suletud; isekustumine toimub tulepoolses või sellele järgnevas lamellis.

Katsetulemuste valguses võib öelda, et 40 mm on sobilik tulele avatud ristkihtpuidu tulepoolse lamelli paksus, kui ei ületata katses kasutatud avategurit.

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