TALLINNA TEHNIKAÜLIKOOL
INSENERITEADUSKOND

Ehituse ja arhitektuuri instituut

RISTKIHTPUIDUST MAJA RUUMTULEKAHJUKATSE – TULE LEVIK LÄBI LIIDETE JA LÄBIVIIKUDE

LARGE SCALE FIRE TEST OF CLT – FIRE SPREAD THROUGH THE JOINTS AND PENETRATIONS

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Tallinn, 2018

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Õppekava, peaeriala: EAEI 02/09, Tööstus- ja tsiviilehitus

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Konsultandid:

Lõputöö teema:

Ristkihtpuidust maja ruumtulekahjukatse – tule levik läbi liidete ja läbiviikude

Large scale fire test of CLT – fire spread through the joints and penetrations

Lõputöö põhieesmärgid:

1. Analüüsida ruumtulekahjukatses tule levikut läbi liidete ja läbiviikude

Lõputöö etapid ja ajakava:

Nr	Ülesande kirjeldus	Tähtaeg
1.	Väike-Maarja ruumtulekahjukatse. Ettevalmistus ja abi läbiviimisel	1.11.2017
2.	Kirjanduse uuring – praktikas kasutatavad ristkihtpuidu liited	
3.	Katseandmete analüüs	
4.	Järeldused ja kokkuvõte. Soovitused	
5.	Renoveerimislahenduste ettepanekud	

Töö keel: inglise või eesti **Lõputöö esitamise tähtaeg:** "28" mai 2018.a

Üliõpilane: Mihkel Karuse ....

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/allkiri/

Juhendaja: **Alar Just** ....

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1. INTRODUCTION

In today's world, society is working towards a cleaner and more sustainable living environment. Being a big part of modern society, construction industry is also leaning towards using the most environment friendly and energy efficient materials and methods to produce buildings. Therefore, during recent years, timber framed structures have seen a surge of interest from clients and construction companies alike. If executed well, timber buildings are less energy demanding, less polluting for the environment as well as visually and aesthetically pleasing. When using pre-fabricated elements and modules, i.e. glued laminated timber (glulam) or cross-laminated timber (CLT), timber buildings provide a quick, hassle-free and easy solution during on-site installation, as well as minimize worker downtime and optimise raw material usage, producing less waste. Properly designed timber buildings are very durable against environmental hazards and can be made to be very energy efficient and even very protective against fires. Wood offers a good weight-to-strength ratio, therefore timber framed buildings are a very popular choice for a one- to three-storey building. However, using massive timber materials such as glulam or CLT, which can withstand greater forces than a regular timber frame, the construction of larger-scale and higher office- or apartment buildings is possible as well. Moreover, the massive solid wood panels offer more airtightness and fire-resistance over a traditional timber beam and column frame.

Higher demand for indoor exposed wooden surfaces may also be related to the fact that humans' psychological and physical well-being is heightened when being in an exposed timber room. A study conducted by Zhang et al. [1] studied and compared the effects of work environments made with different materials (steel, concrete, timber). The authors have stated that giving concrete results about human behaviour with such a small sample is difficult [1], however, having ran a simultaneous test, the results agreed with each other. Therefore, according to the test results, it can be said that humans have more positive emotions in wooden rooms, especially after working and they feel less tension, depression and more vigour [1]. Furthermore, working in a non-wooden environment seems to be more likely to produce fatigue [1]. The survey method used an emotion questionnaire and fatigue self-assessment, which showed that wooden indoor environment has the potential to restore the ability to regulate emotion and relieve stress [1]. Considering these results, the usage of more and more open timber surfaces indoors is a very welcome step towards the well-being of humans working in those compartments.

Timber framed buildings, especially larger and higher buildings, are under tight design and building regulations regarding fire safety. The basic understanding is that timber is an easily combustible material, therefore being dangerous to the inhabitants of a structure in case of fire.

However, due to the increased interest towards using wood as a load-bearing material and facade cladding, more research is being conducted to study how different timber frame types, elements, joints, materials and material systems work in a case of fire. Tests have also been carried out to show how fast response sprinkler systems influence the combustible construction on fire safety, and how these sprinkler systems help quickly contain a fast spreading fire [2]. Moreover, it's a known fact that after a while, the char layer on burnt wood starts acting as a protective layer, preventing further burning. With all the new research made in the last few decades, new design and building principles are emerging, however more definitive research must be conducted, especially for using exposed massive timber frames.

The main problem with exposed CLT panels in a compartment fire situation is the CLT's own contribution to the fire load of the compartment. In recent years, more and more research has been conducted to explore the possibilities of auto-extinction in CLT. A full-scale compartment test was organised in Väike-Maarja to study that phenomenon. Auto-extinction in CLT happens when the temperature drops below 300 °C in the decay period of a fire, which effectively ends further charring of wood, and the layer of char acts as a protection for the timber. Based on the conducted experiment, three theses were written, each analysing different aspects of the test (CLT, joints and penetrations and facades). The author of this thesis played a part in the setup of the test house by installing thermocouples and other measurement devices as well as helping solve problems during the erection of the house.

Some of the previous tests have been carried out on an element level and some have researched a full-scale compartment fire. A small-scale example of this is a series of tests carried out by Frangi et al. [3] to evaluate the charring rates of CLT panels which used different adhesives. Their test used CLT panels with the dimensions of 1,15x0,95 m. The panels were comprised of a different number and thickness of lamellae (10, 20, 30 mm) [3]. A 30 mm board was glued on to the side unexposed to fire which allowed complete charring to take place [3]. The test results showed that the fire behaviour of CLT panels strongly depends on the adhesives used and that when char layer falls off, the lamella underneath chars with increasing rate due to being pre-heated [3]. They also concluded that panels with thick layers had a better fire behaviour and that the load-bearing capabilities of CLT elements are not linearly related to charring [3].

Another small-scale test studied only the structural responses of compression elements in case of fire [4]. The series of tests found the load-bearing failure is caused by three effects induced by charring: (1) reductions in the strength and stiffness of the timber material; (2) increases in the effective slenderness of the column and effective eccentricity of the applied load and (3) reductions in the size of effective cross-section available to resist loads [4].

A large-scale compartment fire test has also shown the self-extinguishment of CLT, with no occurrence of delamination [5]. However, the compartment in the mentioned test had a smaller opening factor as well as a smaller compartment and the fire-side lamellae were thicker [5] than in the test of Väike-Maarja. Moreover, the test had an exposed ceiling and one wall [5], whereas the test described in this thesis used two opposite walls as exposed to fire. Therefore, the results from this test will help build upon results already set in place.

Two other examples of large-scale tests were carried out in 2013 and 2014. The first of these is a 5-part series of tests conducted by McGregor [6] and the second is a 3-part series by Medina Hevia, which follows the tests done by McGregor [7]. Both tests used the same compartment size [6, 7] as the test in Väike-Maarja, which makes it possible to compare the results of the experiments when using different parameters, i.e. opening factor, fire load and the CLT panel's cross-section. In his tests, McGregor used different ways to generate the fire load (furniture, propane) and some tests used fully protected rooms, whereas others did not [6]. Each of Medina's three tests used furniture and clothes as fire load with propane ignition [7]. McGregor concluded from his tests that in fully protected rooms, CLT does not contribute to the growth, duration or intensity of the fire after all combustible material is consumed, but only if the gypsum boards do not fail [6]. In case of gypsum failure, CLT contributes to the fire [6]. Unprotected CLT significantly contributes to the fire, and when delamination occurs, the revealed lamellae provide fuel, which could lead to another flashover, possibly eventually leading to structural failure [6]. The conclusions made by Medina Hevia included that open CLT surfaces contribute greatly to the fire and the temperatures in rooms with unprotected walls dropped at a slower rate [7]. However, the test with only one unexposed wall managed to self-extinguish, similarly to McGregor's test with a fully protected room [7].

In addition to the main purpose of showing the self-extinguishment of CLT, the test in Väike-Maarja also set out to explore and analyse joint solution designs as well as testing materials used to insulate different penetrations as this has not yet been well-documented before. This thesis aims to analyse and document the behaviour of joints and penetrations in a case of a compartment fire. Joints and penetrations are a vital part of fire regulations because fire and smoke could easily spread through them to neighbouring compartments or buildings. There are a lot of different ways to connect CLT panels to each other, and much research is yet to be done regarding the fire safety of those joints. Some of the more popular and simple examples of joint design, amongst of which some were tested in Väike-Maarja, are presented below. The example schemes used are from M. Mohammad's presentation at the UMass Wood Structures Symposium in 2011.

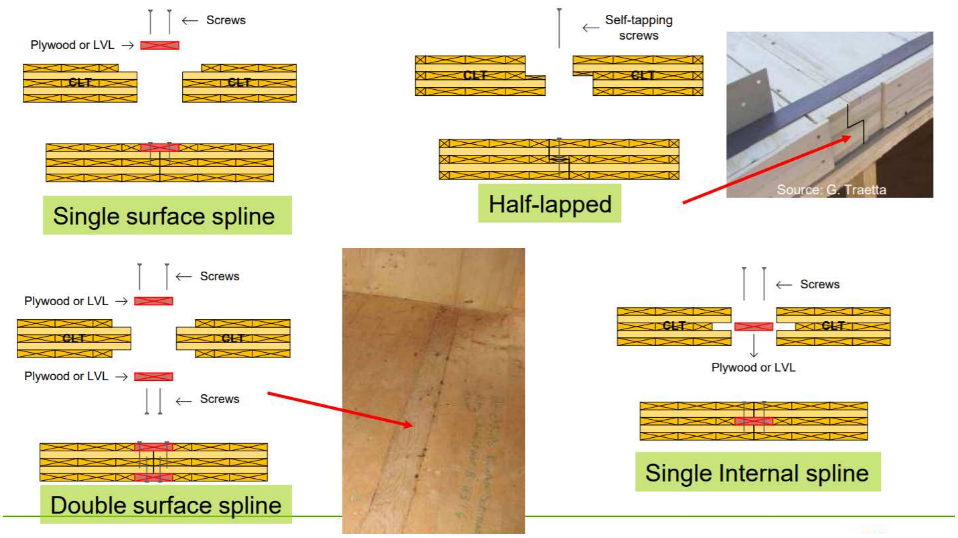


Figure 1.1 Easy-to-assemble examples of continuation of panels [8]

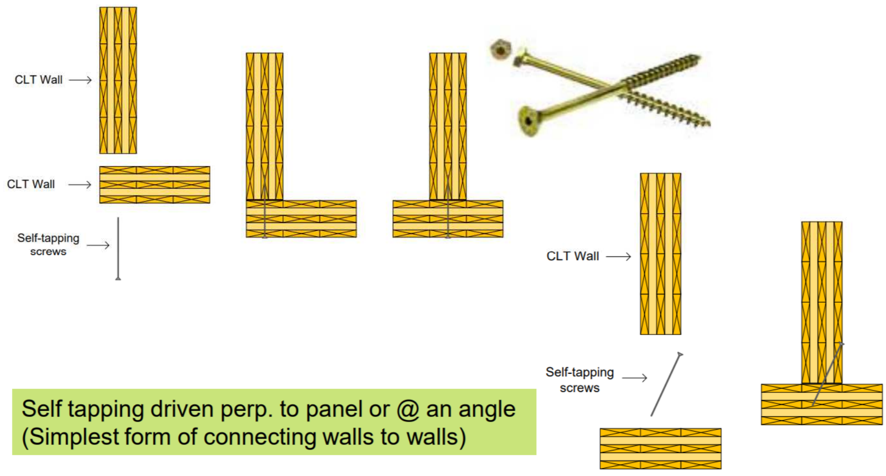


Figure 1.2 Examples of wall-to-wall connections [8]

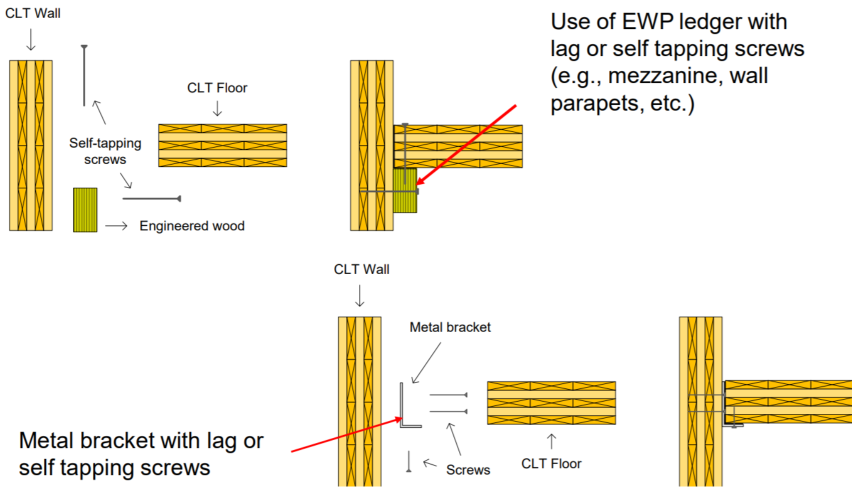


Figure 1.3 Examples of wall-to-floor joint designs [8]

McGregor did not focus a lot on the analysis of joints in his test reports, however, he mostly mentioned the temperatures of joints during the tests, which usually peaked at around 100 °C. In his first test, no sealant was used, and hot gases were observed escaping the joints and even in latter tests with a sealant, some degree of gases was still observed to be escaping. In his fifth test, a joint failed and higher temperatures were observed, indicating the transport of gases from the fire [6]. In Medina Hevia's series, one test saw a critical failure of a joint, which used no sealant, after which caulking was used to seal lap joints. He concluded that using a caulking sealant is needed to prevent hot gases from escaping the joint and to prevent flaming outside the room [7].

Even though penetrations through fire rated assemblies should be avoided if possible, sometimes such penetrations must be used. Therefore, research has been done to develop fire safe penetration sealing materials. An example of this is the study conducted by Werther et al. [9]. Their results were presented at the 2012 World Conference on Timber Engineering. They tested penetration materials, and from the results concluded, that the selected approved penetration sealing materials and systems for separating timber elements are in accordance with the specified design restrictions. No early failure of the penetration occurred in a case of fire [9]. The fire test in Väike-Maarja was a superb opportunity for manufacturers to test how their sealing materials and systems work in case of a compartment fire.

2. TEST DESCRIPTION

The test description was co-written with Hannes Härma 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 [m^2]**	**Volume [m^3]**	**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

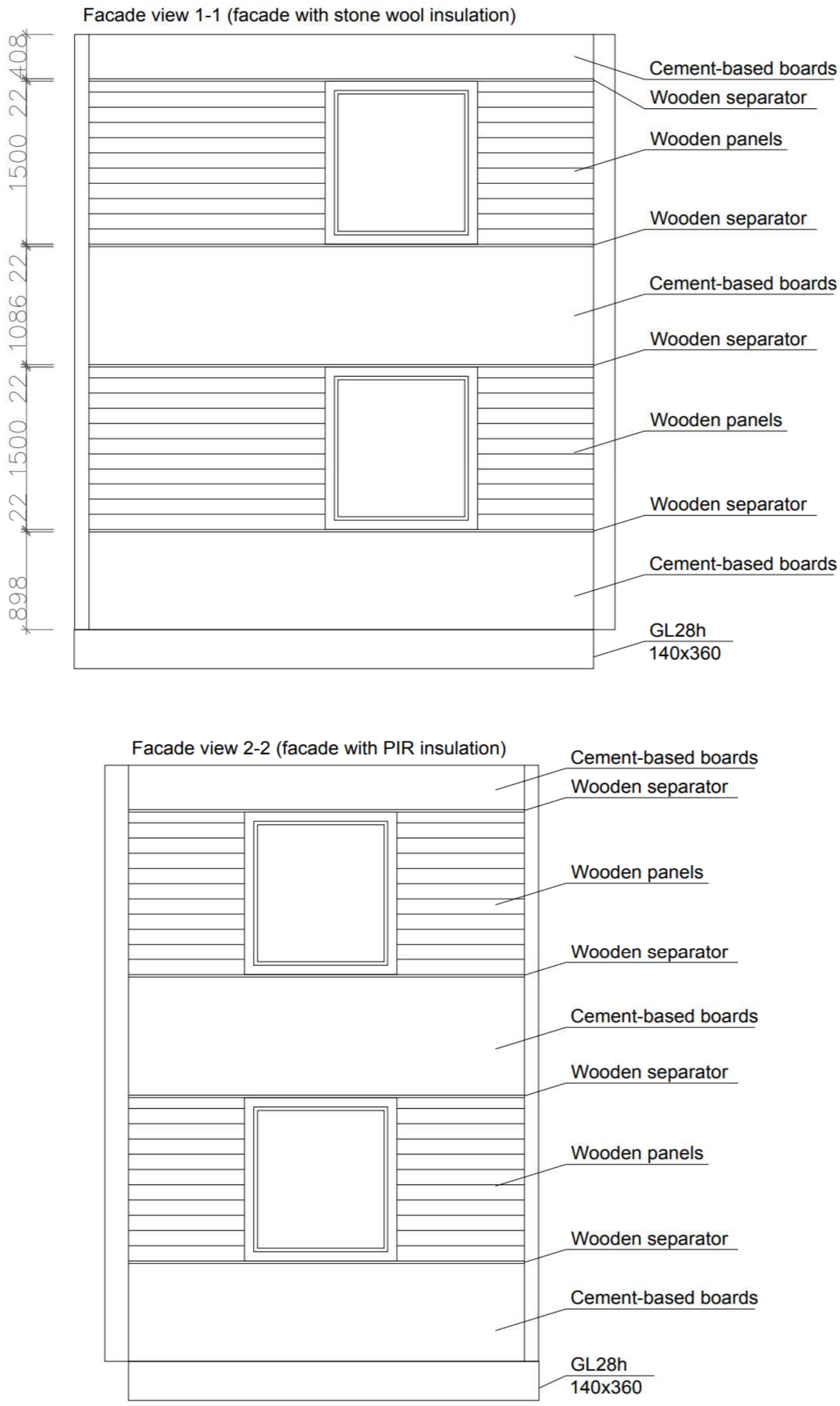


Figure 2.1 Facade views of the test house

The test house was designed with special attention to fire safety. The CLT layers were made thicker than usual, varying from 20mm on the outside and 40mm the fire side. 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.

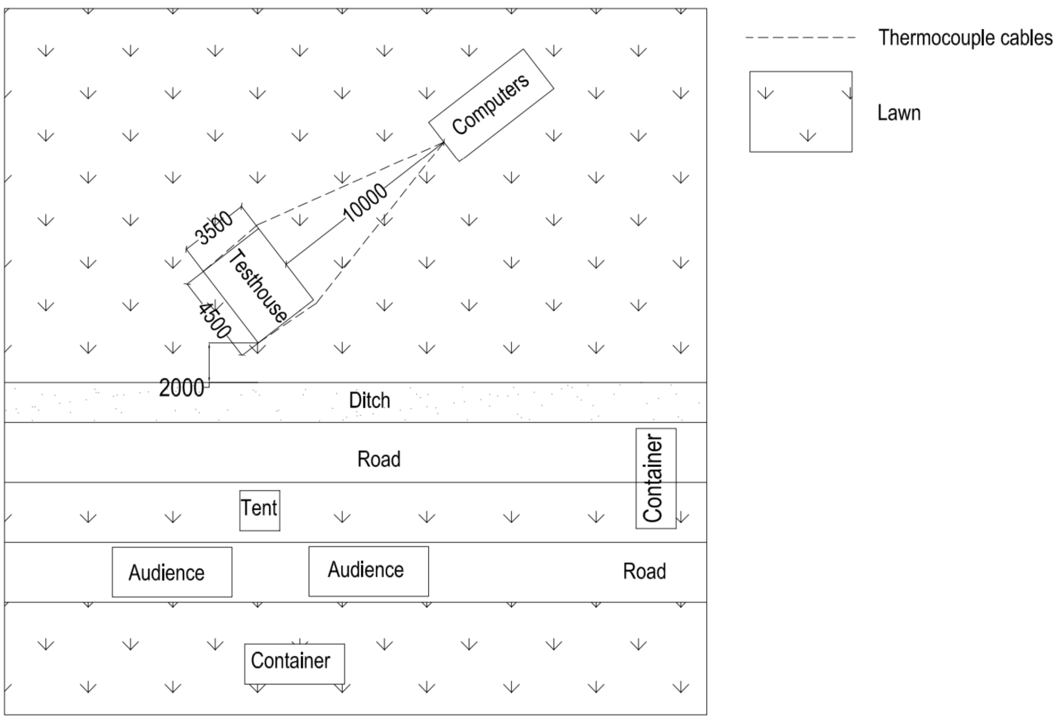


Figure 2.2 Site plan

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

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

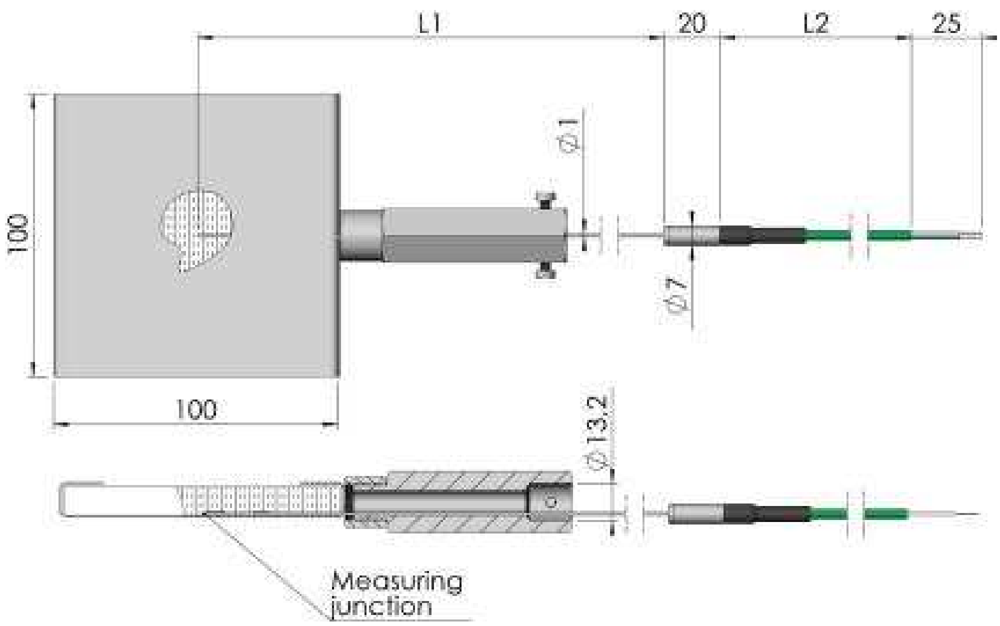


Figure 2.3 Plate thermometers. Image: Pentronic.se

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 [10]. This concept provides a simple design to approximate a post-flashover compartment fire [11]. 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 [12]. 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 [12]. The curve accounts for the fuel load, compartment size, thermal properties of the walls and ceilings and ventilation conditions [11]. 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 [13]. 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 [14].

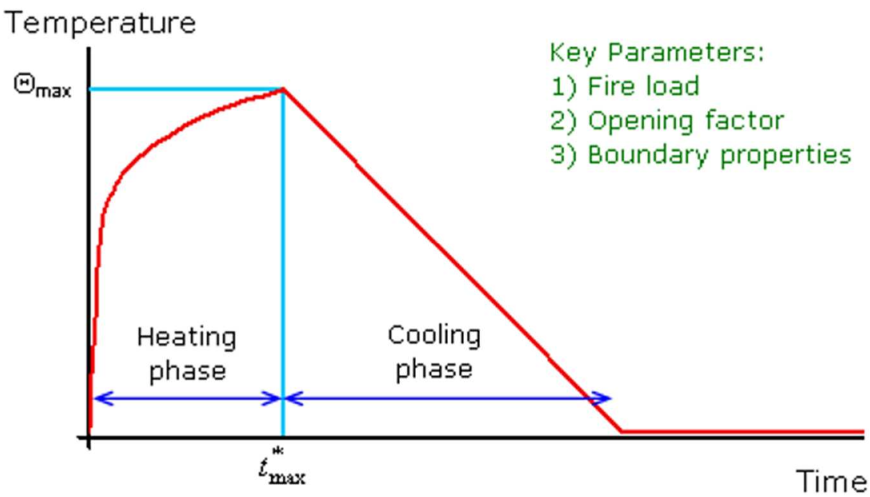


Figure 2.5 Standard physically based fire curve, Θ_{max} – maximum temperature, t^*_{max} – fire duration [14]

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 [15], which lists different materials' burn loads per weight unit. The used table is presented in Table 2.2:

Table 2.2 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 Table 2.3 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 2.3 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"	15,75m²		
	Needed burning load to achieve 600MJ/m²	9450	**Current burning load [MJ/m²]**	**600**

*Polyurethane density ρ = 43,65kg/m³ (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 [13].

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 2.4 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 2.5 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.

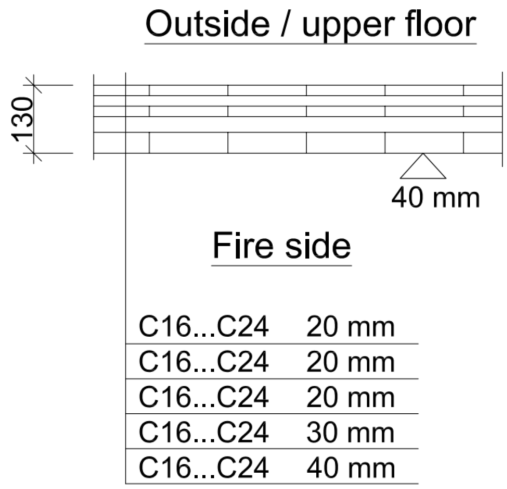


Figure 2.6 CLT panel cross-section

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 100 mm, fastened by self-tapping screws spaced 150 mm apart, see Figure 2.7.

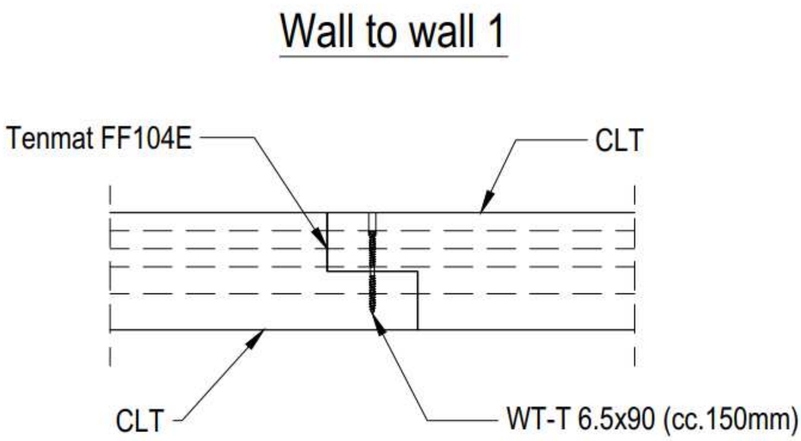


Figure 2.7 CLT+CLT overlapping joint

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 200 mm, see Figure 2.8.

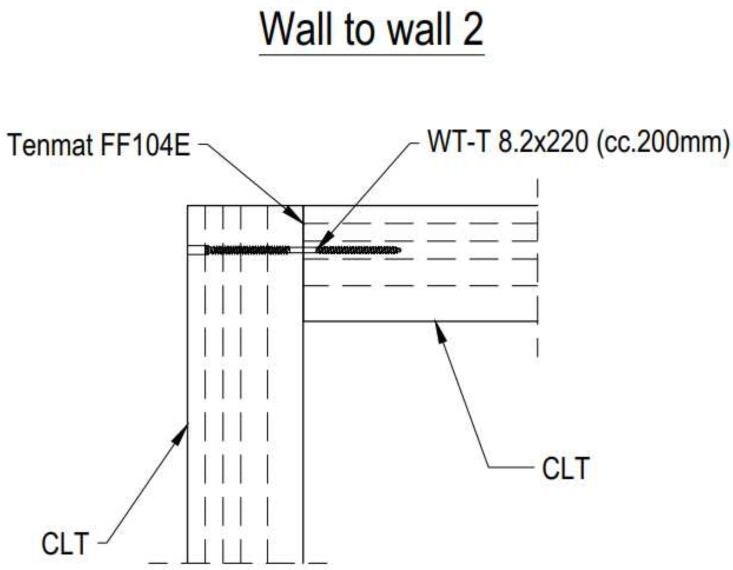


Figure 2.8 CLT + CLT corner joint

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.

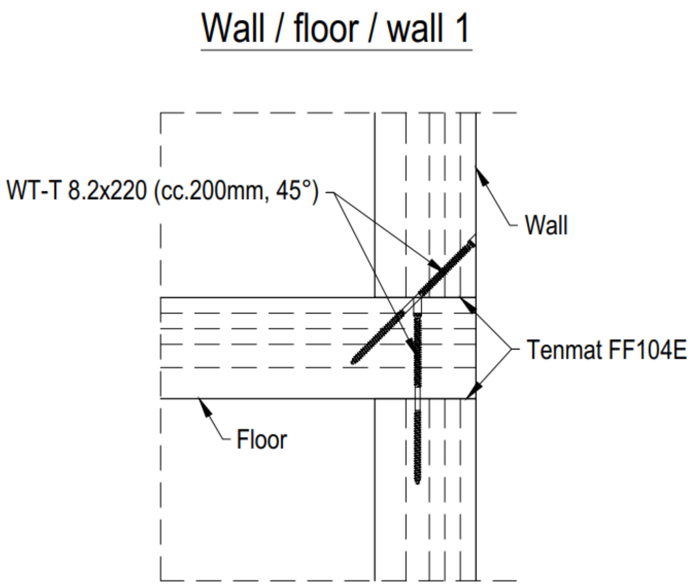


Figure 2.9 Wall-floor-wall joint to be used in smaller buildings

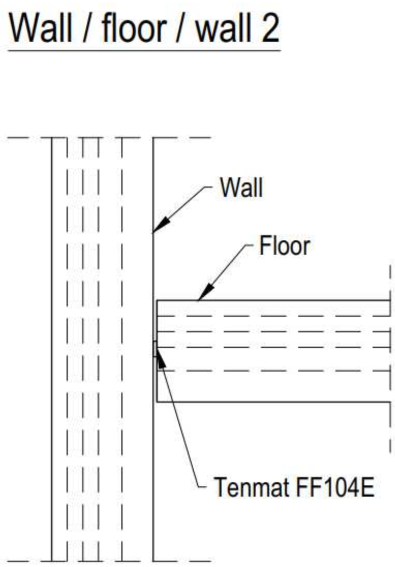


Figure 2.10 Wall-floor-wall joint for larger buildings

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 [16].

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 [17]. The wall around the penetration hole was insulated from the fire with two layers of Protecta FR Board [18], 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 [18]. 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 [19].

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 [20].

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 [21].

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 EI30 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. See Figure 2.13.


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, see Figure 2.14.

Figure 2.14 Flames are reaching the facade of the upper floor

0:46:42 The first flashover occurs, see Figure 2.15**.**

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 (see Figure 2.16). 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 (Figure 2.17). 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, see Figure 2.18.

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. RESULTS AND ANALYSIS

3.1. Analysis and comparison of joint temperatures during the test

Different types of joints were used in this test. As described in paragraph 2.6.1, two different wall-floor joints and a CLT + CLT overlap joint were tested. Another thing to note is that as the house was built with maximal fire resistance in mind, the joints were also made as airtight as possible. Therefore, after the erection of the building, joint connections were also covered with an airtight highly adhesive tape in their entire span.

3.1.1. Joint thermocouple locations

Thermocouples were used in the test to measure temperatures in different points during the fire. The lower floor had three joint thermocouples inside the walls. As shown on Figure 3.1, one was situated in the corner, close to the ignition point of the fire and the two other joints were placed inside the overlapping wall joints.

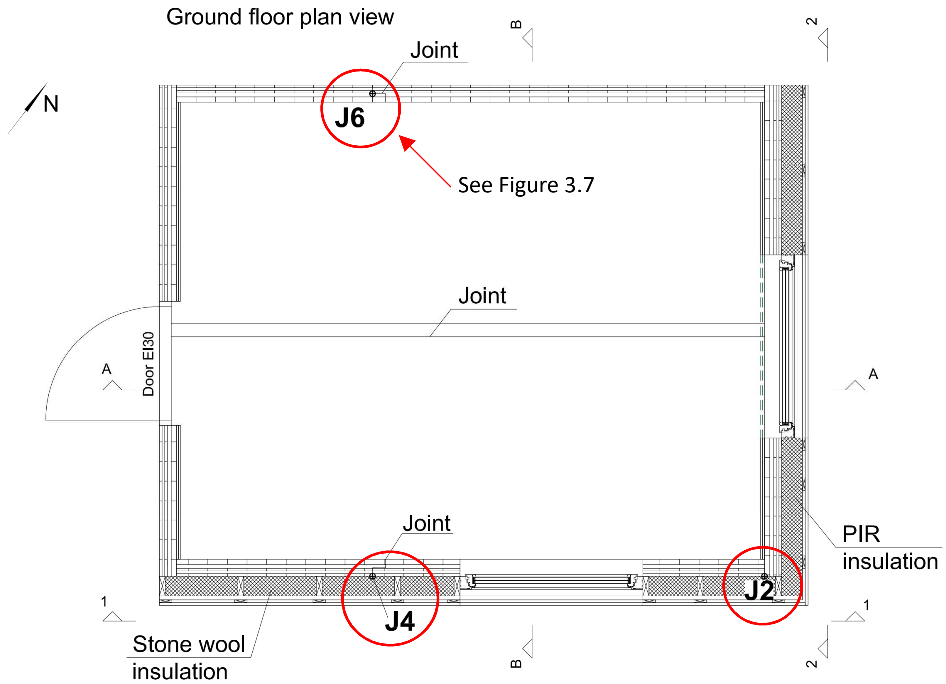


Figure 3.1 Joint thermocouple locations of the lower floor

Thermocouples for the joints on the upper floor were placed near or inside the joints of the floor panel. These thermocouples were used to keep track on how well the upper floor was isolated from heat and fire for the duration of the compartment test. Upper floors thermocouples were placed inside the floors overlapping joint in two locations and just above both wall-floor joints, which are shown on Figure 2.10. To analyse the joint shown on Figure 2.9, a thermocouple was also placed just below and above of said connection.

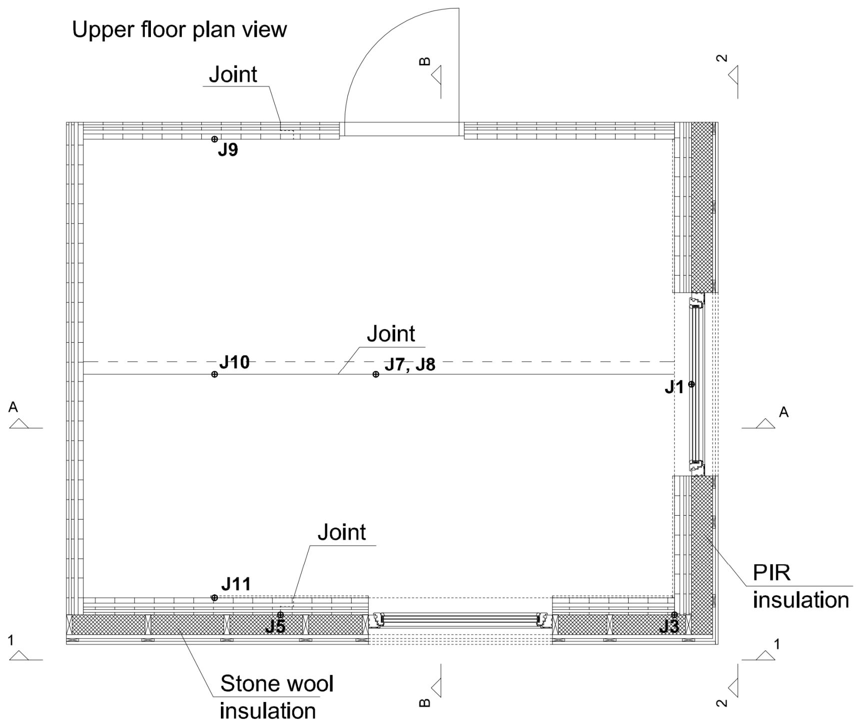


Figure 3.2 Joint thermocouple locations of the upper floor

Lower floor's wall joint thermocouples were placed near the center part of the wall. Vertical locations for joint thermocouples are shown on Figure 3.3 and Figure 3.4.

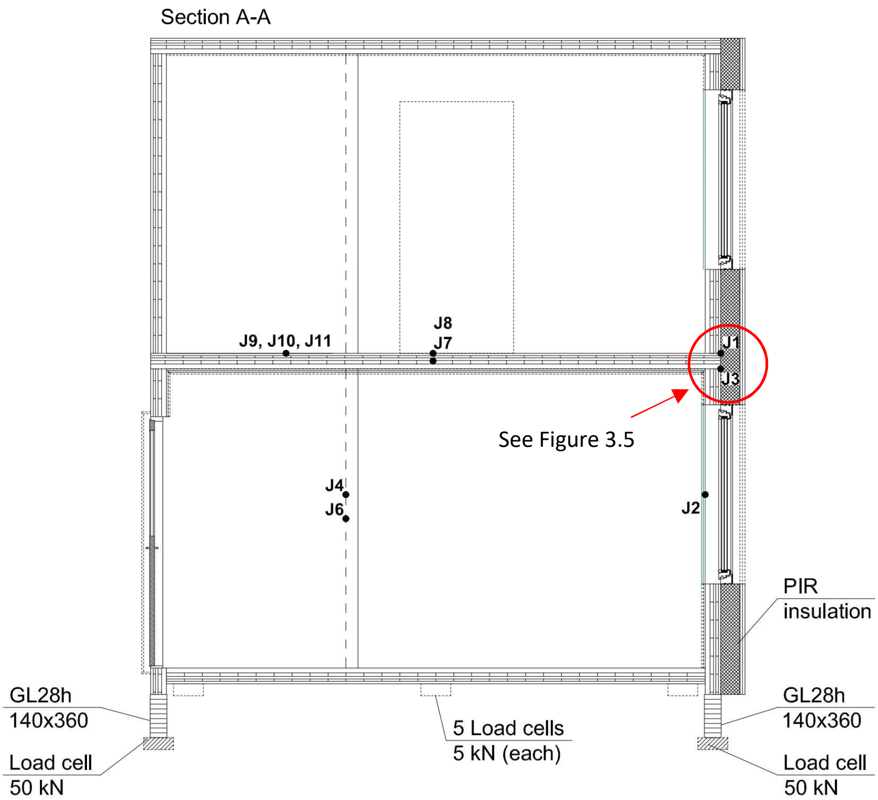


Figure 3.3 Section A-A, vertical locations for thermocouples

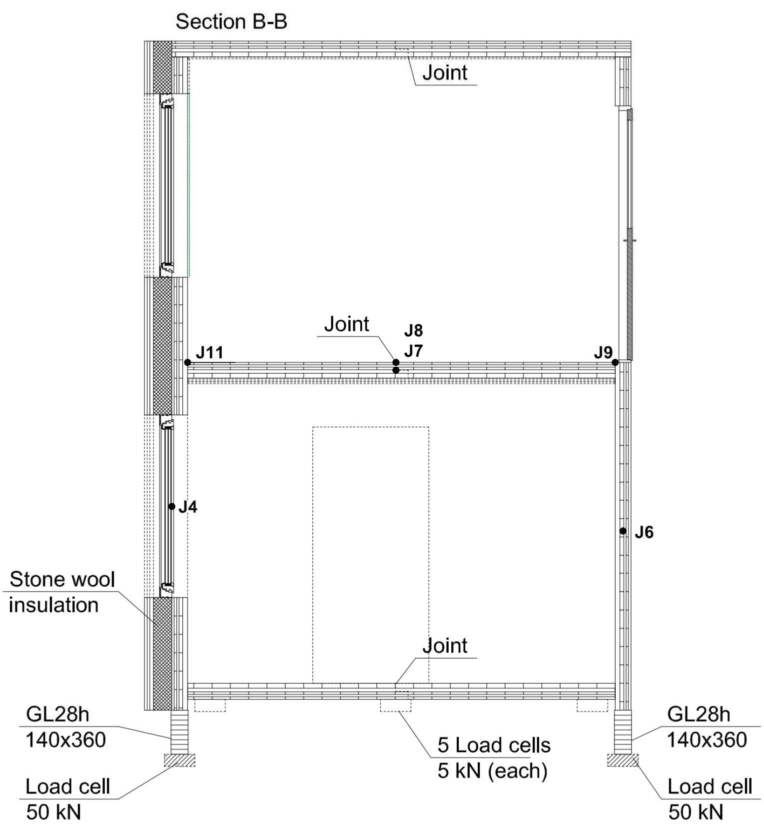


Figure 3.4 Section B-B, vertical locations for thermocouples

3.1.2. Lower floor

Data recorded during the test has shown that temperature within the joints was extremely low for the first 58 minutes of the test, after which a sudden spike can be seen for the thermocouples labelled J2 and J3. This is shown on Figure 3.6. The location for J3 can be seen on Figure 3.2 and Figure 3.3. As seen from the figures, J2 and J3 were both near the ignition point of the fire with J2 being in the middle of the wall panel, placed between the panel and stone wool insulation and J3 placed behind the wall-floor joint.

The sudden temperature rise is thought to be caused by heated gases penetrating the joint after the flashover occurred, which also set all the gases on fire. This means that the joint was not 100% airtight and the heat from the flashover pressed through between the gypsum edges and CLT. Another thing to be noted is that these wall corners did not have gypsum from two sides, but only from one.

As the temperatures rose up to between 250 °C and 350 °C, the intumescent paper was supposed to start expanding inside the joint. However, since the thermocouples were placed on the outer side of the CLT panel, behind the joint, it seems the temperature rise was so sudden that the intumescent paper did not react or expand as quickly, which is why the thermocouples instantly jumped to such a high temperature. After a couple of minutes, the temperatures suddenly dropped, indicating that the intumescent paper reacted and sealed the joint, thus preventing further penetration of heat and fire.

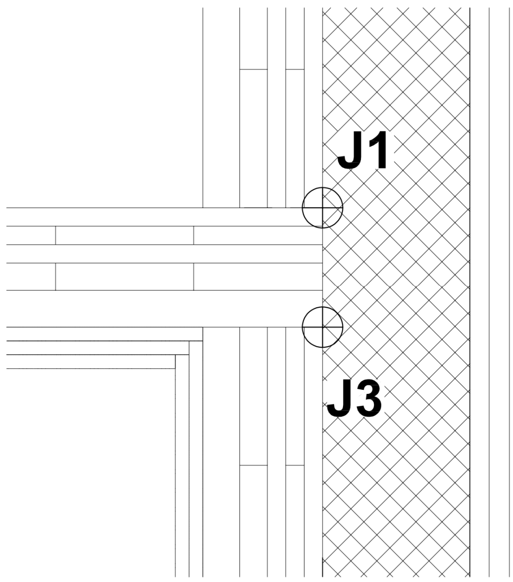


Figure 3.5 Gypsum covering the joint from one corner

An overlapping joint as such could be able to entirely seal the connection and shield it from heat, if guaranteed to be built very accurately and tightly. An additional recommendation would be to add another strip of intumescent paper behind the gypsum, just to where the CLT + CLT joint starts. This would ensure the fire and heat never to spread through the joint.

The same explanation can be given for J2, since it was placed in a similar manner, but on a different height on the wall joint.

Moreover, as the thermocouples were placed on the outer surface of the CLT panel, the same data can also be used to say that the stone wool on the facade also worked extremely well in insulating the timber from the fire on the facades.

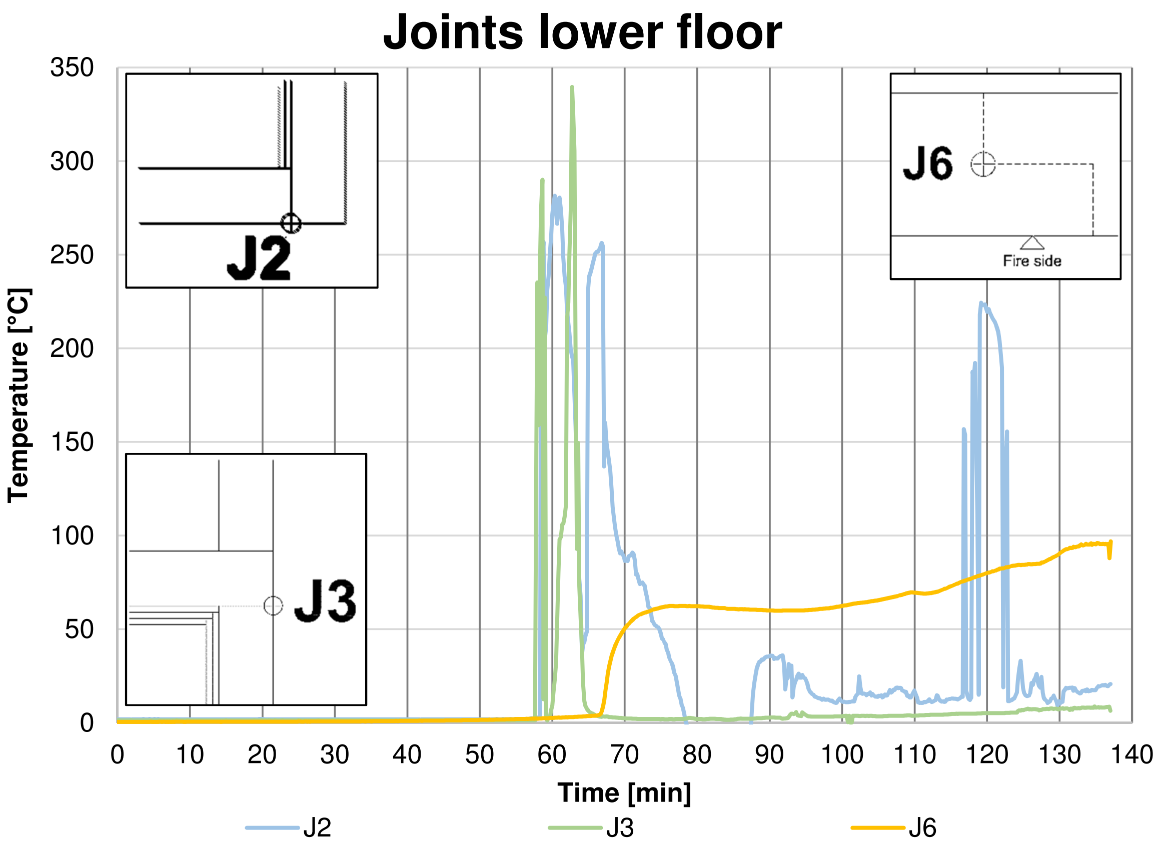


Figure 3.6 Joint temperatures of the lower floor joints

Figure 3.6 shows that right after 60 minutes, the thermocouple labelled as J6 also had a rise in temperature. As seen from Figure 3.1, J6 was placed into the joint on the uncovered CLT wall opposite to the room from the fire ignition point.

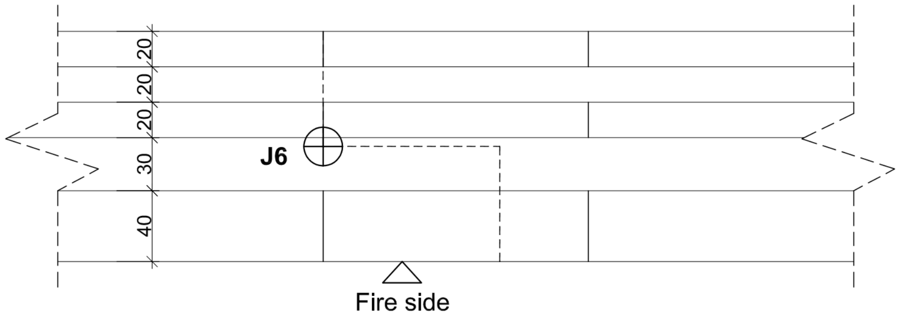


Figure 3.7 Thermocouple J6 was placed into the joint, behind the second layer of CLT

Since the flashover had occurred, igniting the unexposed CLT wall, it can be assumed that heat had started penetrating the joint. However, according to the figure above, the temperature stayed between 50 °C and 100 °C, which is not dangerous due to not being high enough for pyrolysis to happen. Therefore, the joint did not reach the temperature (200 °C according to the manufacturer) required for the intumescent sealing paper to trigger its expanding and sealing properties. This was also confirmed during a post-test site inspection. The joint was partially opened to see how the intumescent paper acted in the fire. As seen on Figure 3.8, the inside of the joint is completely unharmed by fire or heat and the Tenmat paper has not reacted to the heat, confirming that the recorded data is correct.

Figure 3.8 Partially deconstructed CLT + CLT overlap joint proving that the intumescent paper did not reach the required temperature for expansion

Since photos taken with a thermal imaging camera show the wall's temperature to be more than 650 °C, the low temperatures inside the joint are an indicator that the joint design and build quality were good (see Figure 3.9).

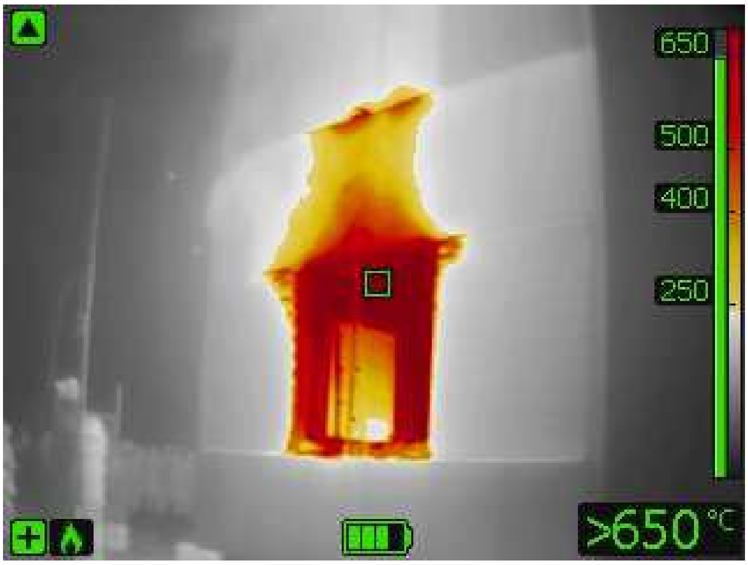


Figure 3.9 Thermal image showing wall temperature inside the compartment

Figure 3.6 also shows that slightly before and at the second flashover, J2 had another sudden, albeit slightly lower than before, temperature spike, which can be accounted to either the same situation as already happened previously, and some heat somehow penetrated the joint, or the heat reached the thermocouple via a corridor behind the stone wool. J3, however stays at a very low temperature until the end of the test and J6 maintains a steady temperature below 100 °C.

A comparison can be made when comparing the temperatures inside the joints with temperatures inside the compartment. The temperatures inside the compartment were measured with plate thermometers which were placed into 5 different locations inside the compartment - three were attached to the walls and two to the ceiling. Next to the plate thermometers (PT), thermocouples (PTC) were also placed to measure gas temperatures.

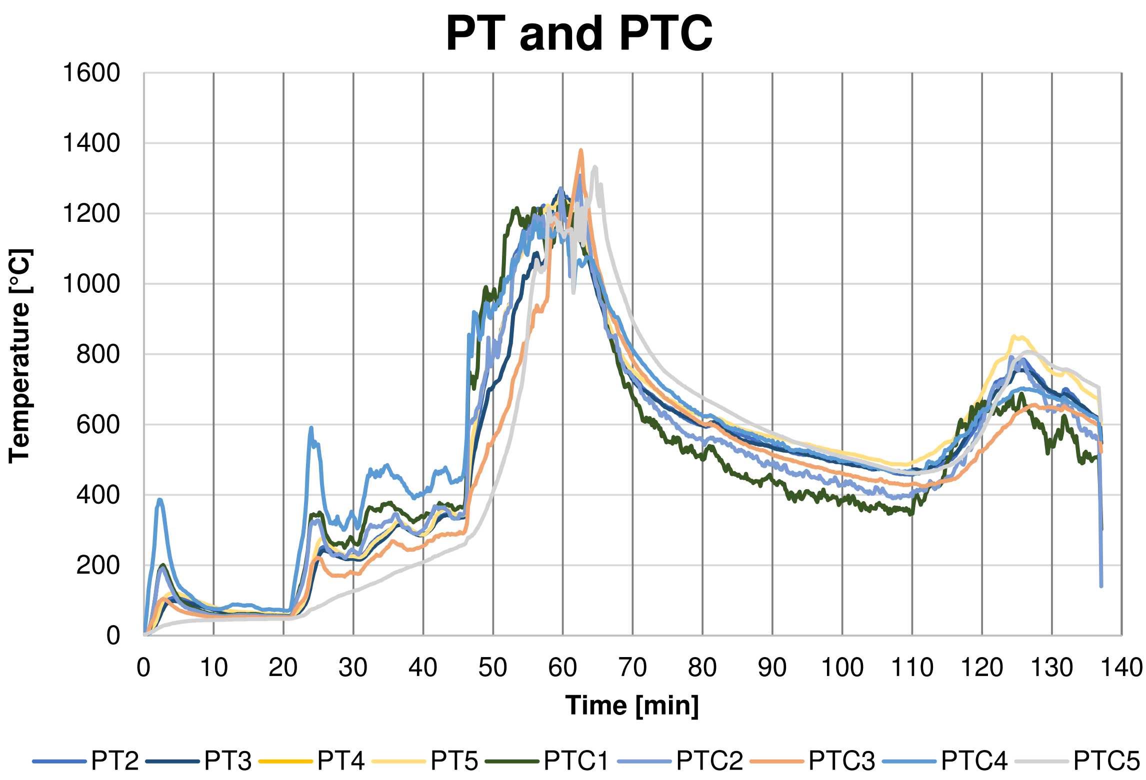
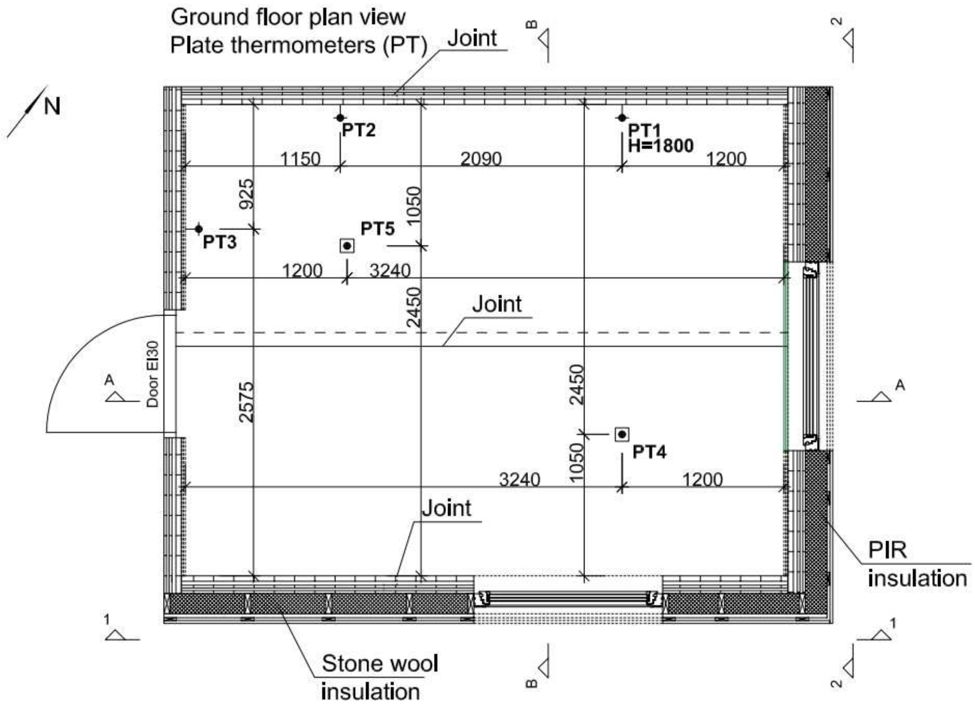


Figure 3.10 Temperatures inside the compartment



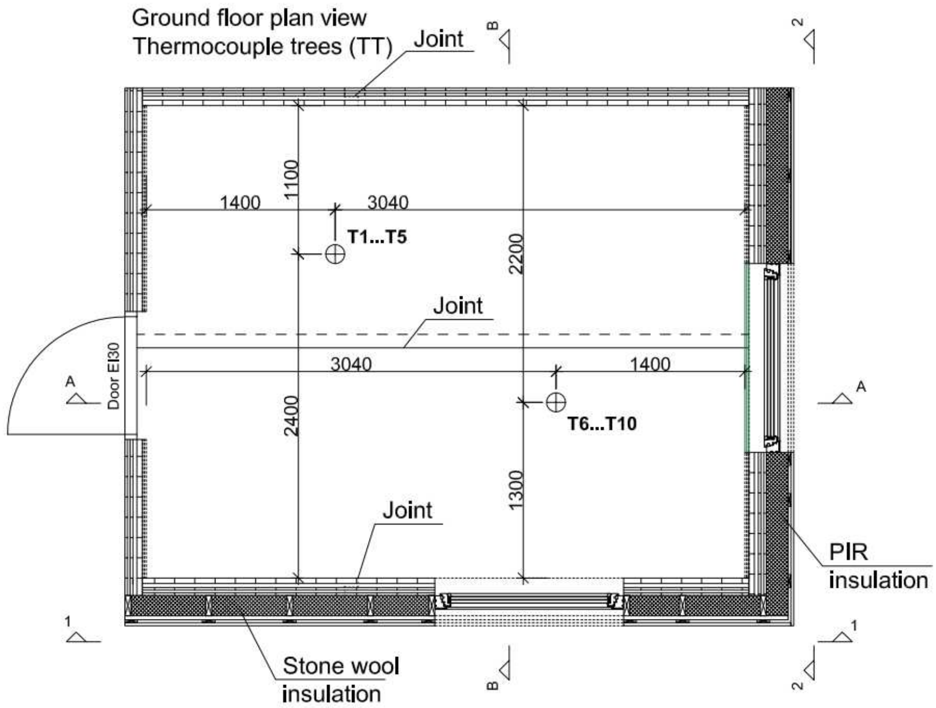


Figure 3.11 Plate thermometer (PT) and thermocouple tree (TT) locations

According to the data recorded from the plate thermometers (Figure 3.10), the temperature rose quickly after the ignition of the couch, after which it fell to below 100 °C. The fire succumbing was also observed from outside during the test, and because of that it became clear that the windows had to be broken manually to let the fire evolve. After breaking the windows at the 20-minute mark, the temperature climbed rapidly. Then, the temperature was rising steadily inside the compartment until the first flashover, after which temperatures rose suddenly, reaching nearly 1400 °C.

In addition to the plate thermometers, two thermocouple trees consisting of 5 thermocouples each were also placed hanging in the room (see Figure 3.11). The thermocouples inside the thermocouple trees were all with a different length, hanging down 40 cm to 200 cm from the ceiling with a step of 40 cm with T1 and T6 being the lowest in both trees.

The data from thermocouple trees also shows the same temperatures, confirming the data from the plate thermometers is correct.

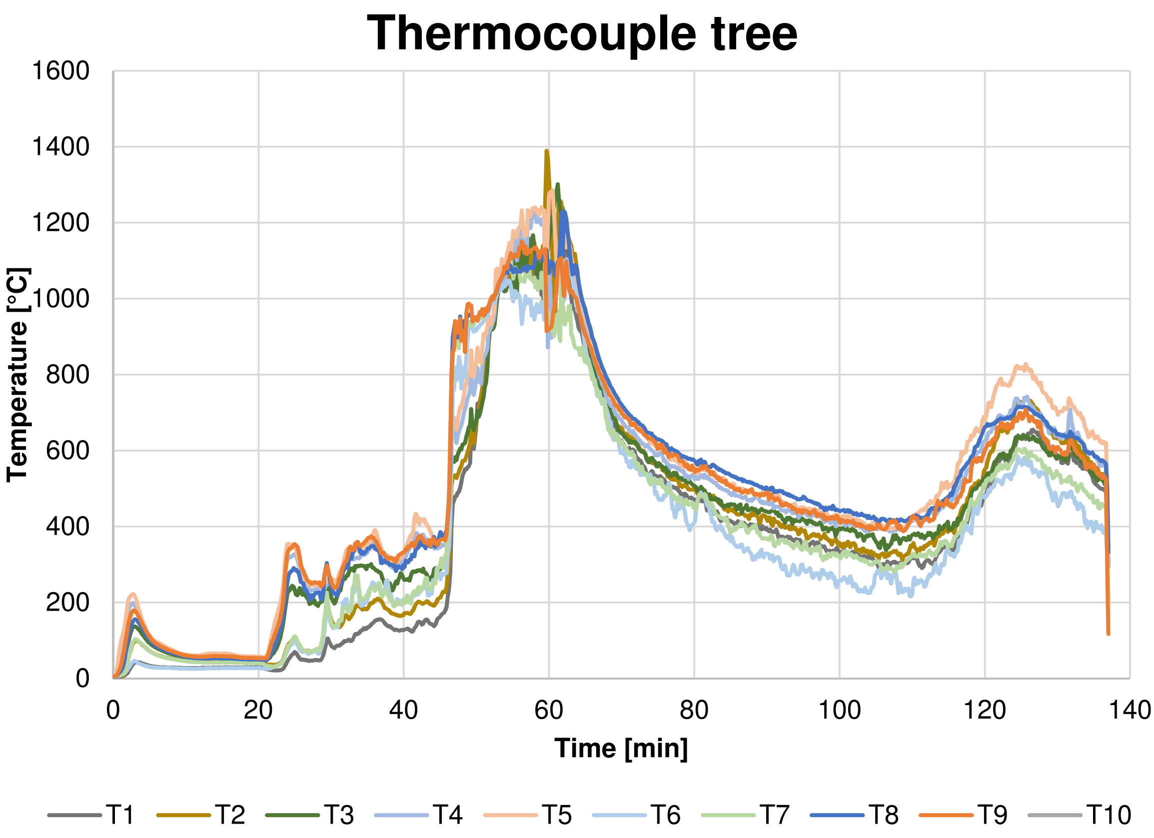


Figure 3.12 Temperatures recorded by thermocouple trees

The peaks of PT, TT, and joint graphs have all happened around the same time. However, the temperatures inside the joints only reached around 25% of those inside the compartment. This goes to show how a well designed and built joint can reduce the amount of heat being transferred, which shows especially well with the joint of the uncovered wall (thermocouple J6).

The effectiveness of the CLT + CLT overlap joint can also be shown with thermocouple J6 as an example. When comparing the recorded raw data to a photo taken with a thermal imaging camera from the outside, the differences in temperatures are drastic. The photo was taken with a timestamp of 13:05:18, which corresponds to 72 minutes into the test. The data shows that inside the compartment, temperatures were about 690 °C and only above 50 °C inside the joint. Figure 3.13 shows three different points along the lower floor span of the overlap joint. Each of these measurement points has a very low temperature of near 0 °C, therefore it is safe to say that the designed joint works extremely well in isolating a burning compartment from the outside.

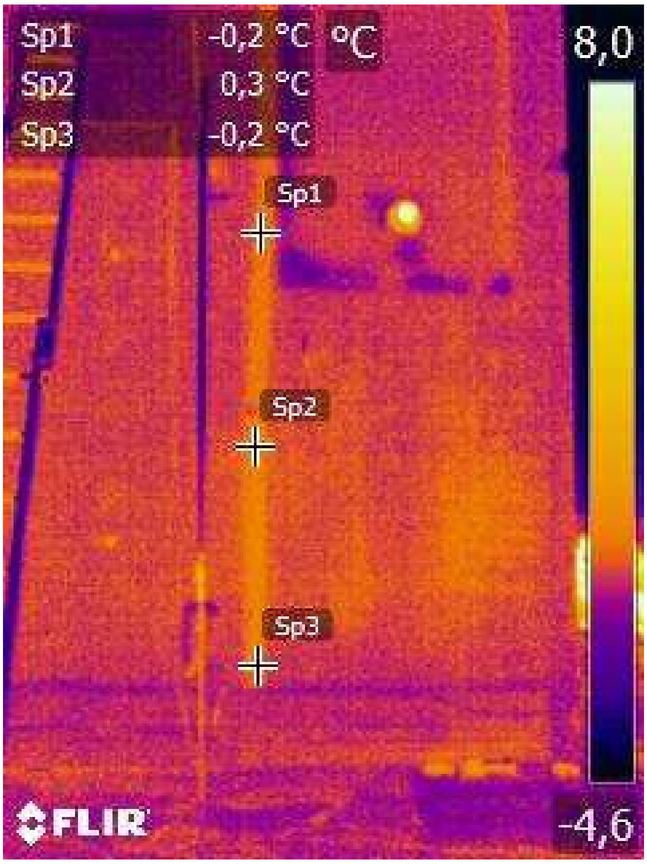


Figure 3.13 Thermal camera image of the joint housing thermocouple J6

Another comparison which shows that the wall overlapping joint worked ideally can be made between joint temperatures and the temperatures behind the first layer of CLT (Figure 3.14) shown on Figure 3.15. Once again, the best comparison can be made using thermocouple J6, because it was on the exposed wall and the measurement results are not affected by gypsum and other protection. According to Figure 3.6 and Figure 3.15, when the temperatures behind the second layer started rising as the CLT was now on fire, so did the temperatures inside the joint.

However, the joint maintained a very safe and steady temperature until the end of the test, unlike the CLT, which kept heating until the second flashover. With the second flashover, the second layer of CLT ignited and had a huge increase in temperature, whereas the temperature inside the joint didn't even reach 100 °C, meaning that such a joint design is fire resistant even after a long duration of fire.

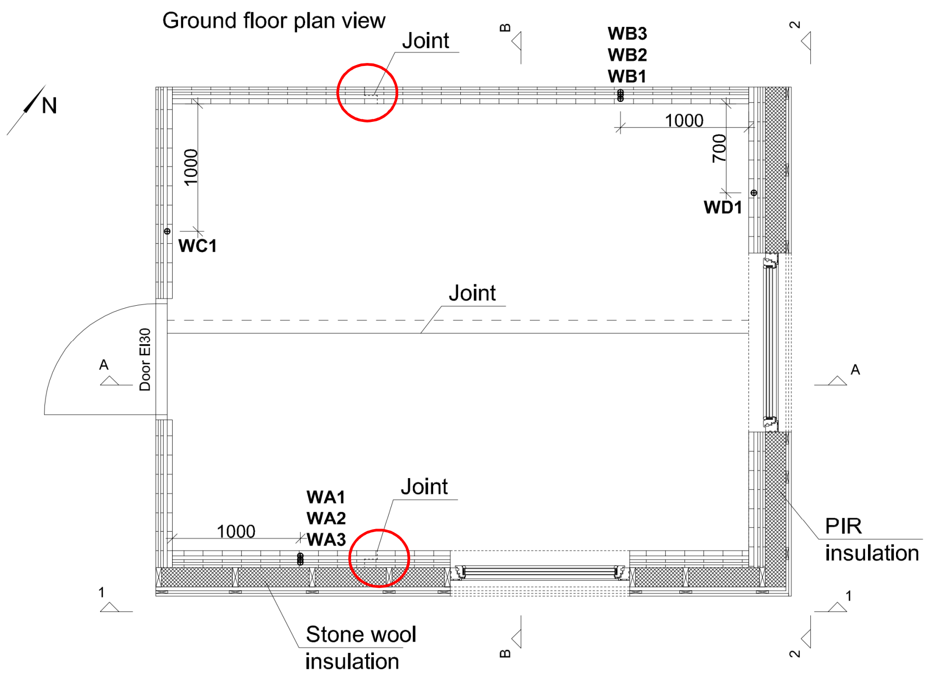


Figure 3.14 CLT thermocouple locations on the lower floor

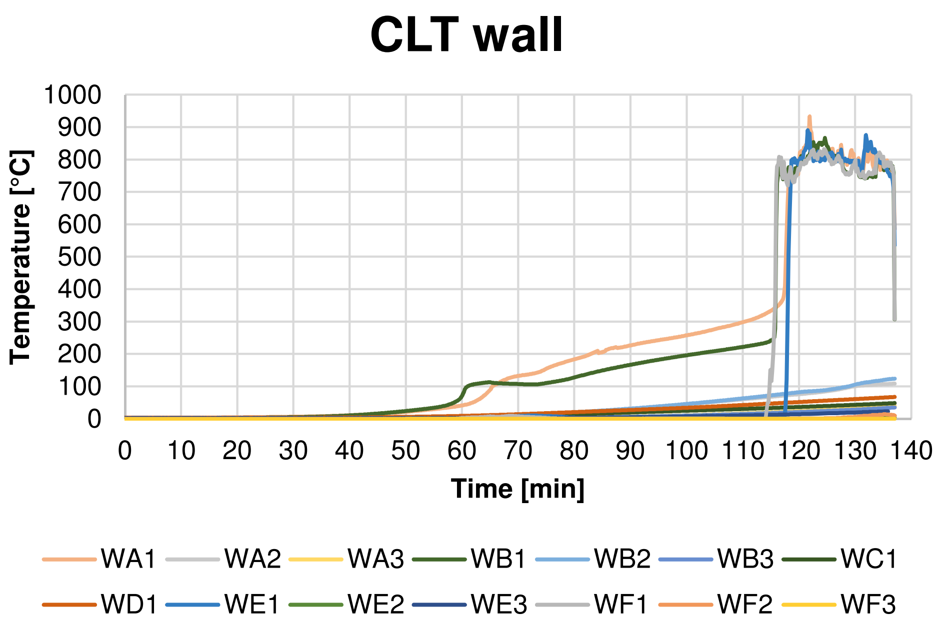


Figure 3.15 CLT temperatures gathered from thermocouples inside the walls

3.1.3. Upper floor

Joint locations for the upper floor are shown on Figure 3.2, Figure 3.3 and Figure 3.4.

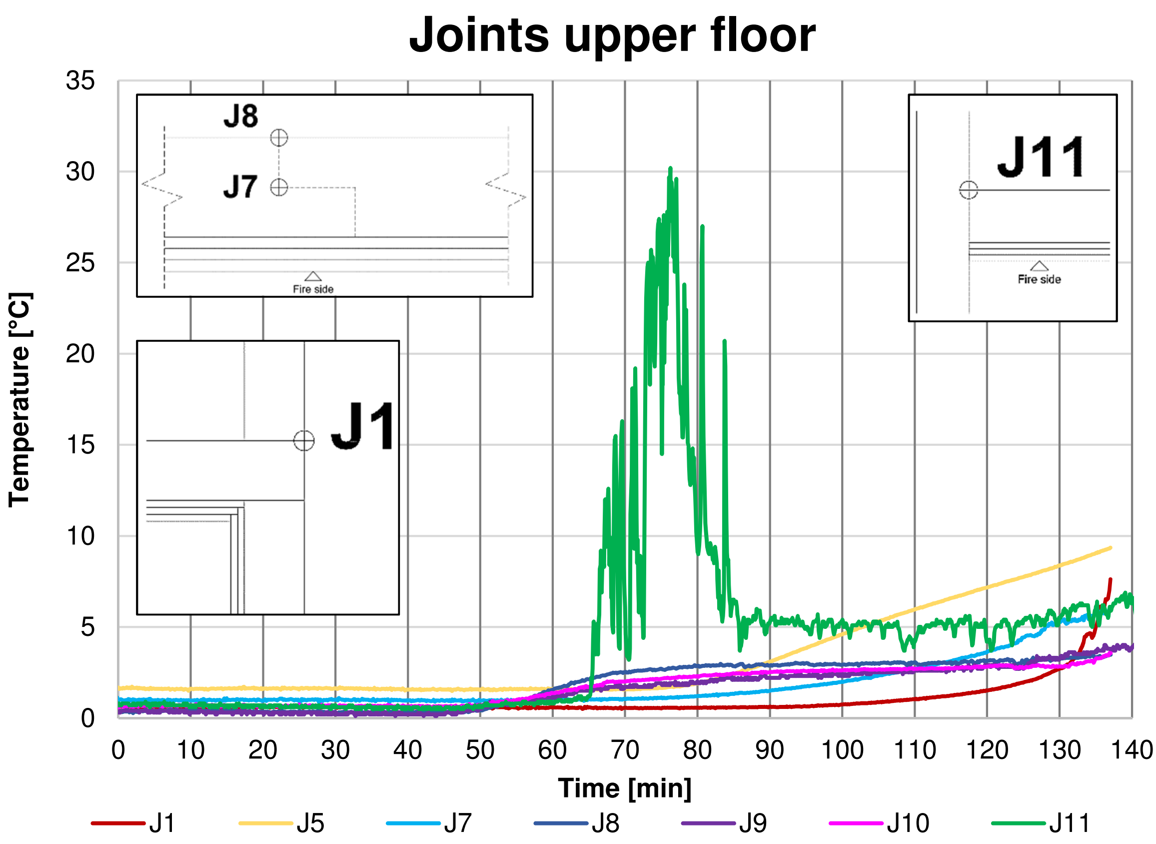


Figure 3.16 Joint temperatures on the upper floor

As shown on Figure 3.16, the temperatures stayed very low behind all the joints separating the lower and upper floor. Most of the temperatures didn't even surpass 10 °C, however a thermocouple labelled J11 peaked at around 30 °C. As seen from Figure 3.4, J11 was located right above the wall-floor joint meant to be used in higher buildings (see Figure 2.10 for scheme), which means this joint has no overlap of CLT. This, however, suggests that either the intumescent paper inside the joint worked perfectly, isolating the upper side of the joint from fire, or the fire simply did not penetrate the joint. Visual inspection also shows that no smoke or grime had reached the upper floor. An example is shown on Figure 3.17 and all other edges of the wall and floor joint are in the same condition.

Figure 3.17 J11's location as seen from the upper floor. Visual inspection shows the joint to have worked perfectly due to no observable smoke or heat damage

Images taken around J11 with a thermal camera also seem to suggest that the intumescent paper had expanded and sealed the joint.

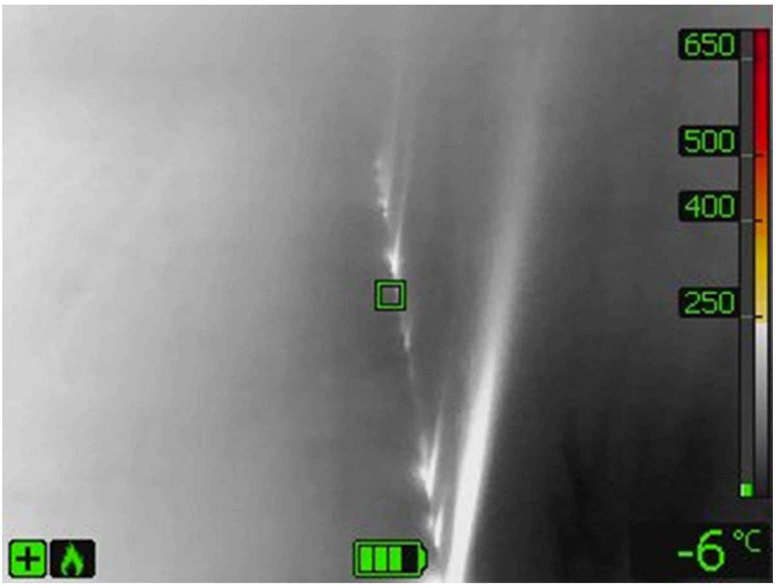


Figure 3.18 Thermal image taken by the fire brigade showing extremely low temperatures on the upper floor side of the joint

As seen on Figure 3.18, the temperature behind the joint on the upper floor was -6 °C. Meanwhile, the lower floors compartment had just had the first flashover and the temperatures inside the room, on the other side of the joint were over 1000 °C. The same can be seen on the image below, which shows the joint across the room.

Figure 3.19 Wall-floor joint across the room from the one shown on Figure 3.18

However, during the post-test site inspection, both of that type wall-floor joints were partially deconstructed near the locations of the thermocouples. The results were unexpected, as the intumescent paper had not even reacted or expanded, meaning that the temperatures did not even reach 200 °C inside the joint itself. Considering the joint had no other form of protection than the ceiling gypsum, this result is surprising, but considered very good. It means that the three layers of gypsum, properly and tightly installed against the wall, withheld the immense temperatures inside the compartment. As seen on Figure 3.20, the CLT has also charred only until the plane of the gypsum. This proves that neither fire nor heat over 200 °C did not reach the inside of the joint to trigger the expansion of the intumescent tape.

The temperatures shown on Figure 3.16 indicate that the other joint type was also not penetrated by heat, which is logical due to having gypsum protection from each side, which did not fail during the test. The figure also shows that the CLT + CLT overlapping continue joint (see Figure 2.7) in the middle of the room had very low temperatures during the duration of the fire. As seen on Figure 3.2 and Figure 3.3, some thermocouples were placed inside the joint in front of the intumescent tape and some behind it. The results however show, that the three layers of gypsum protection on the ceiling kept the temperature inside the joint low and the intumescent tape did not even need to expand.

Figure 3.20 Deconstructed wall-floor joint meant for larger scale buildings. No expansion of intumescent tape has happened

Due to the joints working ideally in a real fire scenario, the expanding properties of the intumescent tape were hard to demonstrate. However, during the post-test inspection and analysis, the expansion of the tape was observed inside each of the corners of the upper floor. This is shown on Figure 3.21.

The joint meant for smaller buildings was behind layers of gypsum, therefore it was to be expected that it would work properly. The results confirm that, with Figure 3.16 showing that the thermocouple J1 (see Figure 3.3 and Figure 3.5) that was behind that joint did not even surpass a temperature of 5 °C. The lower side of said joint has been discussed as J3 in the previous chapter, which was deemed to have worked as well.

Figure 3.21 Intumescent paper Tenmat FF104E after reacting to heat

One explanation why this happened would be that the heat and hot gases might have moved through a corridor which formed in between layers of gypsum. Another could be that the gypsum plates were not as tightly against the CLT in the corner as they were on the span of the ceiling. Whatever might have caused this, it still goes to prove that the intumescent tape provided by Tenmat has worked and isolated the second floor from hot gases and fire.

3.2. HVAC and other penetrations

As the test was prepared, it was also decided that in addition to the CLT it was required to test penetrations and openings used in buildings, such as HVAC systems' penetrations (heating, ventilation, air-conditioning). The HVAC and other penetrations description and materials are introduced in this thesis' chapter 2.6.2. The HVAC duct's temperatures were measured from the outside of the house with a thermocouple stuck between outer gypsum and the outer insulation of the duct. The same principle was used with the smaller diameter tubes penetrating the wall. The penetrations' and their thermocouples locations are described in the schemes below. The thermocouples described under this chapter are labelled O1 and O2.

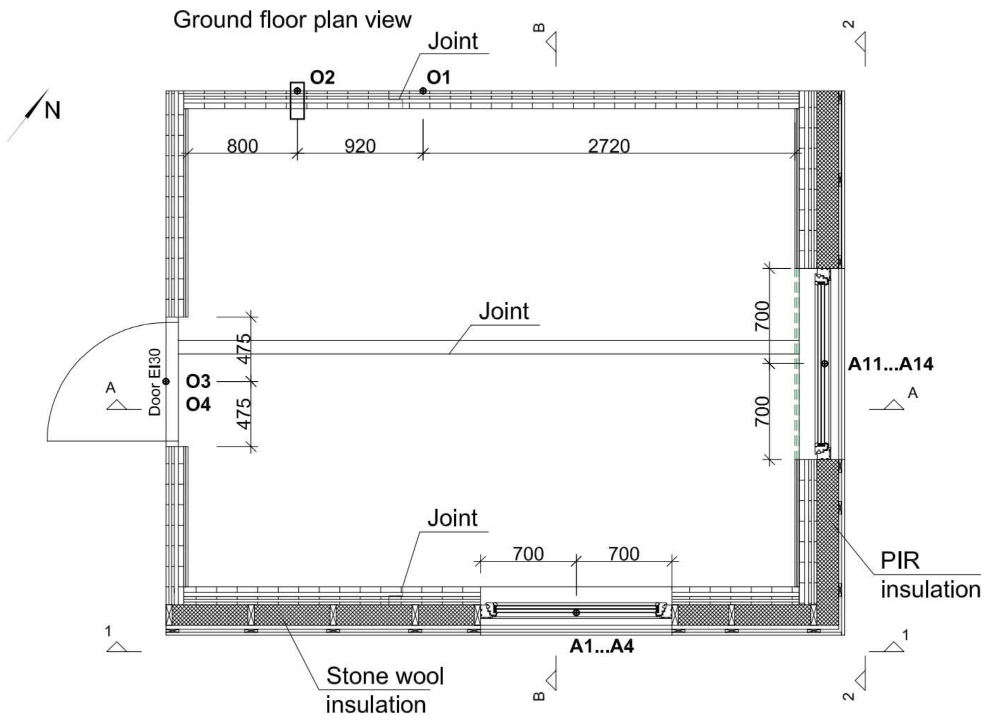


Figure 3.22 HVAC and penetrations plan

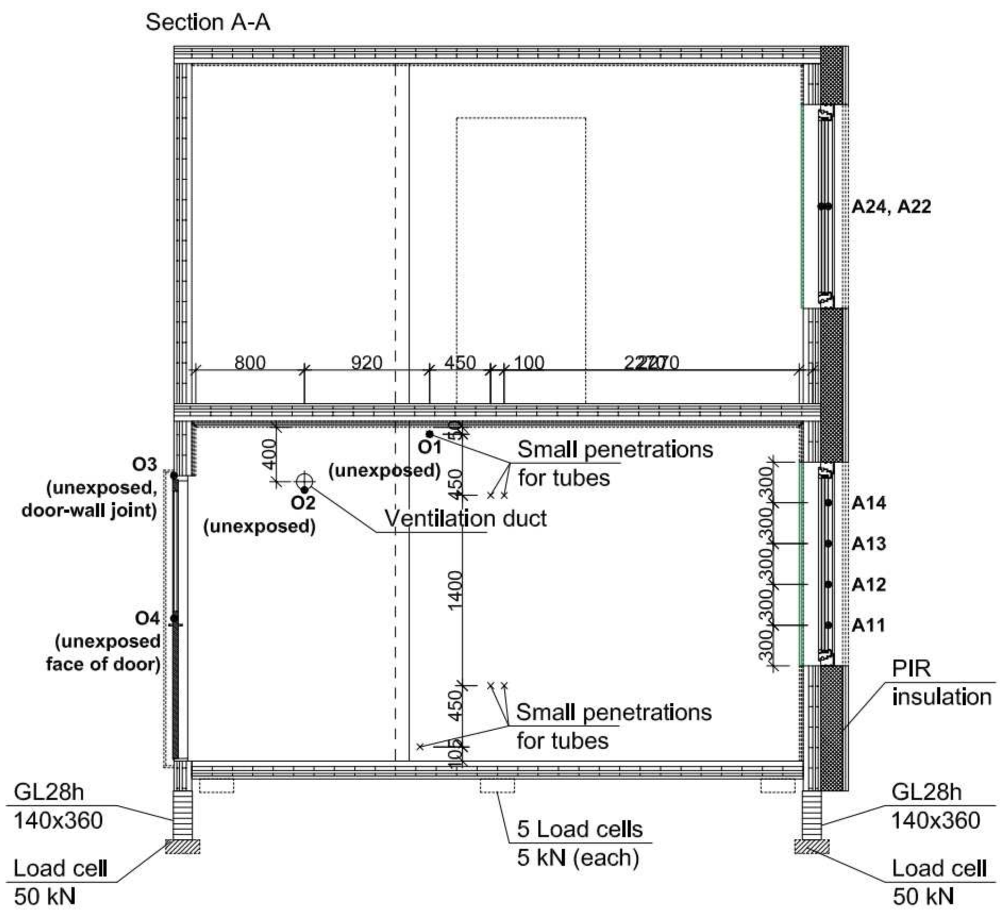


Figure 3.23 HVAC and penetrations section

3.2.1. HVAC duct

The HVAC system penetration duct that was used in this test had a non-mechanical fire damper installed inside the duct. The damper was with a 100 mm diameter and when exposed to heat of over 180 °C, it was supposed to expand and seal the duct, preventing further spread of gases and heat through the duct. During the test, no smoke or fire was observed to come out through the duct or through its penetration hole in the CLT wall. The penetrations were also photographed with a thermal imaging camera from the outside, which also showed very low temperatures throughout the test. To best demonstrate this, a comparison is made between the temperature inside the compartment and the thermal image. For this comparison, the same time and image are used as in chapter 3.1.2.

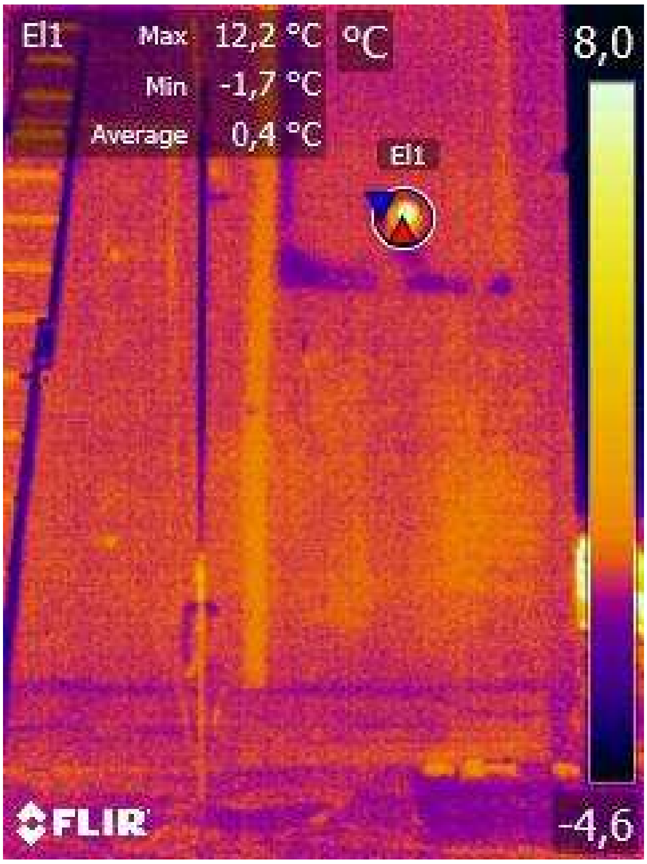


Figure 3.24 Photo from a thermal imaging camera showing temperatures around the HVAC duct

Figure 3.24 shows that outer temperature around and in the HVAC duct is very low, reaching a maximum of 12,2 °C in that area. Comparing this to temperatures from inside the compartment (see Figure 3.12) at 72 minutes into the test, it's clear that the temperature difference is over 650 °C.

However, when looking at the data on Figure 3.25 gathered by the thermocouple O1, it seems that the temperature reached over 30 °C near the end of the test. As the temperature rise is quite steady for the duration of the test, it can be attributed to thermal conductivity of the metal that the pipe is made of. During a real fire scenario, that temperature is trivial and does not pose a threat to either humans nor surrounding materials.

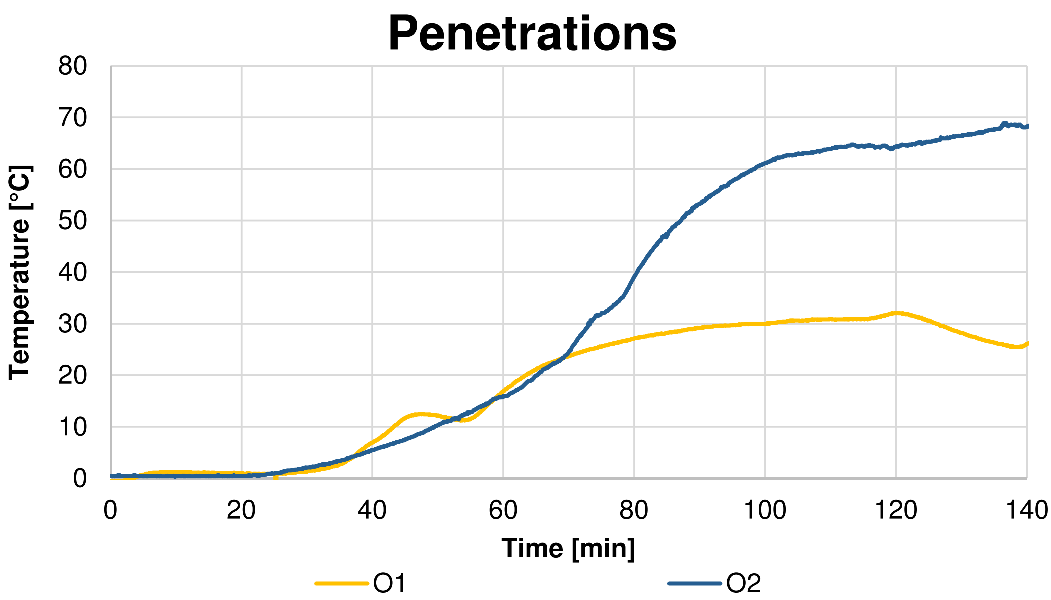


Figure 3.25 Temperatures recorded by thermocouples outside the penetrations

During a post-test inspection, the HVAC duct was also deconstructed to confirm if and how well the tested product had worked. After deconstructing the duct, it was observed that the graphite-based material used in the damper had expanded properly and sealed the entire span of the duct (see Figure 3.26).

Figure 3.26 The intumescent material used in the damper in its expanded form

The HVAC duct’s hole itself was also insulated from the fire using a special fire-resistant high-density stone wool placed in two layers, which held up against the flames for the entire duration of the test. The acrylic sealant used around the hole had also reacted to the heat and expanded.

The analysed data and results show that such design of an HVAC penetration is indeed fire-resistant in a massive timber building and can be subjected to further testing and usage.

Figure 3.27 Acrylic material used to seal the hole

3.2.2. Other penetrations

The small tubes penetrating the CLT wall were also tested. The tubes were meant to be used for pressure measurements of the compartment, but due to a technical malfunction, the measurements could not be recorded. However, the tubes still served a purpose by giving a chance to test another fire-resistant product.

The penetrations were sealed with a putty material which is supposed to expand and seal the hole when exposed to fire. The putty was applied around the penetration by hand and in a conical manner. The putty sealing material was also installed to the outer wall side of the penetration. The locations for the tubes are shown on Figure 3.23 and the thermocouple that recorded temperature from the upper tube was labelled O2.

As with the HVAC, visual observations during the test showed no signs of failure from the small penetrations' sealing materials. Again, a thermal image of the outside wall showed extremely low temperatures, whereas the temperatures inside the compartment were very high as described earlier in this paragraph. The comparison is based on the same timestamp as for the HVAC penetration. On the following image, location of O1 is in the measurement point El 1. Sp 1 and Sp 2 are the locations of the smaller double tubes.

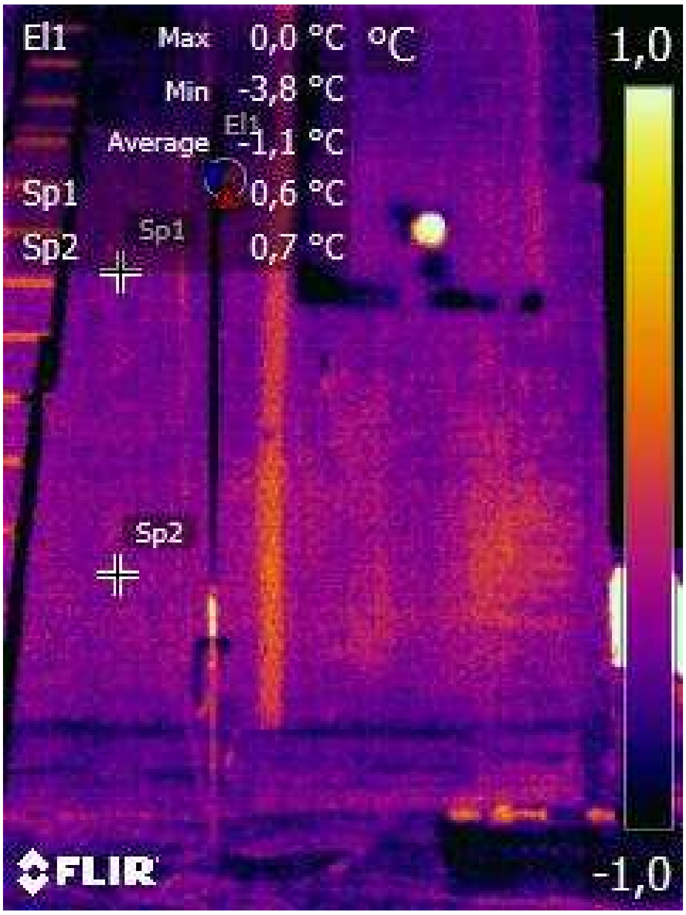


Figure 3.28 Thermal image of the smaller penetrations

Looking at the data on Figure 3.25, it seems that the temperature on the outside of the penetration rose steadily and reached as high as nearly 70 °C, which can again be attributed to thermal conductivity of the metal tube. In a real fire situation, however, such a temperature would still not pose a threat.

Post-test inspection revealed that the sealing material had indeed worked as intended inside the compartment (shown on Figure 3.29). On the outside wall, the putty was in its original form due to temperatures not being high enough for it to react.

Figure 3.29 Expanded intumescent material around the tube

Therefore, looking at the results it can be said that the materials used to insulate small penetrations from a fire have worked excellently in a real-life simulation and such design can be suggested to use in the future.

The plate thermometers and thermocouple trees that were attached to the ceiling had a penetration through to the upper floor. Those penetrations were sealed with a graphite-based sealant. No data was recorded with thermocouples for those penetrations, so the results are based on visual analysis. When the second floor was observed during the test and post-test inspection, no signs of failure were noted (see Figure 3.30). As the penetrations were under three layers of gypsum, it can be assumed that either the heat did not reach the sealant for it to react and expand, or that it expanded within the gypsum layers. However, since there was no visual fire or heat damage to the CLT panel on the upper floor, the penetration was successfully isolated from the bottom compartment.

Figure 3.30 Graphite-based material in the ceiling penetrations as seen from the upper floor

3.3. Conclusions regarding joint and penetration design

The joint designs used in this compartment test were designed with high fire-resistance in mind to show that when properly designed and built, a CLT based house is durable in case of a fire. The joints were accompanied by special fire-resistant insulation materials. Visual observations of joints during the test showed no failure in the joints' capabilities of isolating the burning compartment from the other and the post-test data analysis confirmed that. Comparing the enormous temperature differences inside the compartment, behind layers of the CLT panel itself as well as inside and behind the CLT joints, it is possible to claim that the joint design has been successful. Moreover, the fact that the intumescent tape did not even expand in most joints shows a great degree of airtightness for the compartment. Due to the success of this test through the isolation of the compartment from the upper floor, it can be said that the joint design (Figure 2.10) tested in this experiment can safely be used in the design and construction of tall CLT-based buildings. Even though the other wall-to-floor joint type was under layers of gypsum, it can also be said that such design is safe to use in smaller buildings. The same can be claimed for the overlapping joint.

The HVAC and smaller penetrations were used to test different insulation and sealing materials and products. Results are based on visual observations and the comparison of temperatures recorded by thermocouples outside of the penetrations and inside the compartment. Results show that during the fire in the room, the materials used to isolate the compartment worked as described in their data sheets and no failures were detected. Therefore, regarding penetrations, the test was a success as well and the presented materials and systems are safe to use.

3.4. Doors and windows

3.4.1. General

This chapter describes the effects of the compartment fire on the lower floor door and the upper floor windows described in chapter 2.7. Both upper floor's windows were fire rated at EI30 to isolate the upper compartment from the flames on the facade. The upper floor's door was not on the fire side and therefore an unrated door was used. Lower floor, however used a door with an EI30 fire rating. It was decided that if the flames penetrated the door they would be extinguished in the door's proximity.

The lower floor windows are not analysed in this thesis, because those windows were not under testing, neither were they fireproof. Moreover, those windows were broken manually during the test, therefore any analysis for temperature related glass strength can't be done.

3.4.2. Windows

The windows consisted of 2 layers of glass, with a thin layer of transparent intumescent material on the second layer of glass. As said by the manufacturer, this gel-like material expanded when exposed to heat after the first layer of glass broke, therefore preventing the inner glass from breaking.

The windows were also equipped with thermocouples. The locations of the thermocouples can be seen on Figure 3.23, labelled as A22 and A24, and on Figure 3.31, labelled as A21 and A23. The thermocouples were placed both on the outside and inside of the window. A21 and A22 were on the outside and A23 and A24 were on the inner glass, as shown on the figures. A21 and A23 correspond to facade 1-1 and A22 and A24 correspond to facade 2-2. The placement was chosen to demonstrate how the expanded intumescent material helps isolate the immense heat radiated by the burning facades. During the test, when the first layer of glass was broken, immediate reaction by the intumescent layer was observed and the inner glass was completely isolated from the fire. When the upper floor was visited during the fire, no immense heat was noted radiating through the window, suggesting proper heat isolation from the intumescent material.

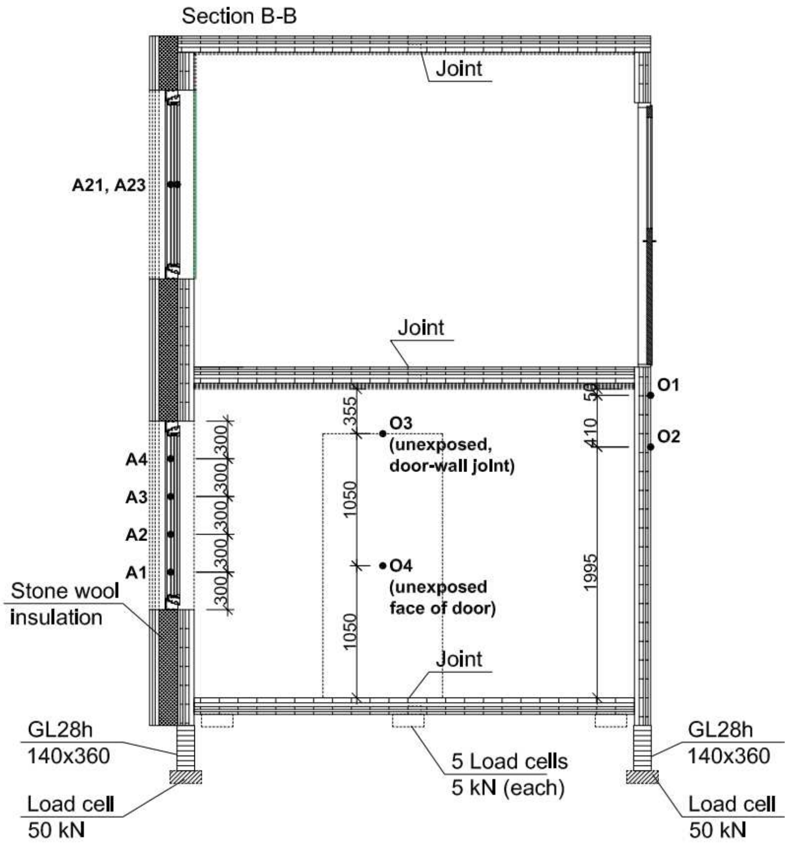


Figure 3.31 Thermocouple locations for windows and door

Figure 3.32 shows the temperatures recorded by thermocouples on the upper floor's windows. The temperatures seen on the graph do not display A23, which was a malfunctioning thermocouple. Therefore, to analyse the temperature of the inner surface, A24 will be used for comparisons. While the temperatures for the outer thermocouples reached nearly 1000 °C, the inner temperatures stayed relatively low at around 100 °C and lower. The described data confirms how the intumescent material had reacted well to the fire and isolated the inner side of the window from the intense heat that was recorded outside.

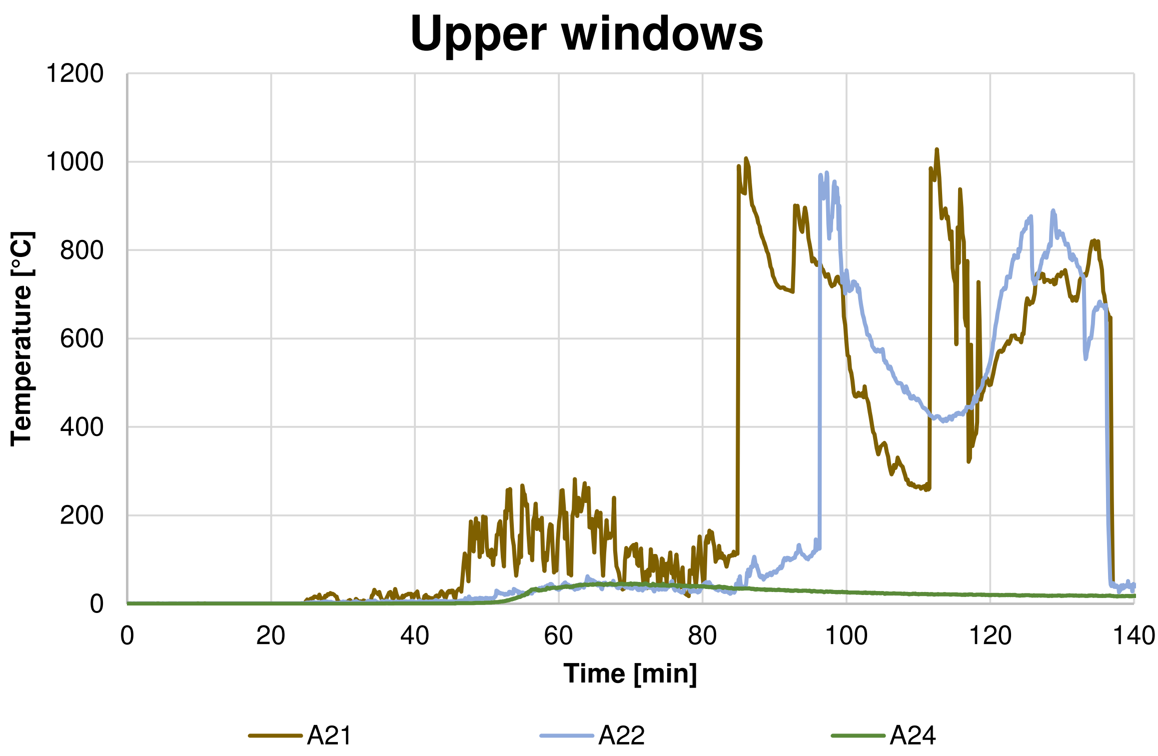


Figure 3.32 Thermocouple data from the upper windows

A comparison graph on Figure 3.33 shows the temperature differences between facades and windows. The facade thermocouples F3, F4 and F5 are on the PIR facade and F8 and F9 are on the stone wool facade. The graph can be used to show that the window measurements are correct. It also shows that while there was intense heat on the facades, the inner thermocouples A23 and A24 remained at low temperatures, therefore once more confirming the claims of last paragraph about the windows heat isolation capabilities.

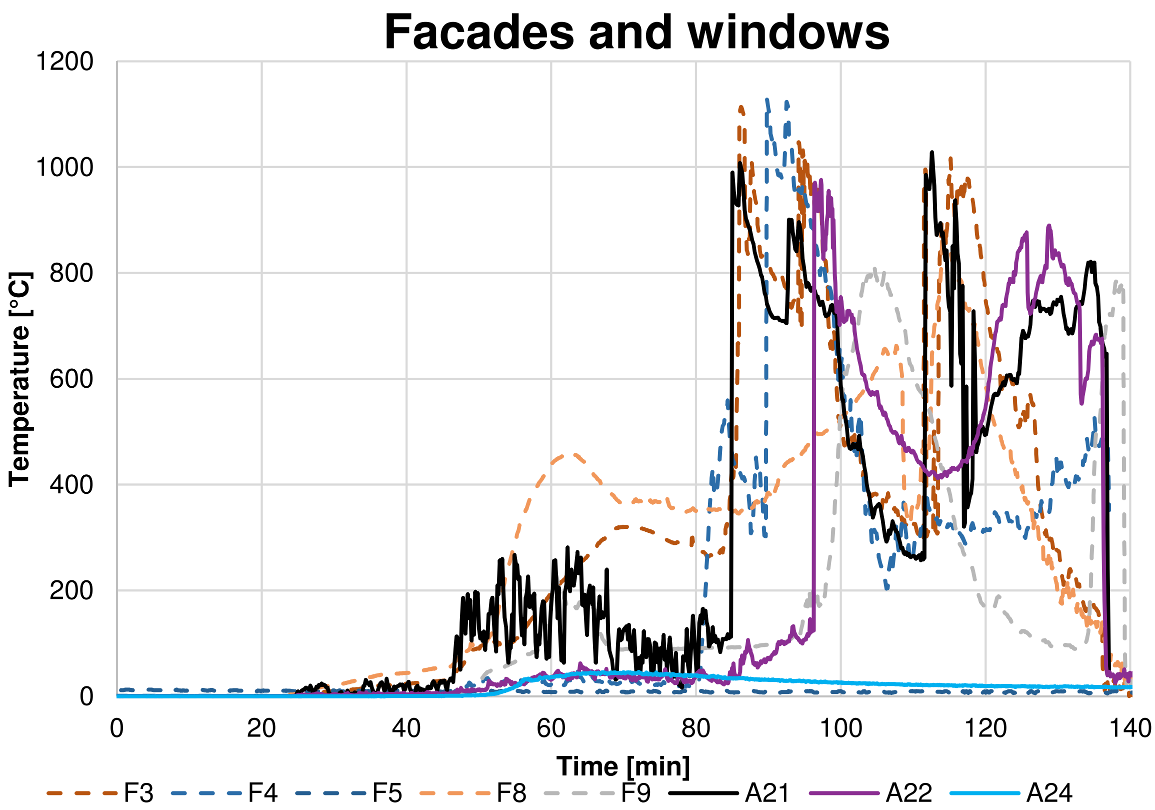


Figure 3.33 Graph comparing the temperatures on facades and windows

Another good way to illustrate the fire and heat isolation of the windows is with thermal images taken from inside of the room. The photo below shows temperature on the inside surface of the window to be 73 °C, which, considering the outer temperatures, is very low. The image was chosen because that was the maximum temperature recorded with the camera. All the other photos showed even lower temperatures.

Figure 3.34 Window on facade 1-1. Image taken from inside

Another thing to note is that these EI30 fire rated windows stayed intact for the duration of the fire. They did not show any signs of failure. The image below (Figure 3.35) shows post-test situation of the windows. The windows worked well in isolating heat and flames and in conclusion it can be said that regarding windows, the test has been successful.

Figure 3.35 Fireproof window on facade 1-1 after the test

3.4.3. Lower floor door

Regarding results, the door on the lower floor was perhaps the most surprising element. The door, being rated EI30, did not fail during the test. Being a standard EI30 door, it also had no intumescent materials or special fire resistance. During the test, no smoke or flames was observed coming from the door. As see on Figure 3.31, the door also had two thermocouples to measure how much heat was coming through the door and it’s joint.

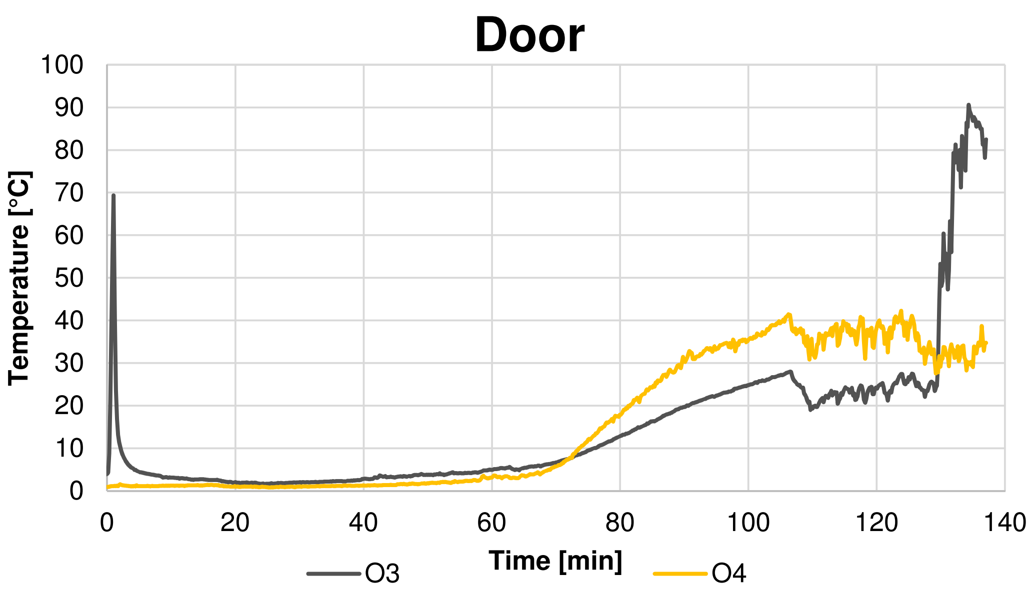


Figure 3.36 Temperatures measured from the lower floor door

The figure above (Figure 3.36) shows that the most heat penetrated through the wall-door joint. However, the temperatures did not even surpass 100 °C, therefore, it would not have been dangerous due to not being high enough to ignite any materials behind the joint. One thing to note is that the joint's temperature showed a sudden spike at the start of the fire, which may be caused by the quick increase in temperature as the fire was ignited. But as the fire started to succumb due to the house being built very airtight, the temperature also dropped rapidly. When the windows were broken, the temperature started slowly climbing again. The sudden rise in temperature near the end of the test can be explained by the hot gases being suddenly pushed out when the fire brigade started extinguishing the compartment. The face of the door stayed relatively cool for the entire test and it can only be said that the door has worked excellently during the experiment.

Figure 3.37 Inner face of the door after the test

3.5. EI30 standard temperature curve compared to test results

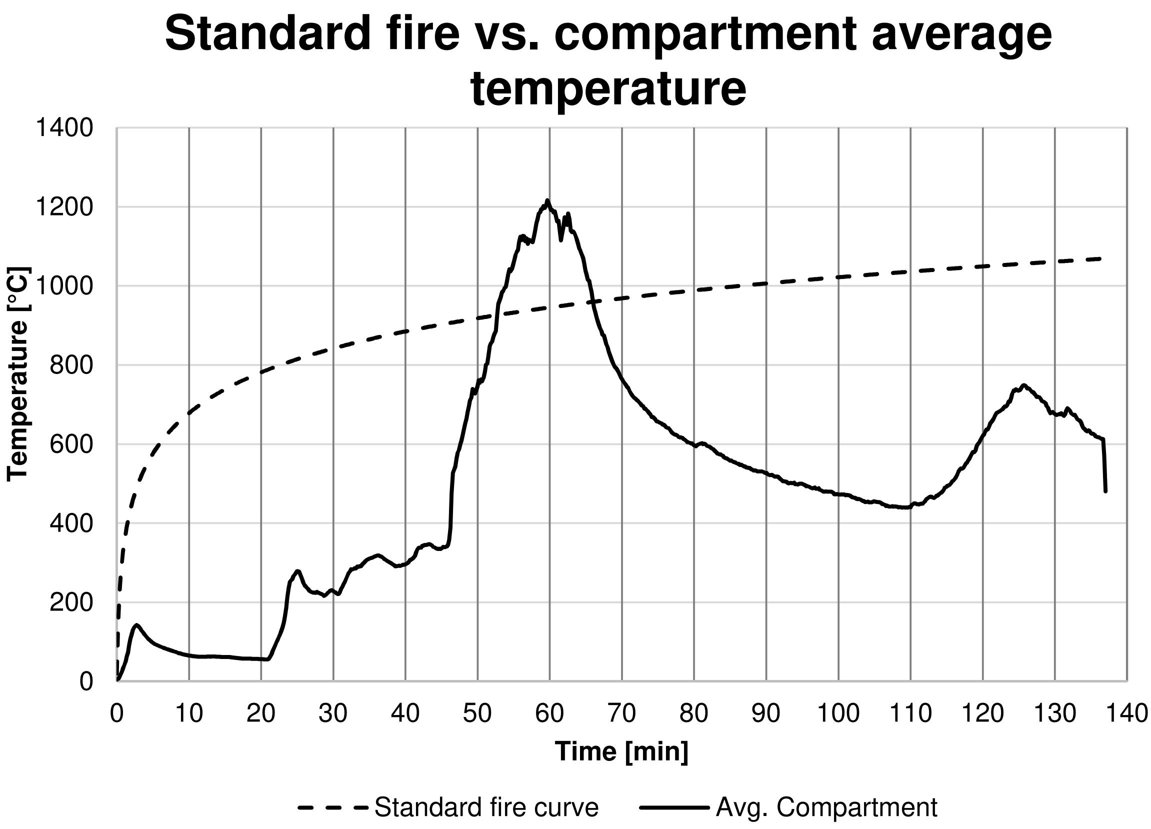


Figure 3.38 Comparison graph between standard fire and the compartments average temperature during the test

The door and windows were rated EI30, which means they are to insulate fire for 30 minutes without losing integrity. According to the standard fire curve, temperatures at the 30-minute mark are over 800 °C. In the compartment test, however, the average temperature at 30 minutes was only measured at near 200 °C. However, during the peak of the fire, the temperatures are lower than recorded from the compartment test. See Figure 3.38 for the comparison graph. The temperatures being higher is dependent on the fire load and compartment size and the temperature shown on this graph may differ depending on the situation. During the decay period, the measured temperatures are once again lower than in the case of a standard fire curve. Therefore, it can be claimed that the standard fire curve is a very conservative method with a big safety factor to use in fire design calculations.

4. SUGGESTIONS FOR RENOVATION OF CLT SURFACES

After a fire, the compartment may not be damaged enough to justify completely rebuilding it, meaning that simple renovation techniques may often be sufficient. Depending on the charring depth and the fire's nature, different strategies may be taken regarding renovation. However, in any case, firstly the char layer must be removed, and then a new layer of timber or cladding must be installed to ensure the designed load-bearing and serviceability capabilities.

If open CLT surfaces are still needed, then no extra fireproofing measures can be added to the timber's own fire resistance. When replacing lamellae, temporary support of the load-bearing elements may be needed while the charred layers are removed and then replaced with new lamellae. The new lamellae should most likely be attached to the old with nails or screws. Gluing could be complicated due to the wall already being erected, therefore, the wall cannot be under a press of some sort until the glue has dried. To also help maintain fire-resistance of the CLT panel, a suggestion would be to pre-drill shallow holes (approximately ½ of the lamella's thickness), into which to install the fasteners. To use nails, a nail gun is necessary. After the lamellae have been fastened, small wooden caps are to be installed into the pre-drilled holes to give the nails a longer duration in case of a fire.

When open CLT surfaces cannot be maintained or are not wanted, then either only the char layer may be removed, or the damaged lamellae can be deinstalled. After only removing the char layer, the surface should be evened, and gypsum boards installed to ensure fire safety. When only removing the char off the CLT and then sanding the surface even, the structural capabilities of the CLT panel should remain sufficient, however, as with any kind of structural element renovation, analysis is required to ensure the elements work as intended. A new layer of lamellae can also be installed below the gypsum as to ensure the cross-section to remain the same as designed. When adding lamellae to this solution, the nails or screws would not have to be specially protected from fire, because of being under gypsum, which is sufficient protection against heat.

5. FURTHER RESEARCH NEEDS IN FUTURE COMPARTMENT FIRE TESTS

Even though this test has been a success regarding joint design and construction, further research is still needed. The types of joints presented and tested in this test are only a few of all the commonly used solutions, and only a few select joints cannot be used for the design of all CLT buildings. Therefore, it is imperative that new tests research different joints as well. These might include joints with metal supporting brackets as well as those where the CLT panel is supported onto an engineered wooden ledge. Moreover, design commonly used in glulam should be tested, such as hidden steel plates and dowels, because these joints are also widely used in the connection of different CLT elements. How these joints react to a fire situation when used in CLT panels is still not studied enough. Putting those designs into a real compartment fire scenario will supply data which helps further upgrade the design solutions regarding fire safety and gain wider approval.

Another perspective should be to investigate methods to further provide airtightness for compartments. This might include the building methods as well as the production of CLT panels to supply the highest quality. The way that the airtightness of a compartment affects fires was seen in the beginning of the test in Väike-Maarja, where the fire started to fade before the windows were manually broken.

6. SUMMARY

On November 1, 2017, a full-scale compartment fire test was carried out in Väike-Maarja. The experiment was organized to analyse and show self-extinguishment of cross laminated timber panels. The test house was designed with high fire-resistance in mind, to give insight into how a properly designed and constructed CLT house consisting of fireproof compartments can be as safe as buildings made from other construction materials. The house was a two-storey house made of CLT panels. The panels were designed to be fire-resistant, with different lamella thicknesses, starting with the thickest on the fire side. Two of the inside walls and the ceiling were covered in double- and triple layers of fire rated gypsum respectively. The floor was also protected with stone wool and cement plates. The gypsum was attached with screws (c/c 300 mm). On the two remaining compartment walls, the CLT was completely open to the fire. This is the first time where this much exposed surfaces had been used in a compartment fire test with as many openings in the walls. The experiment used furniture as combustible material to better simulate a typical office space. Fire rated door was used on the lower floor and fire rated windows were used on the upper floor. Thermocouples and plate thermometers were used to measure temperature in different parts of the compartment. The hypothesis was based on the parametric fire curve and the compartment was meant to self-extinguish during the decay period when the temperature drops below 300 °C and the charring of timber stops. However, the hypothesis was not correct and the CLT delaminated, revealing the second, now preheated layer of CLT, which ignited, and a second flashover happened. Therefore, the house had to be manually extinguished.

This thesis concentrates on describing and analysing the results of joint solutions, penetrations and fire rated doors and windows. Four main types of CLT joints were tested – CLT + CLT continuation, designed as an overlapping joint; wall to wall connection and two different wall to floor connections, one of which is to be used in higher buildings and the other in smaller-scale buildings. The joints were designed and built as airtight as possible and an intumescent tape was used inside the joints. The intumescent tape was to expand and seal the joint when having reached 200 °C. The results of the test showed that the joint design worked impeccably. The compartment was properly isolated from the surroundings and the upper floor and no smoke, heat or fire penetrated the connections. Slight traces of sooty residue could be seen near some joints. Another thing to note is that while there was a full compartment fire, temperature inside and behind the joints was very low and therefore the intumescent paper inside the joint did not even reach its reaction temperature of 200 °C and expand in most locations. Therefore, it is possible to state that the joint design worked perfectly.

Different fire protection materials and products were tested to show ways to fireproof penetrations. An HVAC duct was also tested with a mechanical damper inside, to test how the damper works in a real fire scenario. Other smaller penetrations were used to test different acrylic, putty and graphite-based sealing products. The analysis of recorded data and visual observations during the test as well as a post-test inspection have shown that all the penetrations worked well, and no signs of failure were detected.

The fire rated door and windows also worked as declared by the manufacturers. The EI30 rated lower floor door and both the fireproof upper windows resisted the heat and flames for the duration of the test and showed excellent heat isolation capabilities when analysing the measured data.

Overall, the aim of the test was to show better ways to design fire resistant buildings that would comply to the highest standards regarding fire safety. Further testing and design solutions must be explored. Even though the main hypothesis of the test was not met, different joint and penetration solutions were analysed, and new products tested. The results showed, that all the joints and penetrations as well as the tested door and windows worked well in isolating the compartment with minimal heat and smoke transmission. Because the compartment was successfully isolated from the upper floor for the entire duration of the test, it can be claimed that the wall-to-floor joint designs for both smaller-scale and larger and taller buildings are safe to use. The fact that the fire also didn’t spread horizontally gives proof that lap joints are very safe to use. Finally, when properly used and installed, the penetration sealing materials can be safely used as well. Considering that the compartment fire lasted for over two hours before being extinguished manually, the test has been a success towards showing the proper design and building solutions to make massive timber buildings better approved in modern fire safety regulations.

7. KOKKUVÕTE

Analüüsimaks ja näitamaks ristkihtpuitpaneelide (CLT) iseeneslikku kustumist viidi 1. novembril 2017 Väike-Maarjas läbi ruumtulekahju katse. Testmaja projekteerimisel pöörati erilist tähelepanu kõrgele tuleohutusele, et demonstreerida, kuidas efektiivselt projekteeritud ning ehitatud CLT-põhine hoone on teiste materjalidega võrdväärse tulepüsivusega. Katsemaja oli kahekorruseline CLT paneelidest valmistatud hoone. Paneelid projekteeriti suurema tulepüsivusega, seega olid lamellid eri paksusega. Kõige paksem lamell oli asetatud tulepoolsele küljele. Ruumi kahele seinale oli paigaldatud kahekihiline tulekindel kipsplaat ning lakke kolm kihti sama plaati. Kipsplaat oli kinnitatud 300 mm kruvide sammuga. Kaks seina jäeti tulele täielikult avatuks, mis tegi antud katsest esimese niivõrd suure avatud pinnaga ning avadega ruumtulekahju eksperimendi. Kuna üritati imiteerida osa kontorist, siis kasutati põlemiskoormuse saavutamiseks päris mööblit, kuna see simuleeris kõige paremini reaalset olukorda. Alumisele korrusele paigaldati ka EI30 tuletõkkenõuetele vastav uks ning ülemisel korrusel katsetati tulekaitseaknaid. Ruumi erinevates olulistes punktides temperatuuri mõõtmiseks kasutati termopaare ja plaat-termomeetreid. Katse hüpotees oli rajatud parameetrilise tulekahju kõverale, mille kohaselt eeldati, et ruumis olevad CLT pinnad kustuvad iseeneslikult, kui temperatuur langeb tulekahju hääbumisfaasis alla 300 °C ning puidu edasine söestumine lakkab. Katse lõpptulemus ei vastanud hüpoteesile. Esimene CLT kiht delamineerus, selle all olev teine, eelkuumenenud kiht süttis ning kaasneva temperatuuritõusu tagajärjel toimus ruumis teine lahvatus. Otsustati, et järgnevate kihtide iseeneslik kustumine ei ole seetõttu enam võimalik, päästjatele anti käsk kustutada tulekahju ning katse loeti lõppenuks.

Käesolev magistritöö keskendub hoone sõlmlahenduste, läbiviikude ning katsetatud uste ja akende analüüsimisele. Hoone põlenguga katsetati nelja põhilist sõlmetüüpi: CLT ja CLT omavahelist jätkusõlme, mis oli projekteeritud ülekattesõlmena; kahe seina nurga ühendust ning kaht erinevat seina ja põranda sõlme. Seina ja põranda sõlmedest üht kasutatakse kõrghoonetes ning teist on soovitatav kasutada vaid madalamate ja väiksemate hoonete korral. Sõlmede projekteerimisel lähtuti eelkõige tuleohutusest ning seega jälgiti ka ehitusel, et ühendused oleksid võimalikult hermeetilised. Tulekindluse tagamiseks katsetati ka tuletõkkelinti, mis 200 °C saavutamisel sarnaselt tuletõkkevärviga paisub ning isoleerib sõlme põlevast keskkonnast. Katsetulemuste analüüs näitas, et disainitud sõlmlahendused töötasid ideaalselt. Ruum oli kogu tulekahju vältel ümbritsevast keskkonnast ning teisest korrusest isoleeritud ja suits, kuumus ega tuli ei läbinud sõlmesid. Näha oli vaid kergeid tahmajälgi mõnede sõlmede ligidal. Lisaks sellele oli temperatuur sõlmede sees ning taga väga madal, mille tõttu tuletõkkelint enamikus sõlmedes ei saavutanud 200 °C ega paisunud. Seetõttu võib väita, et sõlmlahendused töötasid sajaprotsendiliselt.

Läbiviikude juures testiti mitme materjali vastupidavust tulekahjuolukorras. Ventilatsioonisüsteemi simuleerimiseks kasutatud ventilatsioonikanali sisse oli paigaldatud spetsiaalne tuleklapp, millega katsetati, kuidas klapp reageerib reaalsele tulekahjule. Väiksemate läbiviikude tihendamiseks kasutati nii akrüüle kui ka grafiidipõhiseid tooteid. Läbiviikude juurest mõõdetud katseandmete analüüs ning visuaalne vaatlus nii katse ajal kui ka hilisemal uurimisel näitas, et kõik katsetatud materjalid töötasid ideaalselt.

Esimese korruse EI30 tuletõkkenõuetega uks ning teisel korrusel olevad tuletõkkeaknad töötasid samuti väga hästi. Nii visuaalne vaatlus kui ka mõõdetud andmete analüüs näitavad, et kõnealused tooted toimisid tulekahjus suurepäraselt, isoleerides nii suitsu, kuumuse kui ka tule leviku kogu katse vältel.

Katse eesmärk oli näidata õigeid projekteerimis- ning ehitusvõtteid, et ka puitkandekonstruktsioonidele rajatud hoonetes oleks võimalik täita kõige kõrgemaid tulepüsivuse nõudeid. Erinevaid sõlmede lahendusi ning läbiviikude võimalusi on vaja veel edasiselt uurida. Kuigi katse lõpptulemus ei kinnitanud hüpoteesi, oli võimalik edukalt jälgida sõlmlahenduste, läbiviikude ning uste ja akende toimimist reaalses tulekahjuolukorras ning katsetada uudseid tooteid. Tulemused näitavad, et katsetatud sõlmlahendused, läbiviikude tihendamise meetodid ning uks ja aknad töötasid tulekahjus täiuslikult, takistades suitsu, kuumuse ning leekide levikut. Kuna alumine korrus oli niivõrd edukalt ülemisest eraldatud kogu tulekahju vältel, on võimalik väita, et katsetatud põranda ja seina ühendussõlmi on ohutu kasutada neile vastavates hoonetüüpides. Tuli ei levinud ka horisontaalselt, seega saab ka öelda, et on ohutu kasutada ka ülekattesõlmi. Ka läbiviikude tihendamise materjale on ohutu kasutada puitkonstruktsioonidega hoonetes, eeldusel, et need on korrektselt paigaldatud. Arvestades, et tulekahju kestus oli üle kahe tunni, on võimalik antud katse lugeda õnnestunuks, jagades sellega kogutud teadmisi ja näidates lahendusi, mille najale rajada edasisi uurimisi ning tulevikus täita ka puitkonstruktsioonidele rajatud ehitistes kõrgeimaid tulepüsivusnõudeid.

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