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Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 1 - Literature Review

FINAL REPORT BY:

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FOREWORD

Recent architectural trends include the design and construction of increasingly tall buildings with structural components comprised of engineered wood referred to by names including; cross laminated timber (CLT), laminated veneer lumber (LVL), or glued laminated timber (Glulam). These buildings are cited for their advantages in sustainability resulting from the use of wood as a renewable construction material.

Research and testing are needed to evaluate the contribution of massive timber elements to room/compartment fires with the types of structural systems that are expected to be found in tall buildings (e.g. CLT, etc.). Previous research has shown that timber elements contribute to the fuel load in buildings and can increase the initial fire growth rate. This has the potential to overwhelm fire protection systems, which may result in more severe conditions for occupants, fire fighters, property and neighboring property.

The contribution of timber elements to compartment fires needs to be quantified and compared against other buildings systems to assess the relative performance. The contribution of exposed timber to room fires should be quantified for the full fire duration using metrics such as charring rate, visibility, temperature and toxicity. This will allow a designer to quantify the contribution, validate design equations and develop a fire protection strategy to mitigate the level of risk to occupants, fire fighters, property and neighboring property. In addition, the effect of encapsulating the timber as means of preventing or delaying involvement in the fire (e.g. gypsum, thermal barrier) needs to be characterized.

This report is part of a larger project with the goal to quantify the contribution of Cross Laminated Timber (CLT) building elements (wall and/or floor-ceiling assemblies) in compartment fires. This Task 1 report summarizes the literature on previous CLT compartment testing.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

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Keywords: tall wood buildings, fire safety, tall timber, cross laminated timber, CLT, compartment fire, fire test, literature review

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FPRF Project

Fire Safety Challenges of Tall Wood Buildings – Phase 2

Task 1 - Literature review:

The contribution of CLT to compartment fires.

Daniel Brandon and Birgit Östman

SP Technical Research Institute of Sweden

Final Report

12/04/2015

Abstract

This literature review is part of the *Fire Protection Research Foundation* project on *Fire Safety Challenges of Tall Wood Buildings* and focuses on the contribution of wood based construction to compartment fires. In order to provide a basis for experimental research, predictive models and comparative studies, this literature review includes a summary of 41 fire test of compartments comprising exposed or protected wood based construction and 4 reference tests of compartments comprising non-combustible steel frame construction. Additionally, overviews of test parameters, results and conclusions are provided.

Experimental methods found in the literature for quantifying the contribution of wood based construction involve measurement of the weight loss, measurements of the average charring depth/rate or heat release calorimetry of all extracted air. Heat release calorimetry has been performed successfully in recent works and requires knowledge of the heat release that corresponds solely to the movable fire load in order to determine the contribution of the combustible construction materials. The heat release of the movable fire load can be obtained from a reference test of a similar compartment consisting of non-combustible construction materials. In cases where combustible gases, such as propane, are used as fire load, the heat release corresponding to the fire load can be controlled by regulating the gas inflow.

Mass loss has previously been determined in order to estimate the heat release rate corresponding to a compartment fire. In order to quantify the sole contribution of combustible construction, either the mass loss of solely the construction or a reference tests without combustible construction materials is required. Charring depths and charring rates have been used to estimate the heat release of the construction materials. This method does not require reference tests.

Studies have shown that the contribution of encapsulated timber to a compartment fire can be non-existing or insignificant. Potential failure of the encapsulation, however, can lead to the involvement of timber in the fire and can eventually lead to a second flash-over. It was shown that the presence of unprotected combustible surfaces leads to an increase of the heat release rate, but does not necessarily lead to increased temperatures within the compartment. In under ventilated fires, the contribution of unprotected timber can lead to significant flaming combustion outside of ventilation openings, such as windows. The contribution can, but does not always, lead to a delayed decay of a fire.

An overview of relevant results such as peak heat release rates, charring rates time to decay of a fire and encapsulation times is given and discussed. Furthermore, complications that have been reported in the literature have been discussed.

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1 Background

Recent architectural trends include the design and construction of increasingly tall buildings with structural components comprised of engineered wood referred to by names including; cross laminated timber (CLT), or glued laminated timber (Glulam). These buildings are cited for their advantages in sustainability resulting from the use of wood as a renewable construction material.

There is concern that timber elements in tall wood buildings could contribute to the fuel load in buildings and could increase the initial fire growth rate with the potential that fire protection systems could be compromised, which may result in more severe conditions for occupants, fire fighters, property and neighboring properties. Research and testing are needed to evaluate the contribution of massive timber elements to room/compartment fires with the types of structural systems that are expected to be found in tall buildings (e.g. CLT, etc.).

In this study, the contribution of timber elements to compartment fires will be quantified and compared against other buildings systems to assess the relative performance. The contribution of exposed timber to room fires will be quantified for the full fire duration using metrics such as charring rate, visibility, temperature and toxicity. In addition, the effect of encapsulating the timber as means of preventing or delaying involvement in the fire (e.g. gypsum, thermal barrier) needs to be characterized. The project results will provide input for use in quantifying the contribution of wood structural elements to a fire, validating design equations and developing a fire protection strategy to mitigate the level of risk to occupants, fire fighters, property and neighboring property.

2 Scope of this report

This literature review is part of phase 2 of the FPRF project on Fire Safety Challenges of Tall Wood Buildings and focuses on natural compartment tests comprising engineered timber as walls and/or ceilings. The work presented here is complimentary to the literature review by Gerard *et al.* (2013) which included a summary of a number of heavy timber and light timber frame compartment tests (Hakkarainen, 2002; Frangi and Fontana, 2005; Lennon *et al.* 2000; Frangi *et al.* 2008). This literature review includes additional compartment tests and discusses compartment tests in more detail, in order to provide a basis for future experimental research, comparative analysis and empirical models. Additionally, an overview of relevant results is provided.

3 Compartment tests under natural fire conditions

Forty-five tests that have been found in the literature are summarized in this chapter. The test names used in this report differ from their original names in the sources. An overview of the tests and test names is given in Table 1 along with information on the dimensions, construction, fire protection and fire load for the test compartments. Main structural members are categorized as *light timber frames* (LTF), *light steel frames* (LSF), *cross-laminated timber* (CLT), *nail laminated timber* (NLT) and *heavy laminated timber* (HLT). The abbreviation *N.F.* is used in cases where the relevant information was not found. Opening factors can be calculated using $A_o\sqrt{H_o}/A_t$, where A_o and H_o are the area and height of the opening and A_t is the total area of the boundary surfaces.

Table 1: overview of compartment tests 1

Test	Reference	Name in reference	Floor area of ignited comp. (m^2)	Ventilation opening area of ignited comp. (m^2)	Open-ing factor	Main struct. mem-bers	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load density (MJ/m^2)	First item ignited
A1	Lennon *et al.* (2000)	*none*	*N.F.*	*N.F.*	*N.F.*	LTF	*N.F.*	*N.F.*	*N.F.*	*N.F.*
B1	Hakkarain-en (2002)	test 1	15.75	2.76	0.042	HLT	None	wood cribs	900[1]	wood crib
B2		test 2	15.75	2.76	0.042	HLT	12.5mm type A	wood cribs	900[1]	wood crib
B3		test 3	15.75	2.76	0.042	HLT	12.5mm type A 15.4mm type F	wood cribs	900[1]	wood crib
B4		test 4	15.75	2.76	0.042	LTF	12.5mm type A 15.4mm type F	wood cribs	900[1]	wood crib
C1	Frangi and Fontana (2005)	BE bb g	18.04	2.55	0.041	LTF	None	cribs & bed	*N.F.*	matress
C2		BE bb o I	18.04	2.55	0.041	LTF	None	cribs & bed	*N.F.*	matress
C3		BE bb o II	18.04	2.55	0.041	LTF	None	cribs & bed	*N.F.*	matress
C4		BU nbb	18.04	2.55	0.041	LTF	18mm non-comb.	cribs & bed	234	matress
C5		BU bb	18.04	2.55	0.041	LTF	None	cribs & bed	211	matress
C6		nbb demo	18.04	2.55	0.041	LTF	15mm non-comb. 12.5mm non-comb.	cribs & bed	237	matress
D1	Chen (2008)	test 1	15.72	2.25	0.040	LSF	12.7mm cement board 15.7mm type X[3]	furniture	397	bed
D2		test 2	15.72	2.25	0.040	LSF	12.7mm cement board 15.7mm type X[3]	furniture	366	bed
E1	Frangi *et al.* (2008)	*none*	11.16	2.00	0.032	CLT	12mm standard 12mm fire proof[2]	cribs & bed	790	wood crib
F1	Kampmei-er (2009)	*none*	14.44	0[8]	0[8]	CLT	31% of CLT $K_2$15 Or $K_2$30	gas	N.F.	gas
G1	Lennon *et al.* (2010)	solid floor joist	12.00	1.40	0.024	LTF	12.5mm type F 12.5mm type F	wood cribs	450	wood crib
G2		OSB web I joist	12.00	1.40	0.024	LTF	15mm type F 15mm type F	wood cribs	450	wood crib
G3		steel truss web joist	12.00	1.40	0.024	LTF	15mm type F 15mm type F	wood cribs	450	wood crib
H1	Peng *et al.* (2011)	1	17.10	1.8[4]	*N.F.*	*N.F.*	*N.F.*	wood	*N.F.*	wood
H2		2	17.10	1.8[4]	*N.F.*	*N.F.*	*N.F.*	wood	*N.F.*	wood
H3		3	17.10	1.8[4]	*N.F.*	*N.F.*	*N.F.*	furniture	*N.F.*	*N.F.*
H4		4	17.10	1.8[4]	*N.F.*	*N.F.*	*N.F.*	furniture	*N.F.*	*N.F.*
H5		5	17.10	1.8[4]	*N.F.*	*N.F.*	*N.F.*	wood	*N.F.*	wood
H6		6	17.10	1.8[4]	*N.F.*	*N.F.*	*N.F.*	wood	*N.F.*	wood
I1	McGregor (2013)	test 1	15.75	2.14	0.042	CLT	12.7mm fire rated 12.7mm fire rated	propane	486	prop. burner
I2[7]		test 2	15.75	2.14	0.042	CLT	12.7mm fire rated 12.7mm fire rated	furniture	533	bed
I3		test 3	15.75	2.14	0.042	CLT	None	propane	182	prop. burner
I4[7]		test 4	15.75	2.14	0.042	CLT	12.7mm fire rated 12.7mm fire rated	furniture	553	bed
I5[7]		test 5	15.75	2.14	0.042	CLT	None	furniture	529	bed
J1	Li *et al.* (2014)	test 4	15.75	2.14	0.042	LTF	12.5mm type C 12.5mm type C	furniture	614	bed
J2		test 5	15.75	2.14	0.042	LTF	12.5mm type C	furniture	610	bed
J3		test 6	15.75	2.14	0.042	LSF	12.5mm type C	furniture	601	bed
K1	Medina Hevia (2014)	test 1	15.75	2.14	0.042	CLT	63% of CLT surface: 12.7mm type X 12.7mm type X	furniture	532	bed
K2		test 2	15.75	2.14	0.042	CLT	58% of CLT surface: 12.7mm type X 12.7mm type X	furniture	532	bed
K3		test 3	15.75	2.14	0.042	CLT	79% of CLT surface: 12.7mm type X 12.7mm type X	furniture	532	bed
L1	Su and Lougheed (2014)	LWF 1	52.54	4.50	0.031	LTF	12.7mm type X 12.7mm type X	furniture	550[9]	bed
L2		CLT	52.54	4.50	0.031	CLT	12.7mm type X 12.7mm type X	furniture	550[9]	bed
L3		LSF	52.54	4.50	0.031	LSF	12.7mm, 15.9mm type X or standard	furniture	550[9]	bed

L4		LWF 2	52.54	4.50	0.031	LTF	12.7mm type X 12.7mm type X	furniture	550[9]	bed
M1	Su and Muradori (2015)	*none*	23.72	4.70	0.064	CLT	16 mm type X[2] 16 mm type X[2]	furniture & wood cribs	790	seat
N1	Kolaitis et al (2014)	*none*	4.93	0.42	0.015	CLT & LTF	12.5mm type DF 12.5mm type DF	wood cribs	420	wood crib
O1	Janssens (2015)	test 1	14.80	3.87	0.084	CLT & NLT	type X type X	furniture	575[5]	sofa
O2		test 2	14.80	3.87	0.084	CLT	type X type X	furniture	600[5]	sofa
P1	Hox (2015) Unpublish-ed	test 1	13.30	3.27	0.070[6]	HLT	29% of walls & ceiling: 13mm standard 15mm fire proof	desk, matress, wood cribs	653	desk
P2		test 2	13.30	3.27	0.070[6]	HLT	29% of walls & ceiling 13mm standard 15mm fire proof	desk, matress, wood cribs	653	desk

[1] backwards calculated in order to ignore the assumed a combustion efficiency of 0.8
[2] see main text for exceptions
[3] two layers of 15.9mm type X gypsum board on the ceiling
[4] based on an assumed door height of 2m
[5] rough estimation using graph in resource
[6] window was initially closed
[7] also reported by Li *et al.* 2014
[8] the compartment was placed on top of a furnace which controlled the ventilation
[9] movable fire load density for Tests L1-L4:

- bedroom 510 MJ/m^2;
- living area 380 MJ/m^2
- kitchen dining area 970 MJ/m^2
- average living/dining/kitchen 575 MJ/m^2
- whole apartment average 550 MJ/m^2

3.1 Lennon et al. (2000)

Timber Frame 2000 (TF2000) was a project that aimed to increase confidence in the market by showing the benefits of timber frame construction. As part of TF2000 a compartment in a full scale 6-storey building was fire tested (Lennon *et al.* 2000). The aims of the tests were assessing the structural performance of protected light timber frame building subjected to a fully developed fire and assessing the fire spread beyond the ignited room.

Temperature measurements were conducted in the compartments and in the cavities of the surrounding structure using thermocouples. Load cells were positioned in order to obtain information regarding the heat release rate. Gas analysis and heat flux meters were used to assess the tenability criteria. Softwood and hard wood cubes were positioned in several rooms in order to study their charring behavior in different environments, to be able to compare the fire to standard fires.

The fire was initiated on the third floor of the building in the living room of an apartment. The floor had inner dimensions of 12.4 x 24.1m and comprised of four apartments, a lobby, stairs and elevator shaft. All apartments comprised of a hallway, bathroom, kitchen, two bedrooms and a living room. Unfortunately, the exact sizes of the rooms and compartment were not found in the literature.

Results showed that flashover took place approximately 24 minutes after ignition. The peak temperatures were approximately 1000°C and sustained until the fire was extinguished 64 minutes after ignition. The authors estimated a peak heat release rate of 6 MW, based on the mass loss measured using the load cells.

The fire load in the bedroom was not ignited during the test and the measured temperatures in the voids were only above 100°C at places where the timber was directly exposed to the fire for some time. The fire was extinguished after 64 minutes, due to direct exposure on the joists. However, there was no structural failure observed during the test. From comparisons between the charring depth of the wooden cubes and the charring depth of similar cubes in a standard fire, it was concluded that the charring depth of softwood was 10% higher in the ignited room (living room) than in a standard fire.

3.2 Hakkarainen (2002)

Hakkarainen (2002) presented four fire tests of compartments, of which three were constructed using heavy laminated timber and one was constructed using light timber framing. The floors of all compartments were made of 22mm thick particle board. The inner dimensions of all compartments were 3.5 x 4.5 x 2.5m and there was a single opening of 2.3 x 1.2m. The fire load consisted of wood cribs and the reported fuel load density was 720MJ/m^2. However, this value was obtained by assuming a combustion efficiency of 0.8. As other authors did not reduce the fuel load density according to a combustion efficiency, the combustion efficiency is ignored in Table 1 to allow comparisons.

The first heavy timber compartment comprised of fully exposed ceiling and walls. The heavy laminated timber elements of the second test were protected using a single layer of 12.5mm type A gypsum plaster board. The structure of the other two compartments were protected using a layer of 12.5mm type A and a layer of 15.4mm type F gypsum plaster board.

Gas temperatures were measured using three thermocouple trees. Additionally, wooden blocks (Figure 1) comprising thermocouples were inserted in the ceiling and a wall to assess the charring and the temperatures inside the timber. Furthermore, a heat flux meter was positioned in a mock facade 2.2 meter above the upper edge of the window opening.

Results of test B1 and test B2 showed relatively low gas temperatures of around 700ºC for the majority of the time. It was stated that this was caused by under ventilation of the fire. Both fires did not show decay and were stopped after approximately 50 minutes due to excessive flaming outside the compartment and a fault in the smoke venting system. In test B2 the gypsum plaster board (type A) started to fall down after 13 minutes. This explains the similarity between the fires of test B1, which involved only unprotected CLT, and test B2.

The gas temperatures in test B3 and B4 were significantly higher, peaking at approximately 1200ºC. Hakkarainen stated that the ceiling and walls did not contribute to the fire during the most intense period, as the layers of gypsum plaster boards remained intact during that period. A decay of the fire was seen, evidenced by a temperature drop and a drop of measured heat flux in the mock facade. Test B4 was stopped after 48 minutes because the ceiling started to burn through.

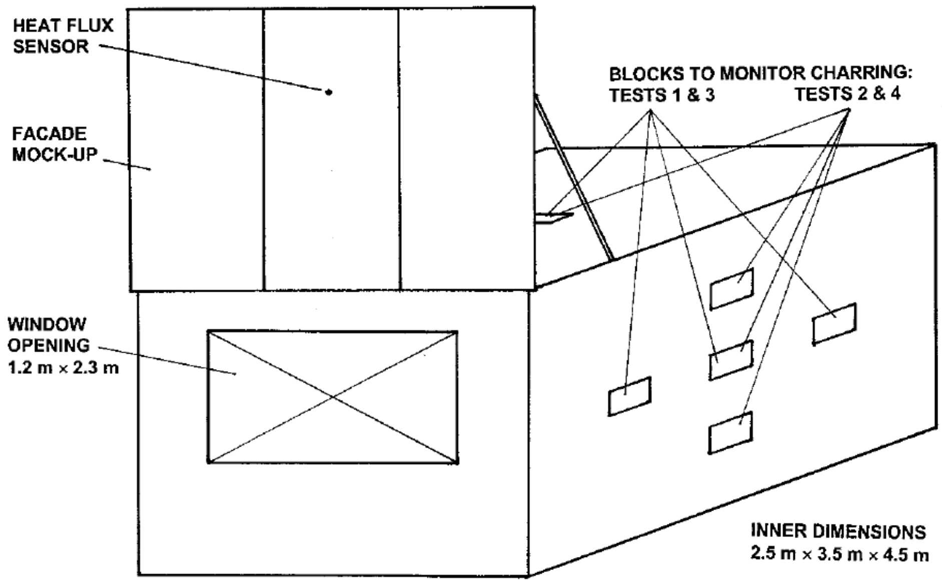

Figure 1: Compartment setup, from Hakkarainen (2002)

3.3 Frangi and Fontana (2005)

Frangi and Fontana (2005) presented three pre-flashover and three post-flashover fire tests of light timber frame compartments. The three pre-flashover tests aimed to study the effect of sprinklers on fires in compartments with combustible linings. The three post-flashover tests were each conducted on a 2-storey setup. The linings of the compartments were either combustible or non-combustible, as shown in Table 2.

The outer dimensions of each compartment were 6.6 x 3.1 x 2.8m. A window of 1.5 x 1.7m was positioned in the short wall and a door (with unknown fire rating) was positioned in the opposing wall.

The structural frames of all compartments were similar, using timber studs in the walls and ceilings and timber joists in the floors, all insulated using wood based fiberboards. The inner lining was different for each compartment. The lower (ignited) compartments of test C5 had an exposed layer of 18mm OSB. The timber frames of test C4 and C6 were protected by a layer of 18mm non-combustible gypsum plasterboard and two layers of 15 and 12.5mm non-combustible gypsum plasterboard, respectively. An additional façade which surrounded the window was made of 19mm timber board that was fixed leaving a 20mm air gap.

Temperatures were measured inside the room, inside the surrounding materials and on the glass surfaces of the windows. Gas analysis was performed and the weight of the entire unit was logged using four load cells.

The pre-flashover tests showed that all sprinklers were activated in 2 or 3 minutes after ignition and that the sprinkler location and ventilation conditions had no significant influence on the effectiveness of the sprinklers. Furthermore, it was concluded that the combustible linings were not involved during the fires and that flashover did not occur in these tests.

Table 2: overview of specimens, from Frangi and Fontana (2005)

Test name	Safety concept	Fire type	Room linings	Window opening
Test C1	Technical (sprinkler)	Pre-flashover	Combustible	Closed
Test C2	Technical (sprinkler)	Pre-flashover	Combustible	Opened
Test C3	Technical (sprinkler)	Pre-flashover	Combustible	Opened
Test C4	Structural	Post-flashover	Lower: non-combustible Upper: combustible	Opened Closed
Test C5	Structural	Post-flashover	Lower: combustible Upper: combustible	Opened Closed
Test C6	Structural	Post-flashover	Lower: non-combustible Upper: combustible	Opened Closed

In the post-flashover fire tests, flashover occurred after four to seven minutes. A thermal camera outside of the compartments showed that the volume of hot gases outside of the ventilation opening of apartments with combustible linings was larger than that of apartments with non-combustible linings, shortly after flashover occurred (Figure 2). Failure of both glasses of the double glazed window on the upper floor occurred after 7.5 minutes in test C5. In both other tests this occurred after more than 40 minutes.

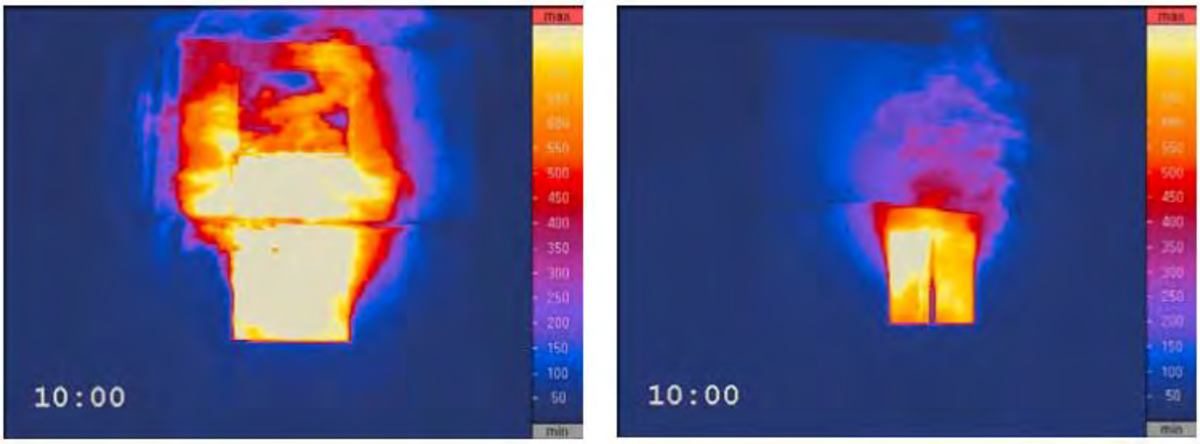

Figure 2: thermal images outside of a compartment with combustible linings (left) and non-combustible linings (right) 10 minutes after ignition, from Frangi and Fontana (2005)

Temperatures near the windows were higher than temperatures at the rear of the compartment. However, no significant temperature differences were measured between the compartment fires. Based on the results, the authors concluded that a significant portion of the combustion took place outside the window as the combustion inside was limited by the oxygen supply.

3.4 Frangi et al. (2008)

A full scale fire test of a 3-storey building was reported by Frangi *et al.* (2008). Prior to the fire test, the test building withstood a shaking table test. The aim of the research was supplying documentation and information regarding the use of CLT (XLam).

The fire room was surrounded by two rooms on the same floor, one room at the ground floor and one room at the top floor. The inner dimensions of the ignited room were 3.34 x 3.34m and the room had two windows of 1.0 x 1.0m and a 60 minute fire resistant door. All except one wall were made of 85mm thick XLam panels. The inner surfaces of these walls were insulated using 27mm mineral wool and protected using one layer of 12mm standard gypsum board and an exposed layer of 12.5mm fire proof gypsum board. The other wall was a room dividing wall made of 142mm thick XLam panels, which was only protected by mineral wool insulation and a layer of 12mm standard gypsum board. The floors were constructed using 142mm thick XLam panels and were covered with 60mm sand, 50mm concrete topping and wooden flooring. Mineral wool and a single layer of 12mm fire proof gypsum plaster board insulated the ceiling. The exterior walls were insulated on the outside using 120mm wood fiber finished with 10mm plaster.

In addition to measurements of gas temperatures, temperatures were measured in the interfaces of the different layers in the walls, floor and ceiling. The gas was analyzed at a single point at 2.2m above the floor. Air pressure measurements were made at the top and bottom of both windows. Two heat flux meters were positioned 3.0m outside the window. Additionally, the temperature of the reinforced glass of the upper floor windows was measured.

The results showed a rapid increase of gas temperatures in the first 10 minutes and after approximately 35 minutes. The latter was caused by the failure of the single layer of standard gypsum board protection that was applied on the thickest CLT wall. Increased flaming outside of the apartment confirmed an increased intensity (Figure 3). Temperatures behind the two layers of gypsum plaster board rapidly increased at approximately 50 minutes after ignition. The results suggested that the insulation behind the gypsum boards fell off almost immediately after the gypsum board failed. Decay of the fire was observed after approximately 55 minutes and the fire was manually extinguished after 60 minutes. The windows of the upper floor did not fail and there was no fire and smoke spread to the upper floor.

Figure 3: Fire after 32 minutes (left) and 40 minutes (right)

The authors concluded that the fire spread in timber buildings could be limited to one room using only passive fire protection. They also concluded that the damage on the XLam panels was relatively small after the test.

3.5 Kampmeier (2009)

As part of a research of multistory timber buildings a compartment fire test was performed at the Braunsweig University of Technology, Germany (Kampmeier, 2009). The aim of the study was assessing the smoke permeability of joints and firefighting strategies concerning timber compartments under fire conditions. This compartment was subjected to a standard fire.

A compartment (walls and ceiling only) with inner dimensions of 3.8 x 3.8 x 1.5m was placed on top of a furnace with inner dimensions of 3.8 x 3.8 x 1.4m. Therefore the effective height of the fire compartment was 2.9m. Two walls were made of 120mm thick CLT (BSpH) and the other two walls and roof were made of 116mm thick CLT (BSH). One of the four walls was protected using a layer of $K_2$15 gypsum board and another wall was protected using a layer of $K_2$30 gypsum board. $K_2$15 and $K_2$30 are German classes, recently converted into European classes ($K_2$10, $K_2$30, $K_2$60) determined in accordance with EN 13501-2 (2009), and correspond to an encapsulation time of 15 and 30 minutes, respectively. Hereby, the encapsulation time is defined as the time required in a standard fire test for the temperature at the unexposed surface of the protective cladding to increase 270°C in a single point or 250°C on average. The other surfaces were unprotected. Three different in plane joints were applied and assessed for smoke-tightness.

Smoke penetration through the joints was observed in several places. Kampmeier stated that joints should not have cavities exceeding 2mm or should be sealed using fire retardant smoke tight seal. A double tongue and groove connection performed best.

After 65 minutes the fire brigade started extinguishing the fire. Temperatures inside the timber at a depth of 10mm dropped rapidly. Temperatures deeper in the specimens dropped more slowly and it took approximately 10 minutes before all measured temperatures inside the timber were below 200^{o}C. After this, at 70mm deep the temperature kept increasing for another 10 to 15 minutes. However, it was concluded that there was no potential for re-ignition.

The encapsulation time corresponding to the $K_2$15 gypsum board was approximately 29 minutes. This was significantly less than the encapsulation time of 55 minutes that corresponded to the $K_2$30 gypsum board.

3.6 Lennon et al. (2010)

Lennon *et al.* (2010) performed three compartment tests in order to assess protected engineered timber floor systems in a natural fire. The compartments were made from concrete blocks and an engineered timber floor system exposed from below. The inner dimensions of the compartments were 4.0 x 3.0 x 2.4m and the dimensions of the two ventilation openings were 0.7 x 1.0m. The tested floors were solid timber floor joists (test G1), engineered I section joists (test G2) and engineered truss joists (test G3). A uniformly distributed load of 0.75kN/m^2 was placed on top of the floor to resemble a typical load of a residential building during a fire.

This project aimed to compare the structural failure caused by fire between engineered floor joists and more conventional solid timber joists. The floors were designed to achieve 60 minutes fire resistance. Therefore, the solid timber joists were protected from below (the exposed side) using two layers of 12.5mm type F gypsum board and the engineered timber joists were protected using two layers of 15mm type F gypsum board.

Gas temperatures and temperatures in the floors were measured using thermocouples. Wood cribs were used as fuel for the fire, resulting in a fire load density of 450 MJ/m^2. Failure of the gypsum board was reported in all tests and occurred fastest in the solid timber joist floor (after 30 minutes).

Table 3: Overview of tested floor joists (Lennon *et al.*, 2010)

	Overall dimensions (mm)	Flange dimensions (mm)	Web	Cladding
Test G1	45 x 220	-	-	2 layers of 12.5mm type F gypsum board
Test G2	45 x 220	45 x 45	9 mm OSB	2 layers of 15mm type F gypsum board
Test G3	72 x 220	72 x 45	Cold formed steel pressed web	2 layers of 15mm type F gypsum board

From this work it was concluded that the two-layers of 15mm gypsum board protecting the engineered joists were very effective and offered protection until the decay phase. The thinner layers of gypsum protecting the solid timber floor joists were significantly less efficient.

The OSB I-section joists may be capable of resisting 60 minutes of natural fire, considering it is protected using two layers of 15mm type F gypsum board. The engineered (steel) truss joint showed large deflections of up to 90mm, which was almost three times as much as the deflections of the solid timber joists.

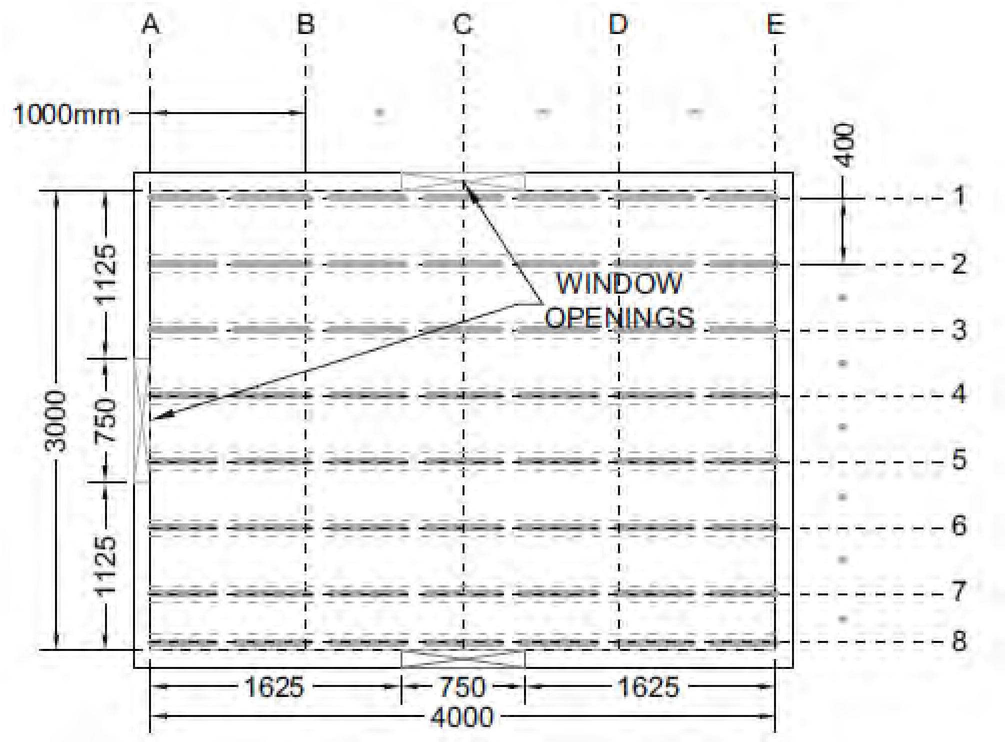

Figure 4: Floor plan, from Lennon *et al.* (2015)

3.7 Peng et al. (2011)

Peng *et al.* (2011) presented an experimental study of fires in an old building in Lijiang, China. The building comprised of six rooms of 3.0 x 5.7m, with only a single door opening, as shown in Figure 5. The walls were entirely made from wood and the fuel for the fire was either raw wood or furniture. Six tests were performed in order to assess the influence of locations of the ignition, the fuel type and the presence of a ceiling under the gable roof on the fire spread. Furthermore, one of the tests included a single sprinkler in order to study the effect of sprinklers to the fire spread. Gas temperatures were measured in the center of the ignited room and in the center of the adjacent room. An overview of the tests is given in Table 4.

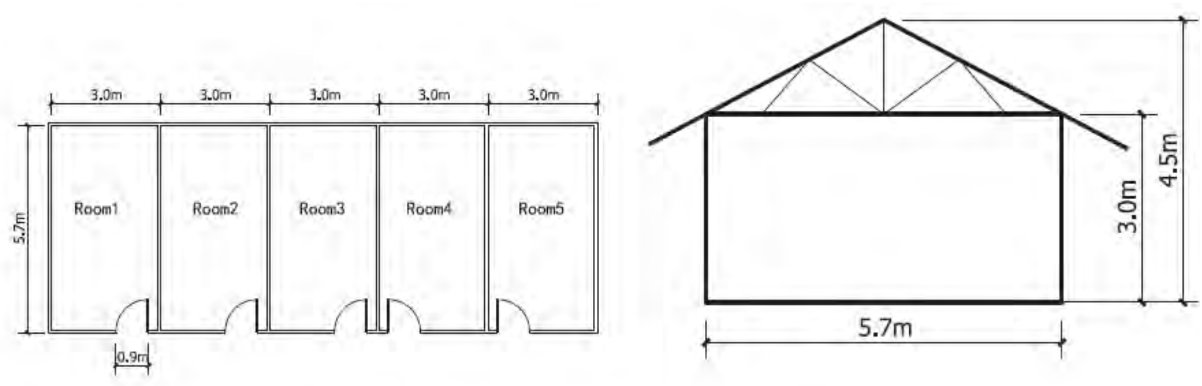

Figure 5: Floor plan and cross section of test building, from Peng *et al.* (2011)

Table 4: Overview of tests and test results, from Peng *et al.* (2011)

	Fuel	Location of ignition	Ceiling	Active fire protection	Door	Time for fire to spread to adjoining room (min)
Test H1	Raw wood	Room corner	With	Sprinkler	Open	-
Test H2	Raw wood	Room corner	With	-	Open	-
Test H3	Furniture	Room corner	Without	-	Open	15
Test H4	Furniture	Room corner	With	-	Open	27
Test H5	Raw wood	Room corner	Without	-	Open	23
Test H6	Raw wood	Room center	Without	-	Open	33

The authors concluded that the fire spread is faster if the ignition source is near a wall and that the fire spread to adjacent rooms can be postponed by the presence of a ceiling under a gable roof. They also concluded that the sprinkler effectively limited the fire spread. However, it should be noted that a lot of technical information, such as fire load density and a description of the structural materials, is missing in the paper.

3.8 McGregor (2013), Li et al. (2014) and Medina Hevia (2014)

At the Carleton University Fire Research Laboratory a total of eleven compartment tests were performed aiming to quantify the contribution of CLT to compartment fires (McGregor, 2013; Li *et al.*, 2014; Medina Hevia, 2014). The inner floor dimensions of all tested compartments were 3.5 x 4.5m and the inner room height was 2.5m. One door opening of 2.0 x 1.1m allowed ventilation in the room during the fire. The walls, floors and ceilings of all compartments were made of 105mm thick 3-ply CLT comprising lamellas of 35x89mm.

McGregor (2013) performed separate propane fueled and furniture fueled tests. The tests included measurements of the gas temperature as well as measurements of temperatures of the walls and ceiling at varying depths. Furthermore, a plate thermometer was positioned 0.1 m from a wall without an opening at a height of 1.5m. Gas analysis of all extracted gas allowed determining the heat release of the fire.

In McGregor's propane fueled fire tests the propane flow was controlled and the heat release rate corresponding to propane was calculated. The contribution of the CLT to the heat release rate was then calculated by excluding the heat release rate corresponding to propane from the measured heat release rate (Figure 6 and 7). In one of the propane fueled tests, test I1, the CLT was protected using 2 layers of 12.7mm fire rated gypsum board. The remaining test, test I3, comprised of directly exposed CLT.

McGregor also performed three furniture fueled tests of which two comprised fully protected CLT and one comprised unprotected CLT. By assuming that fully protected CLT does not contribute to a compartment fire, the heat release rate and temperature increase corresponding to timber could be determined (Figure 8). This assumption was confirmed using the results of the propane fueled test. Table 5 gives an overview of the estimated heat released corresponding to the movable fire load and the CLT.

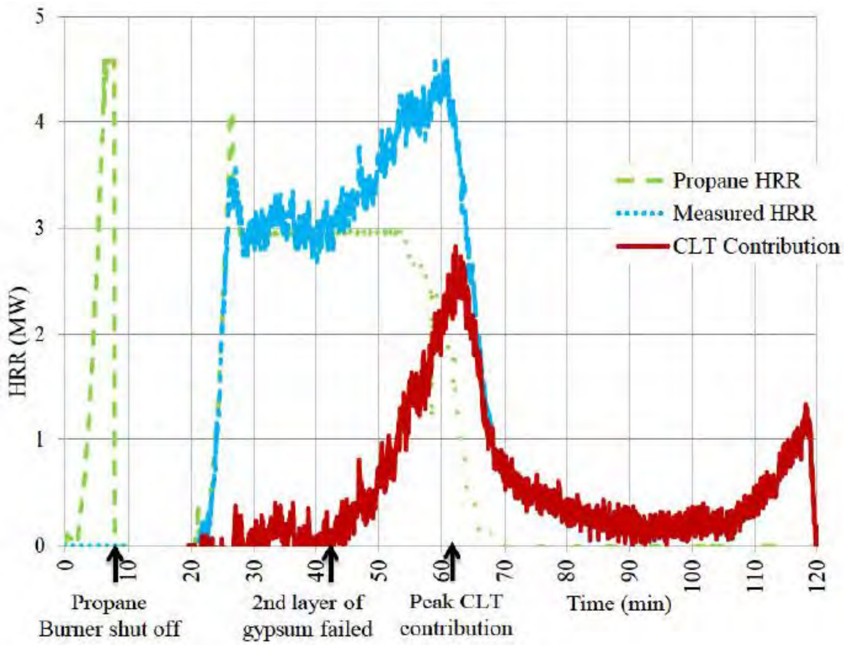

Figure 6: Heat release rate corresponding to propane, the measured heat release rate and the air velocity of the extracted air (test I1), from McGregor (2013)

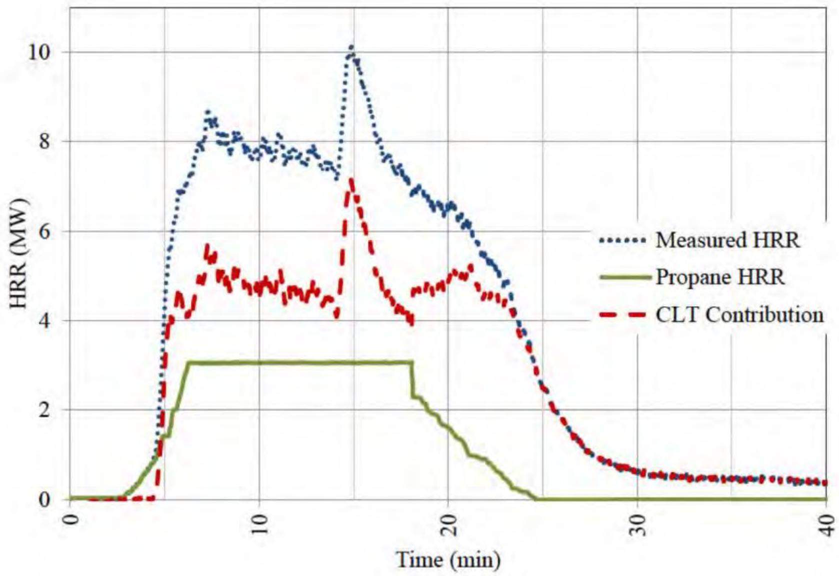

Figure 7: Heat release rate corresponding to propane, the measured heat release rate and the contribution of CLT (test I3), from McGregor (2013)

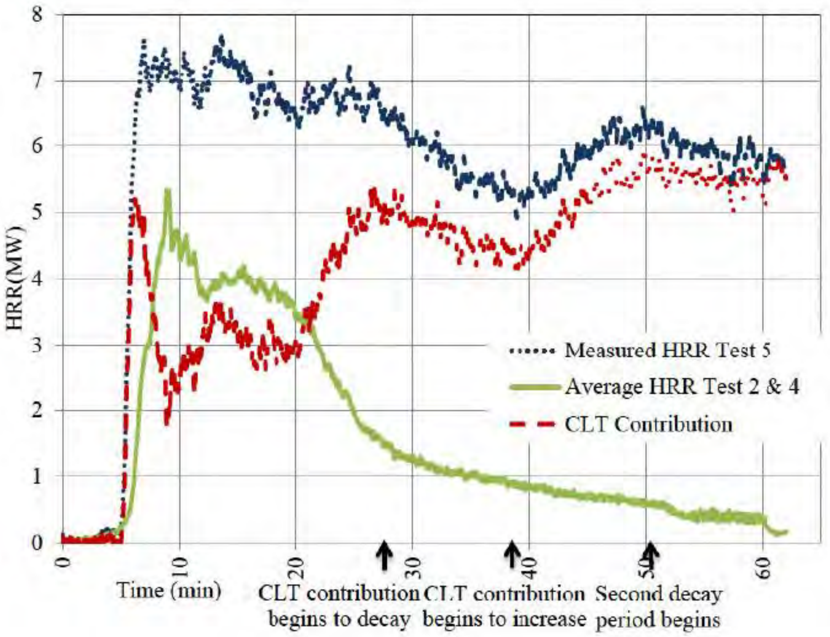

Figure 8: The CLT contribution derived from HHR results of test I5, I2 and I4, from McGregor (2013)

The publication by Li *et al.* (2014) included the three furniture fueled tests described by McGregor (2013) thesis. In addition, Li *et al.* presented three tests including light timber frames or light steel frames of the same size and with comparable movable fire loads. The light steel or timber framing was attached inside a CLT compartment in order to maintain structural stability during the test. One compartment comprised of light steel frame protected by a single layer of 12.5mm Type C gypsum board attached directly onto the studs. A similar test was performed using timber studs instead of steel studs and a third test was presented using a second layer of gypsum board to protect a similar timber frame. All frames were filled with fiberglass.

Table 5: Contribution of CLT to compartment fires (McGregor, 2013)

	Propane		Furniture		CLT	Total heat released (MJ/m^2)
	Heat released (MJ/m^2)	Furniture equivalent (MJ/m^2)	Measured heat released (MJ/m^2)	Estimated fire load (MJ/m^2)	Calculated heat released (MJ/m^2)	
Test I1	486	710	-	-	200	686
Test I2	-	-	379	533	-	379
Test I3	182	266	-	-	408	590
Test I4	-	-	364	553	-	364
Test I5	-	-	366	529	612	978

The authors showed that the temperatures and the heat release rates were similar for all protected tests (I2, I4, J1, J2 and J3). In these tests, the fully developed phase was reached 10 minutes after ignition and lasted for approximately 15 minutes. The mean heat release rate measured during the tests was between 3.6 and 4.1 MW. Decay started 25 minutes after ignition and the fire became fuel controlled instead of ventilation controlled. The tests showed that gypsum board on a light steel frame fell after only 23 minutes off the walls, while the same gypsum board on a timber frame wall remained in place for 60 minutes.

Medina Hevia (2014) performed three tests of similar compartments comprising different extents of protected area. The aim of the work was studying the contribution of CLT to a compartment fire corresponding to several configurations of protected and unprotected CLT surfaces. Furniture was used to fuel the tests and the fire load density and the positions of furniture were the same as in McGregor's furniture fueled tests (Figure 9). This allowed straight forward comparisons between tests of both authors, as shown in Figure 10 and Figure 11. The studies of McGregor and Medina Hevia quantified the contribution of exposed CLT in compartment fires.

It was concluded that unprotected CLT contributes to the fire growth rate, the intensity and the duration of the fire and that the contributions are generally more significant if more surface is exposed. Medina Hevia demonstrated that the fire tested compartment comprising one unprotected wall, accounting for 29.7 % of total room wall area, performed similarly to a fully protected compartment and resulted in self-extinguishment after the room contents were consumed. The compartments comprising two exposed walls showed delamination of CLT lamellas, which resulted in second flashovers. It was found that two opposing walls that were unprotected led to higher heat release rates than two adjacent walls. Furthermore, it was concluded by McGregor that CLT protected by two 12.7mm layers of fire rated gypsum plaster board did not noticeably contribute to the duration or intensity of compartment fires if fall-off of gypsum did not occur. Once the gypsum board failed, the CLT increased the intensity of the fire and a second flashover occurred. In the same way delamination of the CLT has led to a second flash over.

In the early stages of the fire the room temperatures were similar for all tests. Exposed CLT seemed to delay the temperature drop or decay of the fire.

Figure 9: Interior of Test K3, from Medina Hevia (2014)

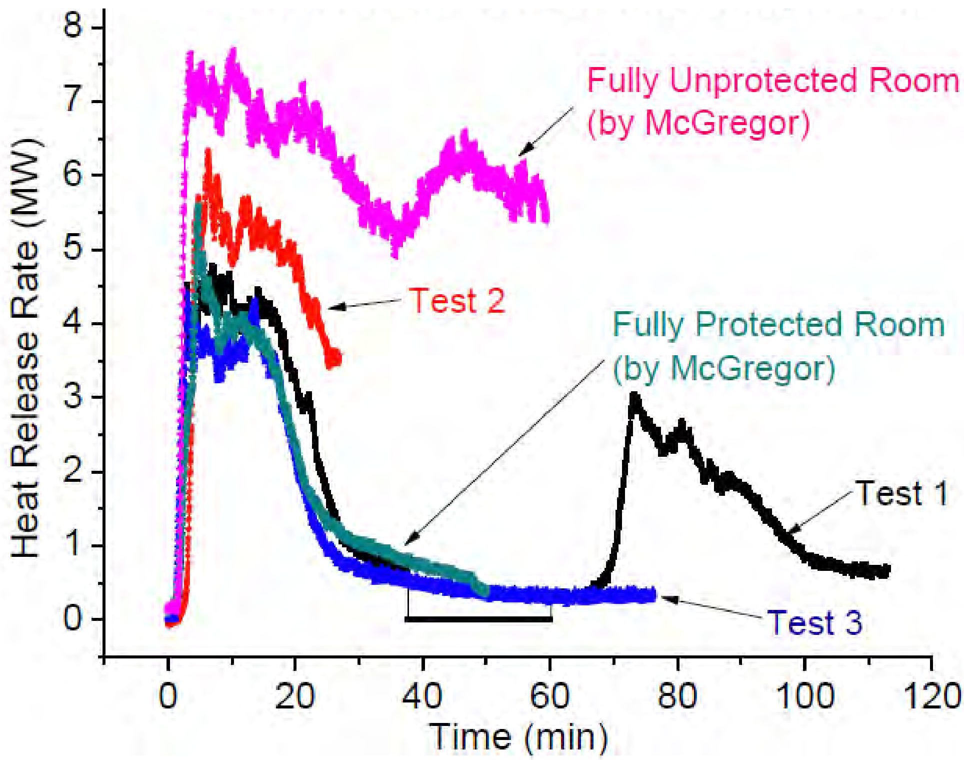

Figure 10: Comparisons between HRR corresponding to test K1, K2, K3 and test I2 (fully protected) and I5 (unprotected)

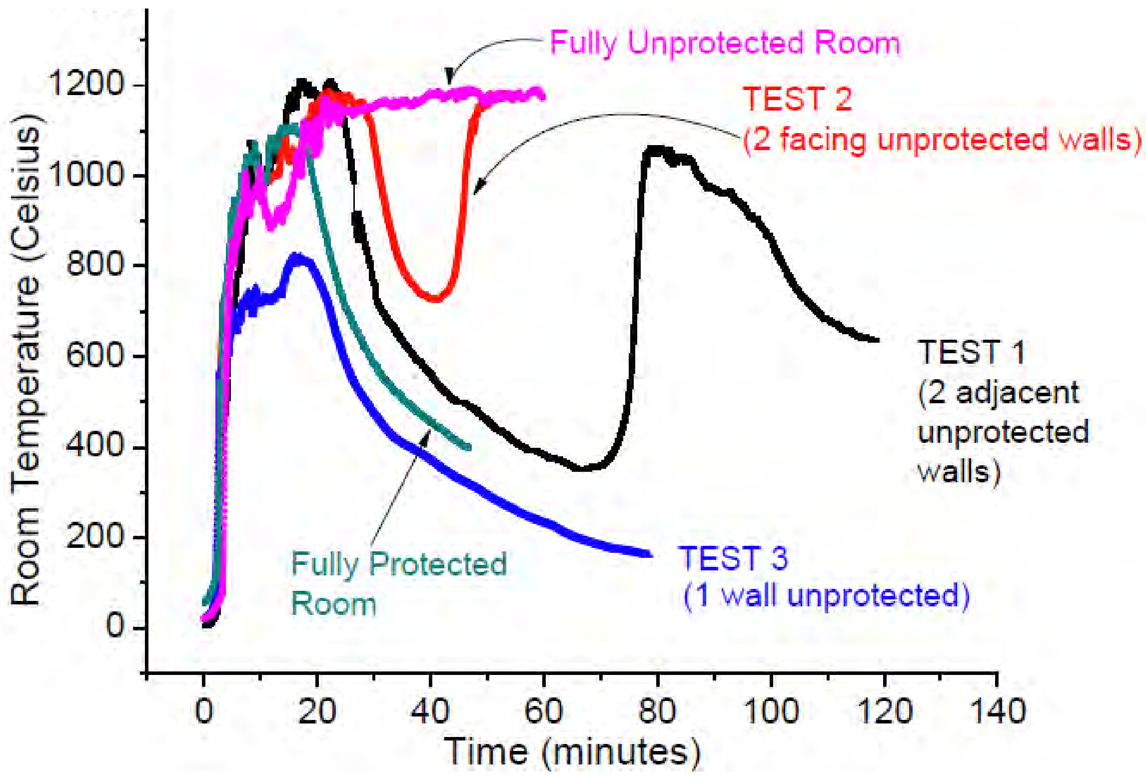

Figure 11: Comparisons between temperatures corresponding to test K1, K2, K3 and test I2 (fully protected) and I5 (unprotected)

3.9 Kolaitis et al. (2014)

A single relatively small compartment test was performed by Kolaitis *et al.* (2014). The inner dimensions of the compartment were 2.2 x 2.2 x 2.1m and there was a single opening of 0.43 x 0.98m. The aim of the study was assessing gypsum plasterboard and wood based panels as cladding materials. The test was fueled using one wood crib with an average fire load density of 420MJ/m^2. Two out of four exterior walls were made of 95mm thick 5-ply CLT protected by a double layer of 12.5mm type DF gypsum plaster board and 40mm Rockwool between the gypsum and CLT. The other two walls were made of timber frames filled with Rockwool comprising 80 x 40mm timber studs and 10mm plywood on both sides. These light frame walls were protected using two layers of 12.5mm type DF gypsum plaster board. A separate light frame interior wall was positioned in the room and was cladded using a double layer of chipboard on one side and a double layer of MDF on the other side. Gas temperatures, surface temperatures and temperatures inside the walls were measured using thermocouples. Additionally, an infrared camera in front of the opening aiming at the interior surface of the northern wall was used to assess the temperature variations. A gas analyzer measured the concentrations of the O_2, CO_2, CO, SO_2, NO, NO_2 and total NOx 300mm below the ceiling (see Figure 12).

The test was stopped after 45 minutes and it was concluded that there was no charring on walls that were protected using gypsum board. The MDF cladding of the interior wall failed after 35 minutes, but the chipboard did not show failure within 45 minutes. The average gas temperatures were found to be below the ISO 834 (1999) and the Eurocode 1 (2002) standard fire curve.

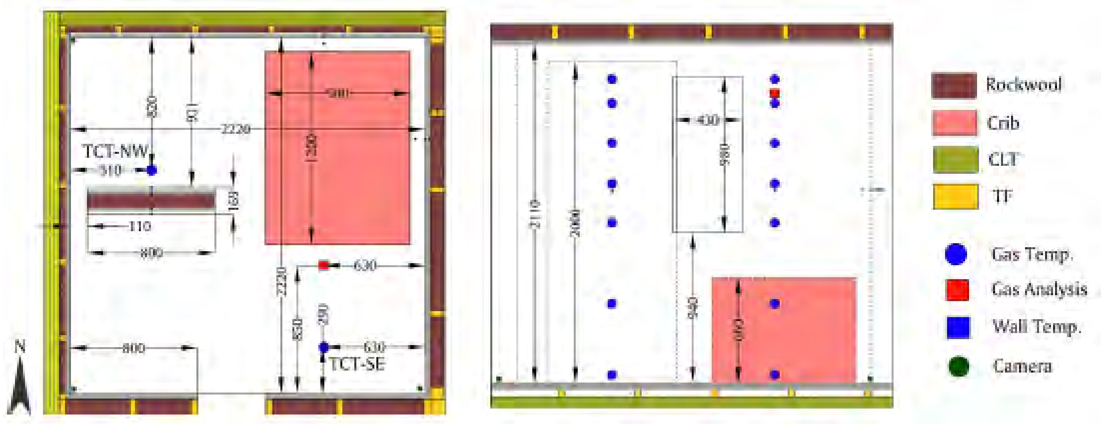

Figure 12: Floor plan (left) and vertical cross section (right), from Kolaitis *et al.* (2014)

3.10 Su and Lougheed (2014)

Su and Lougheed (2014) presented four tests of furnished compartments that were performed at the National Research Council of Canada. The test setup consisted of three stories representing a portion of a 6-storey residential building. The middle storey represented a typical furnished apartment with inner dimensions of 6.3 x 8.3 x 2.4m (Figure 13) comprising a living room, a bathroom and a bedroom. The living room and the bedroom both had a window of 1.5 x 1.5m and there was a steel entrance door with a 45 minute fire protection rating in the hallway.

The compartments were built using different structural systems: light weight timber frame (test L1 and L4); CLT (test L2); and light steel frame (test L3). The aim of the study was assessing encapsulation of combustible construction materials as a fire protection, through a comparative study between fires of light weight timber, CLT and non-combustible light steel frame compartments. All compartments had a similar non-load bearing wall, WA4, which was made of 38 x 89mm wood studs for test L1, L2 and L4 or 250S162-33 steel studs for test L3 protected by a single layer of 12.7mm regular gypsum plaster board on both sides. Additionally, WA4 was insulated using glass fiber for test L1, L2 and L3. The design of WA4 corresponded to the absence of fire resistance requirements.

The CLT compartment walls consisted of 105mm thick 3-ply CLT, insulated using a 38mm thick layer of glass fiber and protected using two layers of 12.7mm type X gypsum board on the exposed side. Protection on the unexposed side varied per wall. The floor and ceiling were constructed using 175mm thick 5-ply CLT panels. The exposed ceiling was protected using 2 layers of 12.7mm type X gypsum board. The exposed floor was covered with two layers of 12.7mm cement board and a floating hardwood floor. Concrete blocks were put in the highest storey to replicate the weight of the furniture and contents of the middle storey (the fire floor).

The light weight timber frame apartments of tests L1 and L4 were constructed from closely spaced studs and a 15.9mm OSB panel as a shear layer on one side (the least vulnerable side of the walls). Glass fiber insulation was applied in all timber frames and two layers of gypsum board were applied on both sides of the walls. The Floor and ceiling were constructed using I joists with a depth of 241mm and 15.9mm OSB subfloor sheathing. The ceiling comprised of two layers of 12.7mm type X gypsum board that protected the I joists. At locations where the walls met the I joist floor, the layers of gypsum board were interrupted. Glass fiber insulation was applied in the ceiling and the floors.

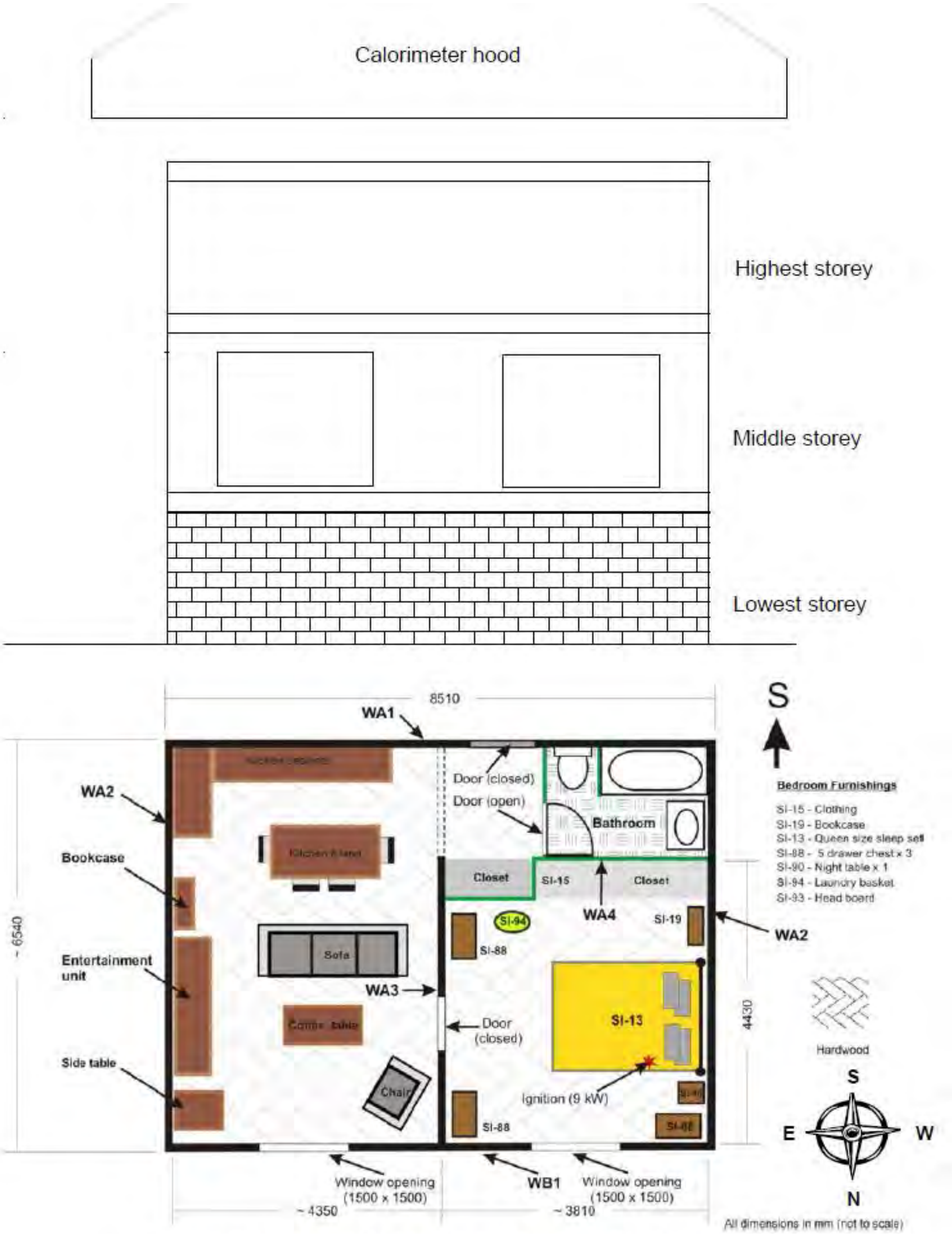

Figure 13: Large-scale compartment test setup, from Su and Lougheed (2014)

The light steel frame apartment of test L3 comprised of cold formed metal studs. All surrounding walls of the compartment were insulated using glass fiber. Walls WA1 and WA2 and WA3 (see Figure 13) were protected by one layer of 15.9 mm type X gypsum plaster board on both sides. WA4 and WB1 were cladded using regular gypsum boards. The floor and ceiling were constructed using cold formed steel joists and a galvanized steel and concrete composite floor. All apartments tested had a hardwood floor finish. The ceiling comprised of a single layer of 12.7mm type X gypsum board that protected the steel joists. At locations where the walls met the ceiling, the layer of gypsum board was interrupted. The ceiling and the floor of the compartment were not insulated.

Measurements of the heat release rate were performed through calorimetry of the extracted air. The heat flux was measured 3.5m above, and 2.4 and 4.8m in front of both openings using heat flux sensors. Furthermore, numerous measurements of the air temperatures and temperatures inside the floor, walls and ceiling were made using thermocouples.

The encapsulation times were determined using temperature measurements on the surface of the protected material. Encapsulation time was defined as the time it took for the temperatures to rise 250ºC on average or 270ºC in a single point on the interface between the encapsulation and the protected layer. The shortest encapsulation times were seen in test L3 with the light weight steel frame compartment as the gypsum plaster board and the sheathing near the window failed within 20- minutes. The shortest encapsulation times in the light weight timber frame compartments concerned the ceiling of the bedrooms and were 30 and 23 minutes for Test L1 and L4, respectively. Temperature measurements in the cavities indicated that the low fire performance of the non-load bearing and non-fire rated wall WA4 led to a decrease of the encapsulation performance of the ceiling above this wall, as temperature measurements in the ceiling cavities near the wall indicated a breach in the ceiling. Failure of the encapsulation led to an increase of heat release rate in steel frame and timber frame assemblies (Figure 15). The encapsulation times corresponding to the CLT compartment were highest, e.g. 65-99 minutes for wall panels. After 170 minutes visible flames at the ceiling CLT panels and an increase of the heat release rate were observed.

The authors concluded that the encapsulation effectively delays the time at which wood starts to contribute to fire growth and fire spread. The encapsulation was most effective for CLT apartments, for which the authors state that the CLT did not contribute to the fire growth and fire spread before 175 minutes had past.

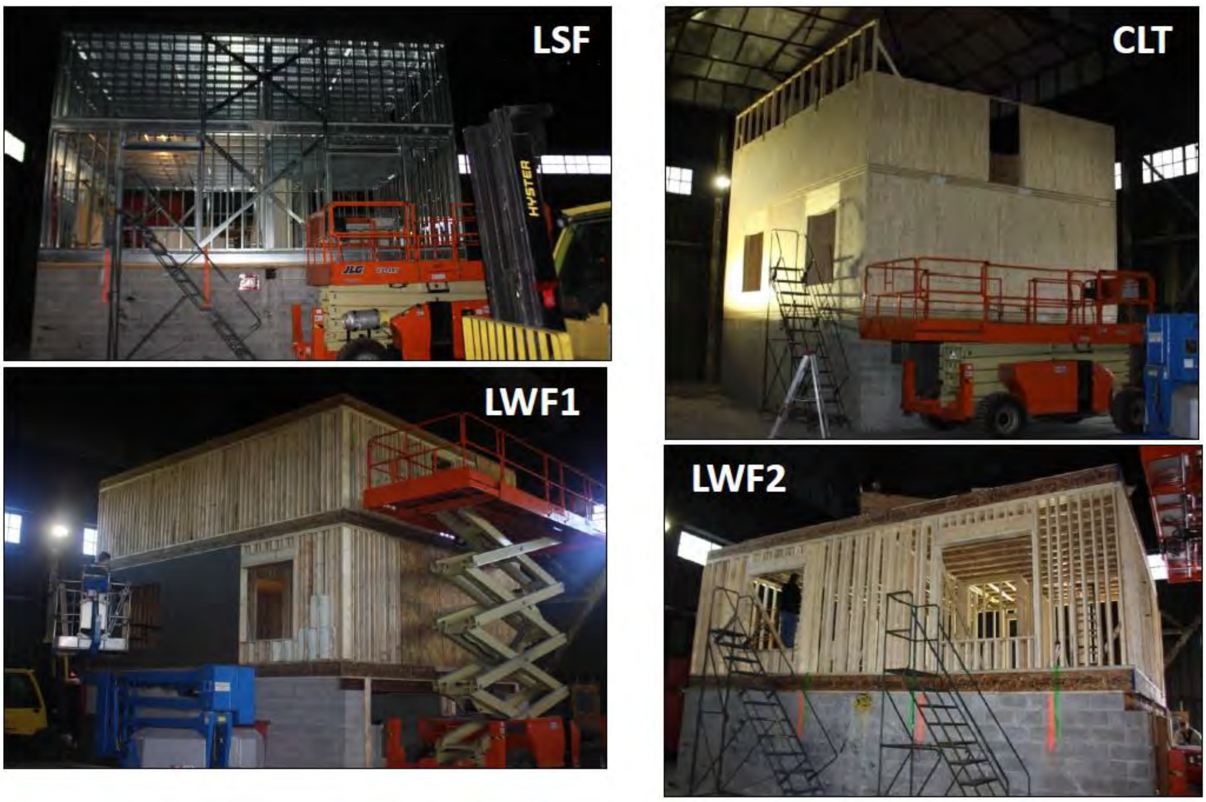

Figure 14: Compartments of test L1 (LWF1), L2 (CLT), L3 (LSF) and L4 (LWF2) under construction, from Su and Lougheed (2014)

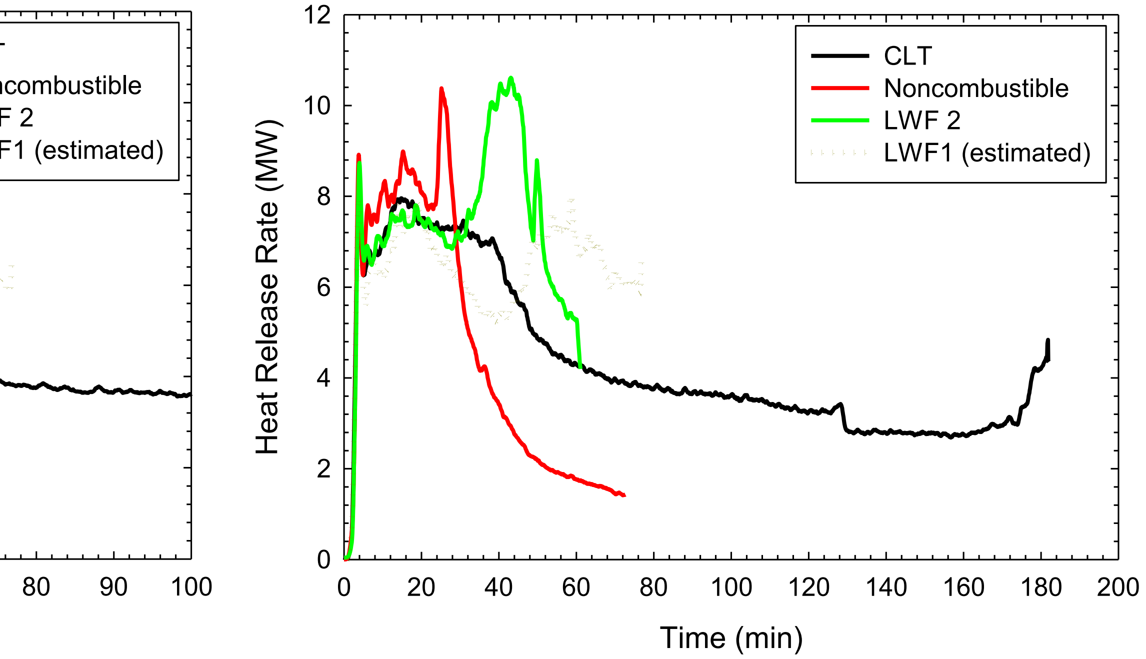

Figure 15: Heat release of test L1 (LWF1), L2 (CLT), L3 (LSF) and L4 (LWF2), from Su and Lougheed (2014)

3.11 Su and Muradori (2015)

Su and Muradori (2015) presented one single large scale fire test of compartments that represented a section of a 13-storey residential building. The setup comprised of an apartment that was located next to an elevator shaft. This project aimed to demonstrate the fire performance of a CLT stair or elevator shaft that was adjacent to an apartment under severe fire. The project was initiated in relation to the design of a 13-storey residential building made of timber in Quebec City.

The inner dimensions of the apartment were 5.2 x 4.6 x 2.7m and the inner dimensions of the elevator shaft were 4.6 x 2.5 x 8.8m. The apartment had a window opening of 2.5 x 1.9m and a door with a 45-minute fire protection rating. All walls were made from 175mm thick 5-ply CLT and the apartment shared a wall with the elevator shaft. The surfaces of the CLT were protected using two layers of 16mm type X gypsum board directly applied on the CLT. The ceiling was insulated using 90mm thick non-combustible fiberglass and protected using one layer of 16mm type X gypsum plaster board. The wall separating the apartment room from the elevator shaft was additionally protected using non-combustible rigid mineral wool and an additional 13mm gypsum board. Concrete blocks were put on top of the ceiling assembly to induce a total load (including the self-weight) of 4.74 kPa.

Temperatures were measured systematically in the interfaces between CLT and the gypsum boards and on the unexposed sides. Additionally, gas temperatures were measured at several heights in the room using two separate thermocouple trees. In the elevator shaft the gas temperatures were measured and an optical density meter was installed at a height of 7 meters to monitor the smoke development in the shaft during the fire.

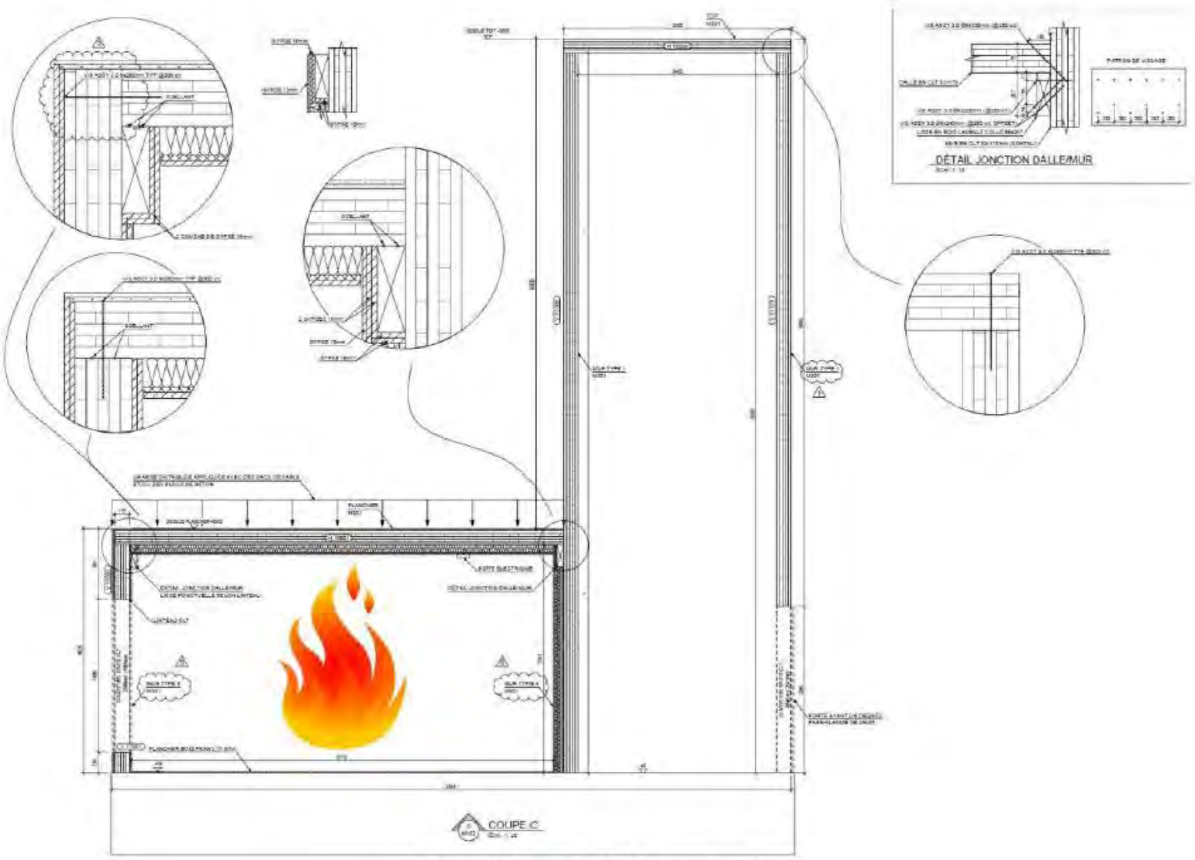

Figure 16: Vertical cross section of apartment and stair/elevator shaft, from Su and Muradori (2015)

Results showed that the CLT ceiling panels started to be involved in the fire, after falling of the cladding occurred, approximately 15 minutes after ignition. Based on the temperature measurements at the CLT surface the encapsulation time corresponding to the wall between the apartment and the shaft was 91 minutes and the lowest encapsulation time measured in another wall was 57 minutes. No changes of temperature and smoke density were observed in the shaft, leading to the conclusion that the rather severe fire had no impact on the conditions in the shaft.

3.12 Southwest Research institute & Marc Janssens (Ongoing)

Very recently, two tests on furnished living rooms have been conducted for an ongoing research performed by the Southwest Research Institute in collaboration with Dr. Janssens. The tests were performed in September 2015 and results are not yet published. However, information is available through a video presentation of Janssens (2015).

The inner dimensions of both tested compartments were 4.1 x 3.6 x 2.4m. Both had an opening of 1.9 x 2.1m. The first tested compartment comprised of 5-ply CLT walls and a 6 inch deep nail laminated timber (NLT) ceiling. The second compartment was constructed using 5-ply CLT for the walls and the ceiling. All interior surfaces were protected using 2 layers of 15mm of type X gypsum board.

Heat release rate calorimetry of the extracted air was performed. Gas temperatures and internal wall and ceiling temperatures were measured using thermocouples. Additionally, a total of three plate thermometers were positioned in front of two walls and the ceiling for determining heat fluxes.

A structural load of 1.82 kN/m^2 (40 psf) was applied on top of the compartment. The fire load densities of both tests were based on the 90th and the 95th percentile of fire loads found through a Canadian survey of fire load densities in living rooms which was performed by the National Research Council of Canada (Bwalya *et al.* 2011).

Both tests showed very similar results, showing a peak temperature of approximately 1200°C, approximately 23 minutes after ignition. The peak heat release rate was of test 1 was approximately 5.5MW which was approximately 0.5 MW higher than that of test 2. In both tests, flashover occurred after approximately 4 minutes. Subsequently the fires remained fully developed for approximately 10 minutes, before they decayed.

The first test was terminated after 3 hours and the second test was terminated after 2:15h. In both tests a part of the first layer of gypsum plaster board fell of the ceiling. In a small area of the ceiling in the first test, the second layer fell as well. The impact of the fire was most intense at the ceiling. However, temperatures measured in between the two layers of gypsum board did not exceed 250°C. Between the gypsum board and the CLT or NLT measured temperature never exceeded 95°C. Very local and minor damage was observed on the timber with charring depths less than 6 mm.

3.13 SP Fire Research (Ongoing)

SP Fire Research in Trondheim, Norway, is currently conducting research of compartment fires, aiming to improve the knowledge of fire development in solid wood structures. Two tests have been performed recently of a 5.8 x 2.3 x 2.8m compartment, which represented a bedroom with bathroom in a 9-storey student accommodation.

The compartment comprised of protected walls and unprotected solid timber walls, an unprotected ceiling, a window and an open door providing entrance from the corridor.

The aim of the first test was assessing the effect of sprinklers and the activation time of a fire alarm in a fire with rapid fire growth. In the second test, sprinklers were deactivated and a post-flashover fire was studied. The fire load comprised mainly of a mattress, wooden pallets and wood cribs and the fire load density was based a statistical study of fire performed by Ramboll Norway. Results and technical details have not yet been published, but will be published by K.Hox.

4 Overview of results

Table 6 gives an overview of test results. In this table the abbreviations N.F. (not found) and N.A. (not applicable) have been used in case results were not available. The shortest failure time of gypsum board is given per layer. Here, the exposed layer is referred to as the first layer.

Care should be taken when interpreting the results. Information given by different authors is often achieved in a different way. An example concerns the falling of gypsum plaster boards, as some authors documented minor falling of plaster boards, while others only reported failure if a more significant surface fell.

Table 6: Overview of test results

Test	Opening factor	Main structural members	Thickness and type of gypsum board protection	Movable fire load density (MJ/m^2)	Test duration (min)	Shortest time to falling of gypsum per layer (min)	First start of charring or encaps. Time (min)	Time to flashover (mm:ss)	Approx. peak temp. (ºC)	Avg. HRR during fully developed fire (MW)	Total heat release after test (MJ/m^2)	Approx. time to start of decay (min)	Average charring rate (mm/min)
A1	N.F.	LTF	N.F.	N.F.	64	N.F.	50[4]	24:00	1000	6,0	N.F.	no decay	0,75
B1	0,042	HLT	none	900[1]	50	N.A.	3	04:50	1100	N.F.	571	no decay	0.8
B2	0,042	HLT	12.5mm type A	900[1]	46	13	20	04:30	1000	N.F.	N.F.	no decay	0.6[2]
B3	0,042	HLT	12.5mm type A 15.4mm type F	900[1]	169	1st: 27 2nd: >169	40	06:00	1200	N.F.	610	35[4]	4[2]
B4	0,042	LTF	12.5mm type A 15.4mm type F	900[1]	48	1st: 32 2nd: *N.F.*	39	06:10	1200	N.F.	N.F.	36[4]	3[2]
C1	0,041	LTF	none	N.F.	N.F.	N.A.	N.F.	N.A.	N.A.	N.F.	N.F.	N.F.	N.A.
C2	0,041	LTF	none	N.F.	N.F.	N.A.	N.F.	N.A.	N.A.	N.F.	N.F.	N.F.	N.A.
C3	0,041	LTF	none	N.F.	N.F.	N.A.	N.F.	N.A.	N.A.	N.F.	N.F.	N.F.	N.A.
C4	0,041	LTF	18mm non-comb.	234	N.F.	1st: 30	N.F.	06:00	1050[4]	N.F.	N.F.	45[4]	N.F.
C5	0,041	LTF	none	211	N.F.	N.A.	N.F.	04:27	N.A.	N.F.	N.F.	N.F.	N.F.
C6	0,041	LTF	15mm non-comb. 12.5mm non-comb.	237	N.F.	N.F.	N.F.	06:58	N.A.	N.F.	N.F.	N.F.	N.F.
D1	0,040	LSF	12.7mm cementb. 15.7mm type X[3]	397,2	29[4]	N.F.	N.A.	04:00	990	3,1	N.F.	9	N.A.
D2	0,040	LSF	12.7mm cementb. 15.7mm type X[3]	366,1	22[4]	N.F.	N.A.	03:00	990	2,9	N.F.	13	N.A.
E1	0,032	CLT	12mm standard 12mm fire proof[3]	790	60	1st: 53 2nd: 57	N.F.	35:00	1100[4]	N.F.	N.F.	55	N.F.
F1	0[7]	CLT	31% of CLT $K_2$15 or $K_2$30	N.F.	95	N.F	$K_2$15: 29 $K_2$30: 55	N.A.	Stand. fire	N.F.	N.F.	Stand. fire	N.F.
G1	0,024	LTF	12.5mm type F 12.5mm type F	450	56	2nd: 30	N.F.	19[4]	1084	N.F.	N.F.	40[4]	N.F.
G2	0,024	LTF	15mm type F 15mm type F	450	>60	no falling reported	N.F.	20[4]	1034	N.F.	N.F.	52[4]	N.F.
G3	0,024	LTF	15mm type F 15mm type F	450	56	2nd: 40	N.F.	19[4]	1036	N.F.	N.F.	no decay	N.F.
H1	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
H2	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
H3	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
H4	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
H5	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
H6	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
I1	0,042	CLT	12.7mm fire rated 12.7mm fire rated	486	119	2nd: 107	26[4]	04:57	1150	4,6[5]	686	25	N.F.
I2	0,042	CLT	12.7mm fire rated 12.7mm fire rated	533	53	1st: 37,1 2nd: >53	N.F.	07:30	N.A.	4,0	379	24	N.F.
I3	0,042	CLT	none	182	53	N.A.	5	04:55	980	8,8[5]	590	45	0,63
I4	0,042	CLT	12.7mm fire rated 12.7mm fire rated	553	53	1st: 39 2nd: >53	N.F.	09:26	1000	4,0	364	26	N.F.
I5	0,042	CLT	none	529	63	N.A.	5	5:00[4]	1000	7,1	978	no decay	0,85
J1	0,042	LTF	12.5mm type C 12.5mm type C	614	42,5	1st: 35 2nd: >42,5	N.F.	06:12	1150	4,1	321	25	N.F..
J2	0,042	LTF	12.5mm type C	610	74	1st: 44	22	05:40	1150	3,8	367	25	N.F.
J3	0,042	LSF	12.5mm type C	601	47	1st: 23.5	N.A.	08:00	1200	3,6	N.F.	25	N.A.
K1	0,042	CLT	63% of CLT surface: 12.7mm type X 12.7mm type X	532	120	2nd: 72	N.F.	04:00	1200	4,8	N.A.	20[4]	0,69
K2	0,042	CLT	58% of CLT surface: 12.7mm type X 12.7mm type X	532	56	1st: 27 2nd: 45	N.F.	05:00	1100[4]	6,3	N.A.	20[4]	0,77
K3	0,042	CLT	79% of CLT surface: 12.7mm type X 12.7mm type X	532	81	1st: 25 2nd: >81	did not occur	06:00	1100	4,4	N.A.	20	0,71
L1	0,031	LTF	12.7mm type X 12.7mm type X	550[9]	84[4]	2nd: 45	30	03:00	1100	8,0[5]	443[7]	25[4]	N.F.
L2	0,031	CLT	12.7mm type X 12.7mm type X	550[9]	185	2nd: >185	36	03:00	1100	8,4[5]	439[7] 910[8]	23[4]	N.F.
L3	0,031	LSF	12.7mm, 15.9 mm	550[9]	74[4]	1st: 20	<20	03:00	1100	10,6[5]	367[7]	15[4]	N.A.

			type X or standard										
L4	0,031	LTF	12.7mm type X 12.7mm type X	550[9]	60[4]	35	23	03:00	1100	10,5[5]	514[7]	24[4]	N.F.
M1	0,064	CLT	16 mm type X[3] 16 mm type X[3]	790	120	1st: 15	15	02:35	1100	N.F.	N.F.	45	0.67
N1	0,015	CLT & LTF	12.5mm type DF 12.5mm type DF	420	49	did not occur	did not occur	no distinct flashover	800	N.F.	N.F.	no decay	N.F.
O1	0,084	CLT & NLT	type X type X	575[4]	180	2nd: 180	N.F.	04:00	1200	5,5[4]	N.F.	14	N.F.
O2	0,084	CLT	type X type X	600[4]	135	2nd: >135	N.F.	04:00	1200	5,0[4]	N.F.	14	N.F.
P1	0,070[6]	HLT	29% of walls & ceiling 13mm standard 15mm fire proof	655	9,5	did not occur	N.F.	did not occur	140[4]	N.F.	N.F.	N.A.	N.A.
P2	0,070[6]	HLT	29% of walls & ceiling 13mm standard 15mm fire proof	655	115	N.F.	N.F.	04:10	1100	N.F.	N.F.	no decay	1.1

[1] backwards calculated in order to ignore the assumed a combustion efficiency of 0.8
[2] charring rate in the ceiling at the onset of charring
[3] see main text for exceptions
[4] rough estimation using graph in resource
[5] peak heat release rate instead of average during a fully developed fire
[6] a triple glazed window was initially closed
[7] 60-min total heat release
[8] 180-min total heat release
[9] movable fire load density for Tests L1-L4:

- bedroom 510 MJ/m^2;
- living area 380 MJ/m^2
- kitchen dining area 970 MJ/m^2
- average living/dining/kitchen 575 MJ/m^2
- apartment average 550 MJ/m^2

5 The contribution of CLT or combustible linings in a fire

The contribution of combustible linings to a fire can be quantified in terms of heat release. A number of authors have estimated the heat release or heat release rate (Lennon *et al.* 2000; Hakkarainen, 2002; McGregor, 2013; Medina Hevia, 2014; Li *et al.* 2014; Su and Lougheed, 2014; Kolaitis, 2014; Su and Muradori, 2015; Janssens, 2015).

Three methods to determine the heat release in a compartment fire have been identified:

1. Through measurements of the average charring depth in order to estimate the heat release corresponding to timber (Hakkarainen, 2002; Li *et al.,* 2014)
2. Through measurements of the weight loss in order to estimate the heat release corresponding to all weighed fire load (Lennon *et al.* 2000; Frangi and Fontana, 2005).
3. Through calorimetry of the extracted air (McGregor, 2013; Li *et al.* 2014; Medina Hevia, 2014; Su and Lougheed, 2014; Janssens, 2015)

The heat release of solid wood can be directly estimated from the charring depth or the weight loss of solely the wood. In the case that the total heat release is determined from weight loss, the moisture content of all weighed contents should be determined before and after the test in order to separate the mass loss of evaporating moisture from the mass loss due to combustion. However, no procedure of this is described in the sources.

In order to quantify the heat release of linings using calorimetry, the contribution of the movable fire load should be identified. This was previously done for propane fueled compartment fires, in which the propane flow and the corresponding heat release were regulated (McGregor 2013). Another method involves reference testing of non-combustible compartments with the same dimensions, fuel load, etc. (Li *et al.*, 2014; Su and Lougheed, 2014). The contribution of the timber can then be estimated by subtracting the heat release corresponding to the non-combustible compartment from the heat release corresponding to the timber compartment.

Li *et al.* (2014) showed that fires in compartments comprising passively protected timber can have very similar fire conditions (heat release rates and temperature developments) compared with a non-combustible compartment comprising light steel framing. Additionally, they showed that the heat release rate corresponding to a fully unprotected compartment was 80% higher than that of fully protected or non-combustible compartments. However, the peak temperature measured in the compartments were not significantly different for unprotected and protected compartments, as a significant part of the combustion took place outside of the compartment. Similar conclusions were drawn by Hakkarainen (2002) and Frangi and Fontana (2005).

Five similar tests have been performed in which the sole difference was the amount of exposed CLT (McGregor, 2013; Medina Hevia, 2014). Parameters of the setup and results are summarized in Table 7. Based on the results McGregor concluded that the CLT in a fully exposed compartment approximately doubled the heat release. Medina Hevia showed that the contribution of CLT can be negligible if one of the room walls is unprotected.

Table 7: Maximum heat release rate and total heat released

Test name	Reference	Floor area of ignited compart-ment (m2)	Opening factor	Main structural members	percentage of CLT protected	Movable fire load density (MJ/m2)	Time to flashover (mm:ss)	Average heat release rate during fully develloped fire (MW)	**Total heat release after 26 min (MJ/m2)**	**Total heat release after 26 min normalized with respect to test H2**	Approx. time to start of decay (min)
Test I2	McGregor (2013) /Li *et al.* (2014)	15.75	0.042	CLT panels	100%	533	07:30	4.0	**4581**	**1.00**	24
Test I5					0%	529	5:00*	7.1	**9864**	**2.15**	no decay
Test K1	Medina Hevia (2014)				63%	532	04:00	4.8	**5275**	**1.15**	20*
Test K2					58%	532	05:00	6.3	**6702**	**1.46**	20*
Test K3					79%	532	06:00	4.4	**4383**	**0.96**	20

*rough estimation using graph in resource

6 *Charring rates of exposed solid timber*

It was shown by many studies (McGregor, 2013; Medina Hevia, 2014; Su and Lougheed, 2014; Kolaitis, 2014; Su and Muradori, 2015; Janssens, 2015) that protected timber often does not show significant char. Minor local charring has been reported behind gypsum board that remained in place. However, fall-off of the protective layer(s) can result in very high charring rates (Hakkarainen, 2002). However, as this occurs locally where the timber is not protected, reported charring rates depend significantly on the locations of the measurements. Therefore, it is difficult to compare charring rates corresponding to protected members. Consequently, this section only gives an overview of charring rates corresponding to unprotected timber.

Table 8 shows an overview of results that correspond to compartment comprising unprotected solid timber. The charring rate corresponding to test A1 was determined from the char layer found on the softwood cube in the living room of the compartment. For test O2 (ongoing), the charring rate was estimated from measurements of the final charring depth after the test. For the remaining tests that are included in table 8, the charring rate was determined using series of thermocouples in the wall. Hereby the char line was assumed to correspond with the 300°C isoline. Using this method, the average was calculated from the onset of charring. All but two tests have the same dimensions and opening factor. The main difference between those compartments is the fire load density. Despite the large differences of fire load densities, the average charring rates of the tests are comparable.

Medina Hevia (2014) conducted tests in which only one or two walls were exposed. Test K1, K2 and K3 had 63%, 58% and 79% of the CLT protected, respectively. However, the charring rates corresponding to the different tests were very similar (Figure 17).

Charring rates show relations with aspects such as the wood density, moisture content and timber species. However, information regarding this was only found in the work of Medina Hevia (2014). Using a Timber Check moisture meter, he measured average moisture contents of 8, 9.5 and 13.5% for tests K1, K2 and K3, respectively. Furthermore, he stated that the timber used was Spruce-Pine-Fir, which refers to a group of Canadian softwoods. No measured values of the density were found.

Table 8: overview of results corresponding to compartments comprising unprotected solid timber

Test name	Reference	Floor area of ignited compart-ment (m2)	Opening factor	Main structural members	Movable fire load density (MJ/m2)	Test duration (min)	Time to flashover (mm:ss)	Approximate peak temperature (°C)	Average heat release rate during fully developed fire (MW)	Approximate time to start of decay (min)	**Average charring rate (mm/min)**
Test A1	Lennon *et al.* (2000)	*N.F.*	*N.F.*	LTF	*N.F.*	64	24:00	1000	6.0	no decay	**0.75**
Test P2	Hox (2015)	13.3	0.070	HLT	653	115	04:10	1100	*N.F.*	no decay	**1.1**
Test B1	Hakkarainen (2002)	15.75	0.042	HLT	900**	50	04:50	1100	*N.F.*	no decay	**0.8**
Test I3	McGregor (2013)			CLT	182	53	04:55	980*	8.8***	45	**0.63**
Test I5	McGregor (2013) /Li *et al.* (2014)				529	63	5:00**	1000*	7.1	no decay	**0.85**
Test K1	Medina Hevia (2014)				532	120	04:00	1200*	4.8	20*	**0.69**
Test K2					532	56	05:00	1100*	6.3	20*	**0.77**
Test K3					532	81	06:00	1100*	4.4	20	**0.71**

* rough estimation using graph in resource
**backwards calculated in order to ignore the assumed a combustion efficiency of 0.8
***peak heat release rate instead of average during a fully developed fire

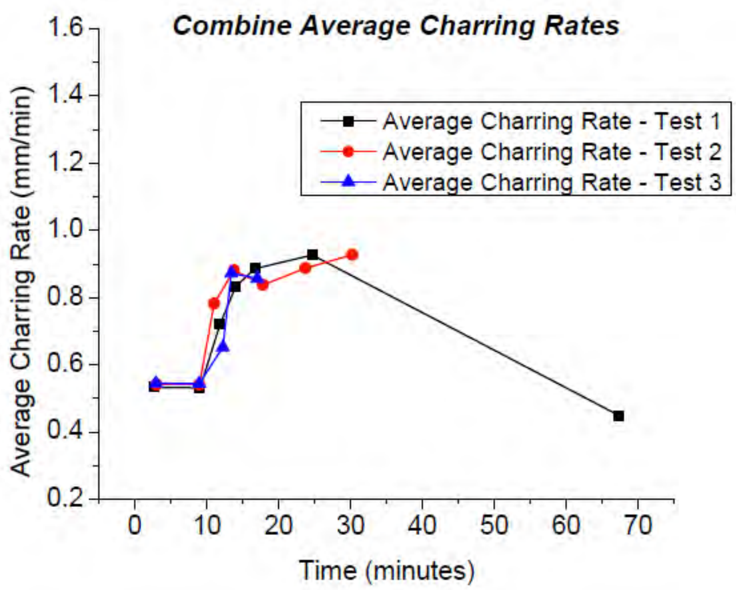

Figure 17: Charring rates in unprotected walls of test K1, K2 and K3, from Medina Hevia (2014)

7 *Decay and Self-extinguishment*

Most compartment fire tests discussed in this literature review, showed a decay phase of the fire before they were extinguished. In Table 9 an overview of the tests that did not show clear decay before they were extinguished is given. Test B1 and I5 involved only unprotected CLT. In test B2 the gypsum board failed after only 14 minutes, which was during the fully developed phase of the fire. In test G3 severe flaming inside the void of the ceiling was observed due to failure of the plasterboard layers. The contribution of combustible linings to the fire can postpone or prevent the decay of a fire. However, a number of tests involved exposed CLT and showed fire decay (Table 10). Test K3 even showed self-extinguishment.

Table 9: overview tests in which no decay of fire occurred before termination

Test name	Reference	Main structural members	Thickness and type of gypsum board protection (exposed layer last) (mm)	Movable fire load density (MJ/m2)	**Time to falling of gypsum plasterboards**	Approximate peak temperature (ºC)	**Approximate time to start of decay (min)**	Test duration (min)
Test A1	Lennon *et al.* (2000)	LTF	*N.F.*	*N.F.*	***N.F.***	1000	**no decay**	64
Test B1	Hakkarainen (2002)	HLT	none	900*	***N.A.***	1100	**no decay**	50
Test B2			12.5mm type A	900*	**The single layer fell in 13 minutes**	1000	**no decay**	46
Test P2	Hox (2015) Unpublished	HLT	29% of walls and ceiling: 13mm standard 15mm fire proof	655	***N.F.***	1100	**no decay**	115
Test G3	Lennon *et al.* (2010)	LTF (floor only)	15mm type F 15mm type F	450	**After 40 minutes the last layer partially fell from the ceiling**	1036	**no decay**	56
Test I5	McGregor (2013) /Li *et al.* (2014)	CLT	none	529	***N.A.***	1000	**no decay**	63
Test N1	Kolaitis et al (2014)	CLT and LTF	12.5mm type DF 12.5mm type DF	420	**The first layer fell from the ceiling but second layer sustained**	800	**no decay**	49

*backwards calculated in order to ignore the assumed a combustion efficiency of 0.8

Table 10: overview tests involving exposed CLT in which decay of fire occurred

Test name	Reference	Main structural members	Thickness and type of gypsum board protection (exposed layer last) (mm)	Movable fire load density (MJ/m2)	**Time to falling of gypsum plasterboards**	Approximate peak temperature (°C)	**Approximate time to start of decay (min)**	Test duration (min)
Test I3	McGregor (2013)	CLT	*none*	182	***N.A.***	980	**45**	53
Test K1	Medina Hevia		63% of CLT surface: 12.7mm type X 12.7mm type X	532	**After 75 minutes the ceiling was completely unprotected**	1200	**20***	120
Test K2			58% of CLT surface: 12.7mm type X 12.7mm type X	532	**Two layers fell after 27 minutes and 45 minutes from the ceiling**	1100*	**20***	56
Test K3			79% of CLT surface: 12.7mm type X 12.7mm type X	532	**First layer fell in 25 minutes from a wall. No falling of the second layer was reported**	1100	**20**	81

* rough estimation using graph in resource
**peak heat release rate instead of average during a fully developed fire

8 Second flashover, delamination and falling of gypsum boards

During the decay phase of a fire it is possible that the temperatures and heat release rate increase due to a change of conditions. This phenomenon is in this report referred to as *second flashover*.

Second flashover has occurred due to delamination of the unprotected CLT in test I1, I5, K1 and K2. The authors stated that sudden exposure to the uncharred lamella led to an increased fire severity. In both studies the CLT comprised polyurethane adhesive. Medina Hevia (2014) stated specifically that the adhesive used was a thermoplastic polyurethane adhesive with a melting point of 210°C. Furthermore, he stated that delamination occurred before the char layer reached the glue line, indicating that the adhesive significantly weakened before the charring temperature of approximately 300°C was reached. McGregor (2013) and Medina Hevia (2014) both stated that more research regarding delamination and the type of adhesive should be conducted in the future. A literature review regarding delamination in fire tests other than compartment tests was included in the phase 1 report on Fire Safety Challenges of Tall Wood Buildings (Gerard *et al.* 2013).

Second flashover was, furthermore, caused by falling of two layers of gypsum board as reported for test I1 after 107 minutes. Likewise, protected CLT started to burn after 175 minutes in Test L2. The connection of gypsum board to walls/wall assemblies is described in a few sources. An overview of descriptions given by different authors is shown in Table 11 together with reported failure times.

Table 11: overview of connections of gypsum boards to walls and reported failure times of gypsum boards

Test name	Reference	Main structural members	Thickness and type of gypsum board protection (exposed layer last) (mm)	Authors' description of gypsum board connections	Shortest time to falling of gypsum per layer (min)
B1	Hakkarainen (2002)	HLT	none	The boards were fixed to the timber frame using self-tapping screws of a length of 41 or 57mm for one or two layers, respectively.	N.A.
B2		HLT	12.5mm type A		13
B3		HLT	12.5mm type A 15.4mm type F		1st: 27 2nd: >169
B4		LTF	12.5mm type A 15.4mm type F		1st: 32 2nd: *N.F.*
G1	Lennon et al. (2010)	LTF	12.5mm type F 12.5mm type F	Firstly 45 mm wide resilient bars were fixed at 400 mm centres spanning perpendicular to the floor joists using 38 mm screws. A layer of either 12.5 or 15 mm fireline plaster- board (depending on the joist type) was then fixed to the resilient bars using 32 mm dry wall screws at 400 mm centres. A second layer of either 12.5 or 15 mm fireline board was fixed through the inner layer of the board to the resilient bars using 44 mm dry wall screws at 230 mm centres. The outer layer of board was staggered such that no joint in either layer was in the same position. All joints in the outer layer were filled with a generic readymix jointing cement.	2nd: 30
G2		LTF	15mm type F 15mm type F		no falling reported
G3		LTF	15mm type F 15mm type F		2nd: 40
I1	McGregor (2013)	CLT	12.7mm fire rated 12.7mm fire rated	Two layers of 12.7 mm fire rated gypsum board were installed directly over the CLT panels on the walls and ceiling in the protected rooms, Tests 1, 2 and 4. The first layer was secured using 35 mm drywall screws on grid at 300 mm intervals on the ceiling and 400 mm intervals on the walls. The second layer was installed at an offset, so that no joints were aligned with those in the next layer, using 55mm drywall screws using the same grid system as the first layer. All screw heads, joints and corners in each layer of gypsum were taped and skimmed with building compound to provide a completed seal.	2nd: 107
I2		CLT	12.7mm fire rated 12.7mm fire rated		1st: 37,1 2nd: >53
I3		CLT	none		N.A.
I4		CLT	12.7mm fire rated 12.7mm fire rated		1st: 39 2nd: >53
I5		CLT	none		N.A.
K1	Medina Hevia (2014)	CLT	63% of CLT surface: 12.7mm type X 12.7mm type X	To attach the gypsum boards to the CLT panels, drywall screws of different lengths for the first and second layer were used at a distance of one screw per foot in the vertical and horizontal direction. For the first layer, drywall screws with a length of 1-5/8 inches were used. Every drywall screw head was covered with plaster to protect it from thermal breaching. For the second layer, drywall screws with a length of 2 inches were used and every screw head was also covered with plaster. All the joints between the gypsum boards were taped and plastered to prevent passage of flames. The joints between the first and second layer of gypsum board were staggered to further protect from any passage of flames to the CLT panels.	2nd: 72
K2		CLT	58% of CLT surface: 12.7mm type X 12.7mm type X		1st: 27 2nd: 45
K3		CLT	79% of CLT surface: 12.7mm type X 12.7mm type X		1st: 25 2nd: >81
M1	Su and Muradori (2015)	CLT	16 mm type X 16 mm type X	The gypsum boards were attached to the CLT wall panels with 51 mm (2") long type S screws spaced at 300 mm on centre, starting at 150 mm from the edges of the assembly for the first (or base) layer and 200 mm from the edges for the second (or face) layer. Screws were placed at a minimum distance of 38 mm (1½") from the edges of all gypsum board sections. On the face layer only, joints between board sections were covered with tape and joint compound and all screw heads were covered with joint compound.	1st: 15

9 Reference light steel frame compartment tests

Su and Lougheed (2014) presented a fire test of a non-combustible compartment constructed using light steel framing. The steel frame was protected using gypsum board panels on both sides. The layer of gypsum board on the ceiling and walls started falling from the steel frame relatively quick (at approximately 20 minutes). 26 minutes after ignition the exterior gypsum board failed, opening the façade and significantly increasing the effective dimensions of the ventilation opening of the compartment. This resulted in an increased severity of the fire.

A similar finding was reported by Li *et al.* (2014), who concluded that type C gypsum plaster board attached to a light steel frame failed (test J3) significantly quicker than the same board attached to a timber frame assembly (test J2). However, as CLT was present at the unexposed sides of the steel frames in test J3, the early failure of gypsum board could not lead to additional openings in the façade.

Chen (2008) performed two fire tests of compartments, constructed from light steel frames. The dimensions and ventilation factor of the compartments were the same as compartments tested by Hakkarainen (2002), McGregor (2013), Li *et al.* (2014), Medina Hevia (2014). No failure of the cladding materials was reported. The walls were protected using 12.7mm cement board on both sides and an additional 12.7mm type X gypsum board. The ceiling/roof was cladded using two layers of 12.7mm type X gypsum boards on the exposed side and 15.9mm plywood on the unexposed side.

Compartment tests reviewed in this work have suggested that a single layer of gypsum board is often not sufficient to protect light steel frames. Tests presented by Chen suggested that cement board protection or application of two type X gypsum board layers can prevent preliminary cladding failure.

10 Testing complications

In order to prevent complications from reoccurring in future tests a summary of complications that occurred during tests is given in this chapter.

10.1 Flaming outside the compartment

It was reported that the amount of exposed combustible construction material inside a compartment can increase the intensity of the fire that occurs outside of the compartment (Hakkarainen, 2002; Frangi and Fontana 2005, McGregor 2013, Li et al 2014). The intensity of the fire can cause safety risks inside the testing facilities. This has previously led to the termination of test B1 or to lowering of the propane fuel load in I1.

Flaming outside the compartment can also occur due to failure of joints between walls or a wall and the ceiling, as occurred in B3 and K1. This led to the recommendation to use fire rated caulking in order to seal the joints (Kampmeier, 2008; Medina Hevia, 2014).

10.2 Problems caused by falling of gypsum board

Falling of gypsum from a ceiling commonly occurred during compartment tests. However, this led to a few complications previously. In test M1, K2 and N1 this led to falling of thermocouple trees, which made the locations of the thermocouples uncertain.

In test J3, comprising non-combustible steel framing, the isolative gypsum board fell in an early stage covering some fire load and leaving a part of it unburned. This reduced the effective fire load of the tests and influenced the fire conditions.

10.3 Problems regarding extraction and calorimetry

Failure of the extraction system during a compartment test causes safety risks and has led to the termination of test B2. Additionally, complications regarding calorimetry of the extracted air have been reported. The speed of the extraction fans had to be adjusted during test I3 to clear smoke. Therefore, the amount of smoke analyzed was increase temporarily, resulting in a questionable peak of the calculated heat release rate. Also failure of the calorimetric system has led to data loss previously.

10.4 Loss of data

Significant data loss has been reported due to a failure of a single data logger in test I2. However, measurements of the heat release were logged in another system. Therefore, useful results have been obtained.

10.5 Problems regarding steel frame reference tests

As discussed in chapter 9 and section 10.2, two problems that occurred in reference tests of non-combustible compartments constructed using steel frames were related to failure of the gypsum board at an early stage. Failure of gypsum boards at an early stage has covered fire load, leaving it unburned. Additionally, failure of gypsum on the exposed and unexposed sides has led to increased ventilation openings, which impacted the intensity and duration of the fire.

11 Conclusions

Summaries and overviews of parameters and results were provided for 45 compartment fire tests, of which 41 tests involved wood based construction materials and 4 tests involved non-combustible materials.

Three methods to determine the heat release in a compartment fire have been identified:

1. Through measurements of the average charring depth or charring rates in order to estimate the heat release corresponding to timber;
2. Through measurements of the weight loss in order to estimate the heat release corresponding to all weighed fire;
3. Through calorimetry of the extracted air.

An overview of charring rates corresponding to compartment fire tests has showed that charring rates of unprotected solid timber are generally similar for apartments that have similar dimensions. From the charring depth, the heat released corresponding to the timber can be estimated.

In order to determine the contribution of combustible construction through measurements of the weight loss, or calorimetry of the extracted air, the contribution of the movable fire load should be known. This knowledge can be obtained using reference tests of compartments comprising non-combustible exposed materials. Additionally, for determining the contribution through measurement of weight loss, the moisture content of all weighed material should be known. It is also possible to regulate the contribution of the movable fire load if gas (e.g. propane) is used as fire load.

Studies have shown that the contribution of encapsulated timber to a compartment fire can be non-existing or insignificant. Potential failure of the encapsulation, however, can lead to the involvement of timber in the fire and can eventually lead to a second flash-over. It was shown that the presence of unprotected combustible surfaces leads to an increase of the heat release rate, but does not necessarily lead to increased temperatures within the compartment. In under ventilated fires, the contribution of unprotected timber can lead to significant flaming combustion outside of ventilation openings, such as windows. The contribution of exposed timber can, but does not always lead to a delayed decay of a fire.

The data and results of this literature review will be further analyzed and used for Task 2, which concerns the development of a test plan for this project.

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