FIRE RESEARCH

Summary Report

Fire Safe implementation of visible mass timber in tall buildings – compartment fire testing

Daniel Brandon, Johan Sjöström, Emil Hallberg, Alastair Temple and Fredrik Kahl

RISE Report 2020:94

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Corrigendum

This report includes corrections made on 12/03/2021, which includes a corrected list of authors, clarification of the objectives, and a correction of the figure for Test 3 of Table 1.

Abstract

Summary Report

Five real scale compartment fire tests, constructed of CLT slabs and glulam beam and column in accordance with current US product standards, were performed. The compartments had surface areas of exposed mass timber equal to up to two times the area of the floor plan. The 4 hours long tests showed that compartments with such quantities of exposed wood can exhibit continuous decay to hot-spots and embers after flashover. The tests indicate that the presence of two exposed wall surfaces in one corner should be avoided to ensure this.

Key words: Mass Timber, CLT, Fire, Compartment fire, Glued laminated timber

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Content

Preface

This report provides the test results of a research project of fire safe implementation of visible wood in tall timber buildings. The main funder of the project is the **US Forest Service (USFS), US Department of Agriculture** (*USFS Grant Number 2019-DG-11083150-022)*, the project owner is the **American Wood Council** (AWC), and **Research Institutes of Sweden** (RISE) is the contractor for this research project.

Other project partners and funders of this project are: **Katerra** providing ANSI/APA PRG 320 (2018) compliant CLT, **KLH** providing ANSI/APA PRG 320 (2018) compliant CLT; **Henkel** providing the required ANSI/APA PRG 320 (2018) compliant timber adhesive and additional funding, **Boise Cascade** providing ANSI A 190.1-2017 compliant glued laminated timber; **USG**, providing Type X gypsum boards; **Rothoblaas**, providing mass timber screws, sealants, tapes, resilient profiles and equipment for lifting anchors mass timber members; the **Softwood Export Council** providing shipment costs of US products to the test site in Sweden; **Brandforsk** providing **additional** funding for the inclusion of façade extension measurements. The façade measurements are out of the scope of this report. Technical in-kind contributions were provided by **NIST** for recording of videos in severe fire conditions.

A Steering Group was assembled for this project, comprising of:

Kevin Naranjo (USDA)

Kuma Sumathipala, Jason Smart, Kenneth Bland (AWC)

Sean DeCrane (Building & Life Safety Technologies, UL)

Gordian Stapf, Christian Lehringer, Daniel Current, Chris Whelan (Henkel)

Hans-Erik Blomgren (Katerra)

Sebastian Popp, Johannes Habenbacher (KLH)

Kyle Flondor, Ajith Rao, Young-Geun You (USG)

Susan Jones (Atelier Jones)

Rodney McPhee (Canadian Wood Council)

Dan Cheney (Boise Cascade)

Hannes Blaas, Andres Reyes, Paola Brugnara (Rothoblaas)

All steering group members provided in-kind technical contributions in this project.

1 Introduction

This summary report discusses a compartment fire test series and includes a discussion of the setup and a summary of basic results and observation. The selected results aim to allow an assessment of the occurrence of a decaying fire. The final project report, to be issued at a later date, will have a full overview of all results, including a case study to repair a portion of a fire damaged structure.

1.1 Background

New US building regulations for the International Building Code (IBC) 2021 have recently been approved, which allow the construction of tall buildings with mass timber structures. The IBC 2021 includes three new building types dedicated for mass timber structures, namely IV-A, IV-B and IV-C. Buildings of type IV-A can be up to 18 stories and have the most strict fire safety requirements, including required protection of all mass timber surfaces, using non-combustible fire protection contributing to no less than 2/3 of the required fire resistance rating of the mass timber itself (2 hrs. for IV-A). Buildings of type IV-B can be built up to 12 stories and can have limited portions of the ceiling (20%) or limited portions of walls (40% of the floor area) exposed. Buildings of type IV-C can have all mass timber surfaces exposed, but have stricter limitations of building height, depending on the type of occupancy. It should be noted that other fire safety requirements hold for all building types, such as the presence of NFPA 13 compliant sprinklers, as summarized by Breneman et al. (2019).

The limitations for buildings of type IV-B were based on two compartment fire tests performed by Zelinka et al. (2018), in which relatively small surface areas of timber were exposed. Both fires continuously decayed after a period of flashover for at least three hours, and were continuously decaying at 4 hours after ignition, which has been a primary acceptance criterion for the ICC TWB Ad hoc committee.

There has, however, been a change of requirements in the CLT product standard (ANSI/APA PRG320, 2018), requiring the face bond adhesive of CLT to withstand a 3-hour long full-scale compartment fire test without the occurrence of delamination and to pass a bench scale test. As previous research (McGregor 2014, Medina Hevia, 2015, Su et al. 2018, Brandon et al. 2018, Hadden et al. 2017, Emberley, 2017) demonstrated the significant effect that CLT delamination can have on compartment fire dynamics, this change in the ANSI/APA PRG320 can significantly change the outcome of fires in compartments made of CLT.

The tests by Zelinka et al. (2018) were initiated before the 2018 version of ANSI/APA PRG 320 was published and the tested CLT was not compliant with the new product standard, compromising the potential fire performance of the structure. In addition, the tests by Zelinka et al. involved the highest heat release rates of any indoor CLT compartment fire test and possibilities of increasing the surface areas of timber in any indoor fire test at this scale would be limited because of the laboratory's exhaust and calorimeter limitations.

A first study of fires in compartment made of ANSI/APA PRG320 (2018) compliant CLT, was performed at NRC-CNRC in Canada (Su et al. 2018b). This study showed an improved potential for compartment fires of CLT structures to decay. However, due to charring behind two layers of ½ inch gypsum plaster boards and some details in the design, some of these fires did not fully decay.

1.2 Aim and objectives of this study

This study aims to assess possibilities for safe increases to US code-prescribed limits of visible mass timber surface areas, for mass timber products that comply with current US product standards.

The specific objectives are, therefore, to:

- Perform a series of compartment fire tests in structures constructed of PRG 320-2018 compliant CLT with varying amounts of exposed mass timber areas.
- Provide background for possible[1] justification of increases to code-prescribed limits of exposed mass timber surfaces consistent with the fire performance criterion[2] used for changes to the International Building Code.
- Identify additional measures necessary (if any) to ensure the International Code Council (ICC) established fire performance criterion and additional criteria discussed in Section 3 are met.

In addition, secondary objectives are defined:

- Design and test intersections between exposed mass timber members that are practical, affordable and sufficient for the entire fire duration of compartment fires.
- Develop and test a method of restoring exposed CLT members after a fire. *Note: this objective is not further discussed in this summary report.*
- Allow for comparisons of the fire exposure measured on the front façade above ventilation openings of compartments that are fire tested. The exposure of three of these tests is expected to be statistically severe (with respect to quantity of external combustion and duration). *Note: this objective is part of the project add-on funded by Brandforsk (as noted in the Preface) and is not further discussed in this summary report.*
- Map the influence of increasing the surface area of exposed mass timber on the façade exposure. *Note: this objective is part of the project add-on funded by Brandforsk (as noted in the Preface) and is not further discussed in this summary report.*

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[1] This clarification is added on 12/03/2021

[2] ICC TWB Ad Hoc committee used a fire performance criterion where a compartment fire should continue to decay at 4 hours following fire initiation.

2 Experimental setup

Five compartment fire experiments were performed for this study. The compartments had internal dimensions of 23.0 ft x 22.5 ft x 9.0 ft (7.0 m x 6.85 m x 2.73 m). Four of these compartments had two ventilation openings (Figure 1) of 7.4 ft x 5.8 ft (2.25 m x 1.78 m, width x height) resulting in an opening factor[3] of 0.112 $ft^{1/2}$ (0.062 $m^{1/2}$). The compartment dimensions and the opening factor were based on a probabilistic analysis and surveys of data of tall residential buildings, as discussed in Annex B. The remaining compartment test had six larger openings, resulting in an opening factor of 0.25 $m^{1/2}$ (0.453 $ft^{1/2}$), which is approximately equal to the midrange of opening factors for office compartments found in the survey of Annex B.

Figure 1: Fully developed fire of Test 1

The compartments were constructed of ANSI/APA PRG 320, 2018 compliant 6.9 inch (175 mm) thick 5-ply CLT (each ply 1.38 inches, 35-35-35-35-35 mm) and ANSI A 190.1-2017 compliant glued laminated timber. The average moisture content of the mass timber members was 13%. It is important to note that in contrast with most previous studies, the tested CLT lay-up with the specific enhanced poly-urethane adhesive fulfills the requirements specified in Annex B of the 2018 version of ANSI/APA PRG 320. In this study, varying mass timber surfaces were protected with Type X gypsum boards. All CLT, glued laminated timber and gypsum boards used during the tests complied with current US regulations and standards.

[3] Definition of opening factor: $O = A_0\sqrt{H_0}/A_t$, where $A_0 = \sum A_i$ is the sum of all opening areas, A_t is the total enclosing area (incl. openings), $H_0 = \sum (A_i h_i)/A_0$, and h_i is the height of each opening

The floor plan of Test 1, 2, 3 and 5 is shown in Figure 2. The Floor plan of Test 4 is shown in Figure 3. Drawings of all facades with openings are shown in Annex A.

The dimensions of the compartment, size of the openings and fuel load density were determined from a probabilistic analysis aiming to test a severe fire scenario that is based on the designs of real buildings, which is summarized in Annex B. The combination of the compartment dimensions, fuel load density and opening factor results in the 85th percentile of expected total char damage for fire scenarios in residential buildings where sprinklers are not activated, flashover takes place and fire service interference is absent. Details of this analysis are indicated in Annex B. The target fuel load density resulting from the probabilistic study is 560 MJ/m^2 (52 MJ/ft^2).

The fuel used was a combination of typical apartment furniture, particle board sheets on the floor to represent a wooden floor, and additional wood cribs representing fuel in storage spaces. The calculation of the moveable fuel load is provided in Annex C, in which the fuel items denoted with the letters A to J in Figure 2 and Figure 3 are specified. The total mass of the moveable fuel on the floor was measured using load cells under the floor for every test and was 2881 ± 22 lb (1307 ± 10 kg) in total.

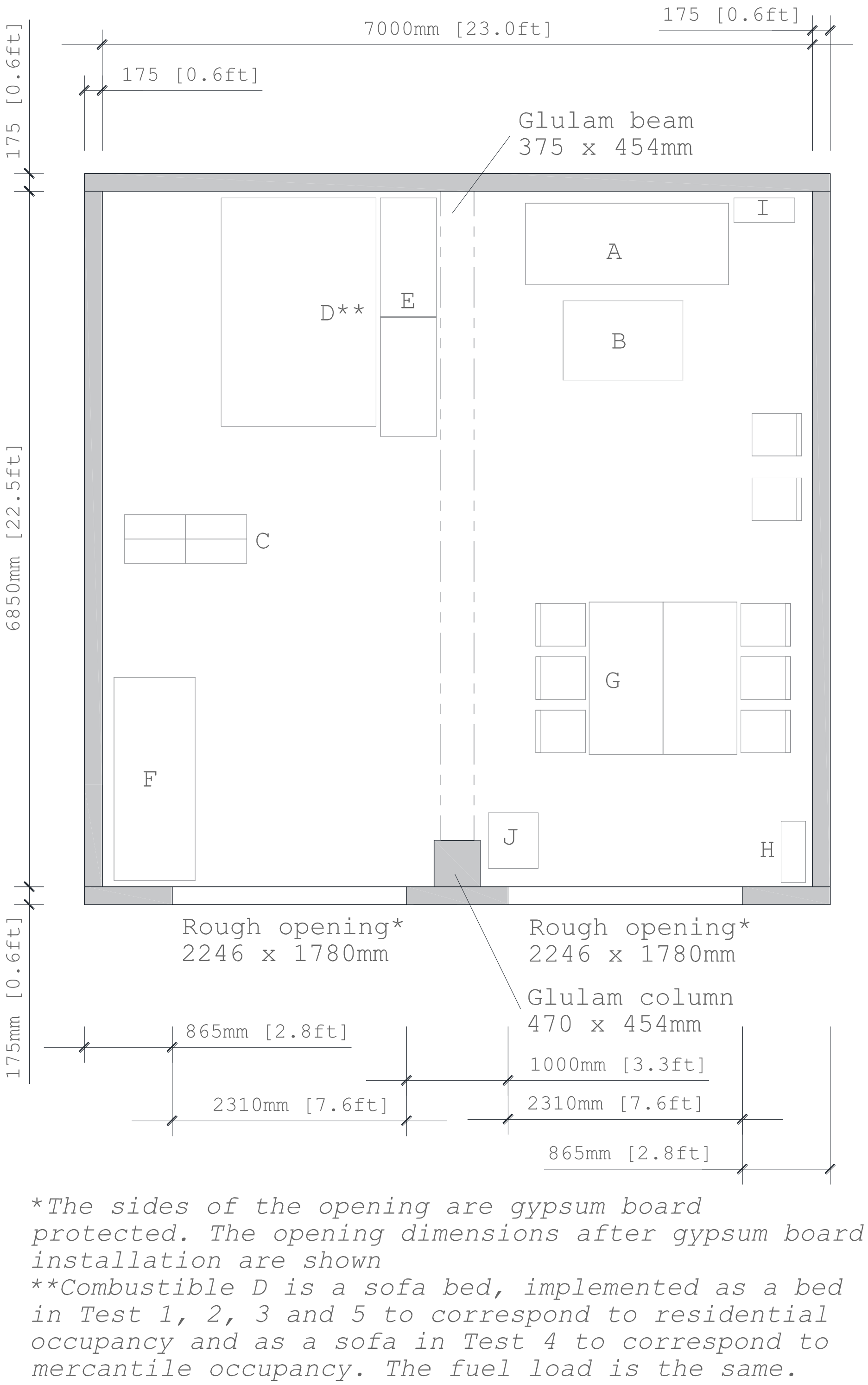
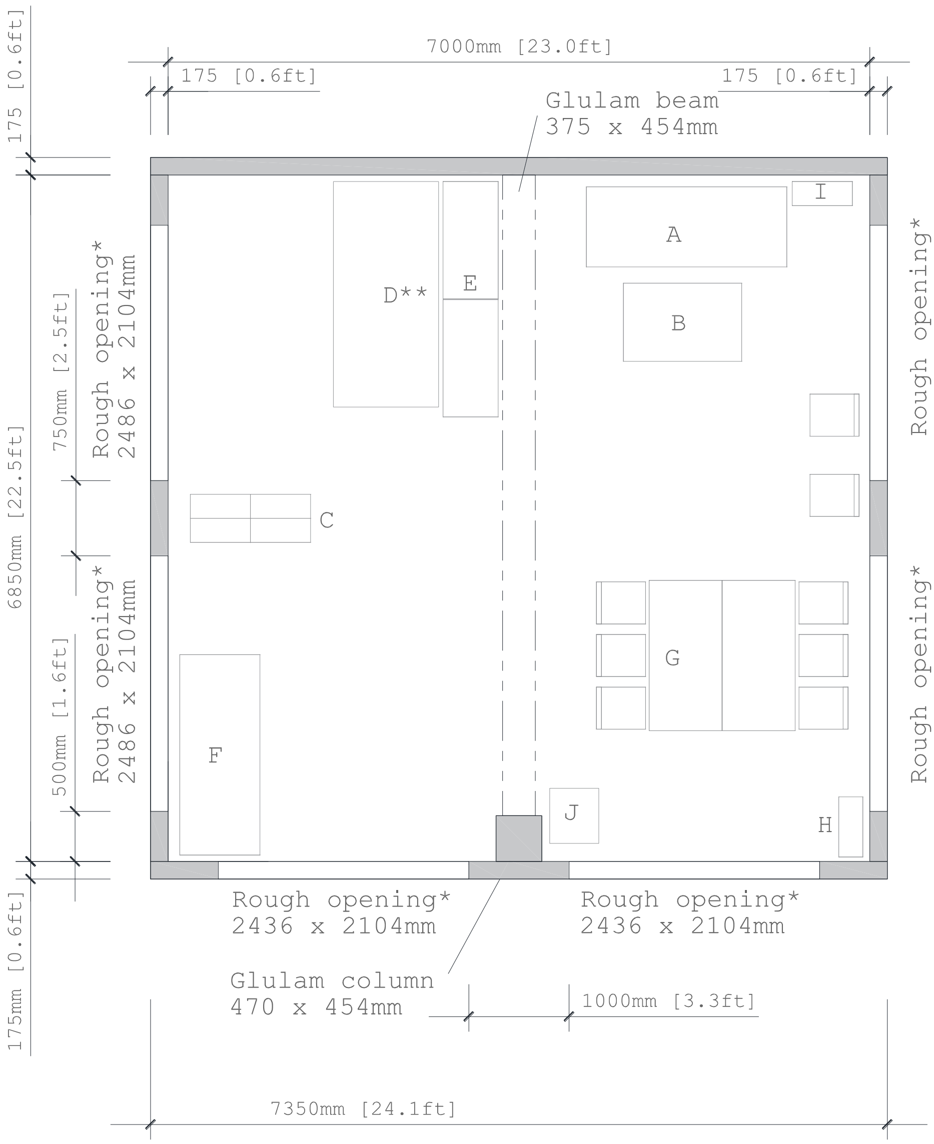


Figure 2: Floor plan of Test 1, 2, 3 and 5



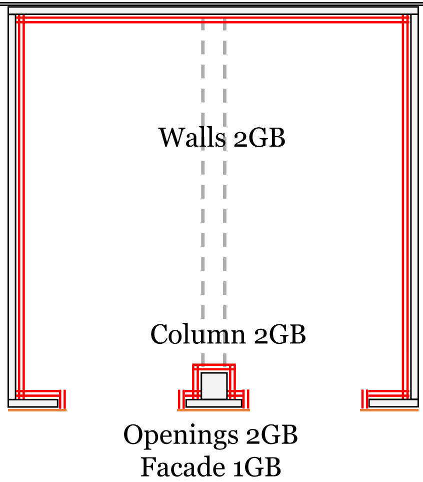
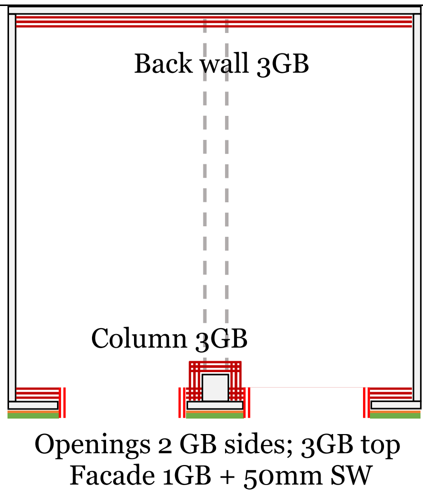
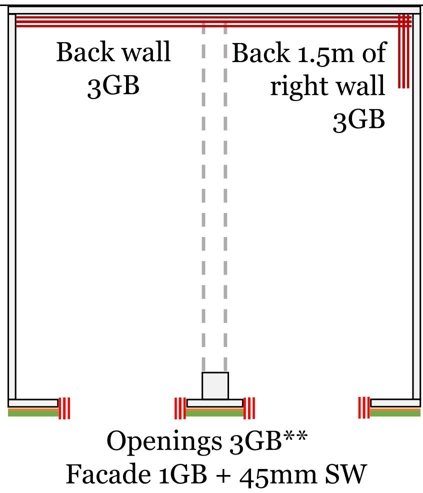
*The sides of the opening are gypsum board protected. The opening dimensions after gypsum board installation are given
**Combustible D is a sofa bed, implemented as a bed in Test 1, 2, 3 and 5 to correspond to residential occupancy and as a sofa in Test 4 to correspond to mercantile occupancy. The fuel load is the same.

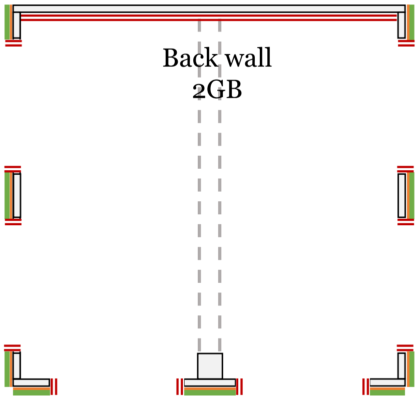
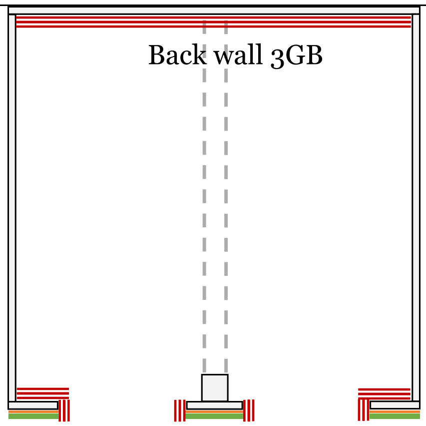
Figure 3: Floor plan of Test 4

The locations of gypsum board protection and the number of layers of gypsum board protection along with the percentages of exposed surface areas are provided in Table 1. The CLT ceiling and the glued laminated timber beam were exposed in all tests. The table includes the number of 5/8 inch thick (15.9 mm) Type X gypsum board layers (GB) that were implemented on interior surfaces. Schematic floor plans (not to scale) indicate the locations of the protected surfaces. In addition, the drawings also indicate the fire protection that was implemented on the sides and top of the opening and on the fire exposed façades. All gypsum board layers were attached with gypsum screws at a maximum relative distance of 10.8 inch (274 mm) in both horizontal and vertical direction. Edge distances of 2.5 inch (64 mm) were implemented for screws at the edge of the gypsum boards. The lengths of the gypsum screws were 1.6 inch (41 mm) long for the base layer, 2.2 inch (55 mm) long for the second layer and 2.8 inch (72 mm) long for the third layer. Specialized equipment was used to prevent the screw heads from punching through the paper surface of the gypsum boards and prevent premature damage of the boards. On the exposed surface all screw heads and joints between gypsum boards were finished with regular joint compound.

Of the small opening tests (tests 1, 2, 3 and 5 - representative of dwellings), Test 1 had the least surface area of exposed wood followed by Test 2. Test 3 and 5 had the same exposed wood surface area, but in Test 5 no corners with two exposed walls were present. For Test 4 (large opening – representative of mercantile occupancy) all internal, walls except for the back wall were exposed.

Table 1: Test matrix (GB indicates gypsum boards; SW indicates stone wool)

Test name Window Opening size	Gypsum Board (GB) Protected interior surfaces*	Exposed wood surfaces	Floor plan (schematic)***
Test 1 Two window openings 86 ft² (8.0 m²) of exterior wall open	- All walls and - Column protected by 2 layers of GB	100% of ceiling exposed and 100% of beam exposed No exposed wood surfaces in walls	
Test 2 Two window openings 86 ft² (8.0 m²) of exterior wall open	-Back wall and -Front wall protected by 3 layers of GB	100% of ceiling, 100% of beam, and 100% of left and 100% of right-side walls exposed No exposed wood wall surfaces meeting in a corner	
Test 3* Two window openings 86 ft² (8.0 m²) of exterior wall open	-Back wall and -Back 5 ft (1.5 m) length of right wall protected by 3 layers of GB *Note: figure on right side is corrected on 12/03/2021*	100% ceiling, 100% beam, and 100% of left side and 78% of right-side walls, and 100% of front wall and 100% of column exposed. **Two** exposed wood wall surfaces meeting in a corner (front left and front right)	

Test name Window Opening size	Gypsum Board (GB) Protected interior surfaces*	Exposed wood surfaces	Floor plan (schematic)***
Test 4* Six Window openings 336 ft² (31.2 m²) of exterior wall open	Back wall protected by 2 layers of GB	100% ceiling, 100% of beam, and 100% of left and 100% of right-side walls, and 100% of front wall and column exposed. **Two** exposed wood wall surfaces meeting in a corner (front left and front right)	
Test 5* Two window openings 86 ft² (8.0 m²) of exterior wall open	-Back wall and -2.3 ft (0.7 m) on left and right-side edges of the front wall protected by 3 layers of GB	100% ceiling, 100% beam, and 100% of left-side and 100% of right-side walls, and 60% of front wall and 100% of column exposed. No exposed wood wall surfaces meeting in a corner	

**To be able to weigh the floor separately from the structure, the floor was not directly attached to the walls of the fire test compartment. The small gap, between the floors and the walls was filled with stone wool insulation for all tests. In Test 2, some of the stone wool fell out of place and resulted in fire spread downward from the compartment floor in this (artificially created) gap. Therefore, for subsequent tests, a 10 cm (4") strip of gypsum board was applied to the bottom of all exposed walls to cover the wall/floor gap in Test 3, 4 and 5.*

*** In Test 3 and 5, three layers of gypsum boards were applied on the side of the ventilation openings instead of two layers. The extra layer made the openings slightly narrower than the openings of Test 1 and 2. To compensate for this, the height of the ventilation opening was increased so that the opening factor for Tests 1, 2, 3 and 5 was the same.*

****Protection on the façade and façade details at the opening have been changed iteratively. Annex F gives an overview of details and pictures after the tests. A full discussion will be included in the final project report.*

2.1 Intersections

One of the secondary objectives of this study was to "*Design and test intersections between exposed mass timber members that are practical, affordable and sufficient for the entire fire duration of compartment fires*" (Section 1.2).

For intersections of mass timber building elements with other building elements, where both are required to be fire resistance rated, the IBC 2021 requires the use of sealants in accordance with ASTM C920 and ASTM D3498. Instead of complying with IBC 2021, it was aimed to study the performance of alternative solutions that potentially increase practicability and possibly lower costs. To this end several types of commercially available sealants were applied between mass timber elements during this study. This report contains a limited discussion of the performance of such sealants. The final project report, to be issued at a later date, would contain a thorough discussion of all details.

Sealants were applied between mass timber elements to reduce the risk of fire spread through mass timber intersections, in particular, CLT-CLT intersections, by eliminating the flow of hot gasses between mass timber elements at intersections. It is expected that sealing materials do not need a high temperature resistance if the sealant is used in locations not directly exposed to a compartment fire. The tested sealants were primarily those generally used to improve air tightness, water proofing or acoustic performance. Test results should indicate if these are suitable to prevent fire spread through intersections. Table 2 gives an overview of the materials used to seal the intersections, including information of their temperature resistance, if available.

Table 2: Materials used at intersections of CLT members.

Product	Common functions	Detailed description
Construction tape	Water proofing Improving air tightness	Tape comprising of a polyethylene film, with reinforcing Polyethylene grid and acrylate adhesive. Width: 60 mm (2.36 inch); Thickness: 0.25 mm (0.01 inch); Temperature resistance: -40/80˚C.
Expanding tape	Improving sound insulation Improving air tightness	Elastic expanding tape developed to fill irregular gaps, sound proofing up to 58 dB. Width: 20 mm (0.8 inch); Max expansion (thickness): 20 mm (0.8 inch). Temperature resistance: -30/90 ˚C.
Resilient profile	Sound proofing Improving water tightness	Resilient profile of polyurethane. Width: 140 mm (0.46 ft); Thickness: 0.24 inch (6 mm); Thermal conductivity: 0.2 W/mK. Maximum processing temperature: >200 ˚C.
Construction sealing	Improving air tightness Improving sound insulation	Expanded EPDM (synthetic rubber). Width: 46 mm (0.15 ft); Thickness: 3 mm (0.12 inch); Temperature resistance: -35/100 ˚C.
Fire Sealing adhesive	Fire sealing Acoustic insulation	1-component silicon elastomer adhesive. Up to 90 minutes fire rated. Sound proofing up to 60 dB.

Figure 4 shows details of the CLT intersection and indicates which sealing material was used in each test.

Spline board joints with Ø0.24 x 3.1 inch (Ø6 x 80 mm) washer-head screws with 10 inch (250 mm) spacing were used to connect CLT panels in the ceiling. Four different variants were used to seal the spline board joint, using either construction tape or expanding tape. It was expected that a slight offset of height between two CLT members may cause a channel of air along the spline board in the details of Test 1 and 3. For that reason, tape that sealed the end of the channel (at the ends of the spline board) was implemented in those tests. This was not done for the other tests, because the implemented tape was expected not to allow hot gasses in any potential channel under the spline board.

Lap joints were used to connect wall elements that were in the same plane. The members were connected using Ø0.32 x 4.7 inch (Ø8 x 120 mm) countersunk head screws with 10 inch (250 mm) spacing. In Tests 3, 4 and 5 no sealing materials were implemented for lap joints in gypsum protected walls. For exposed walls two variants have been implemented using either construction tape or expanding tape as shown in Figure 4 C.

Butt-joints between CLT walls and ceiling panels were implemented using Ø0.32 x 11.8 inch (Ø8 x 300 mm) washer-head screws. Three variants to seal the joints were implemented using resilient profile and/or construction tape. The resilient profile was positioned centrically on top of the walls. Since the CLT wall is 35 mm wider than the resilient profile a small void was formed between the construction tape and the resilient profile on the external side in Tests 2, 4 and 5. Although it was not expected that high temperatures would be reached in this void, a small amount of fire sealing adhesive was used every two meters, to limit flow of gasses in the longitudinal direction of the void in case it would manage to pass the resilient profile. For locations at which the walls were gypsum board protected, a small amount of fire sealing adhesive was used to avoid gasses flowing into the void between the resilient profile and the gypsum boards. Fire sealing adhesive was used to fill up some visible voids between the resilient profile and the CLT in a few locations of the left and right walls of the Test 2 and 3 compartments.

CLT wall corner joints were connected also using Ø0.32 x 11.8 inch (Ø8 x 300 mm) washer-head screws. Three variants to seal the joints were implemented, using construction sealing, construction tape, or expanding tape (Figure 4 D). The construction sealing was stapled to the end of the walls before assembly.

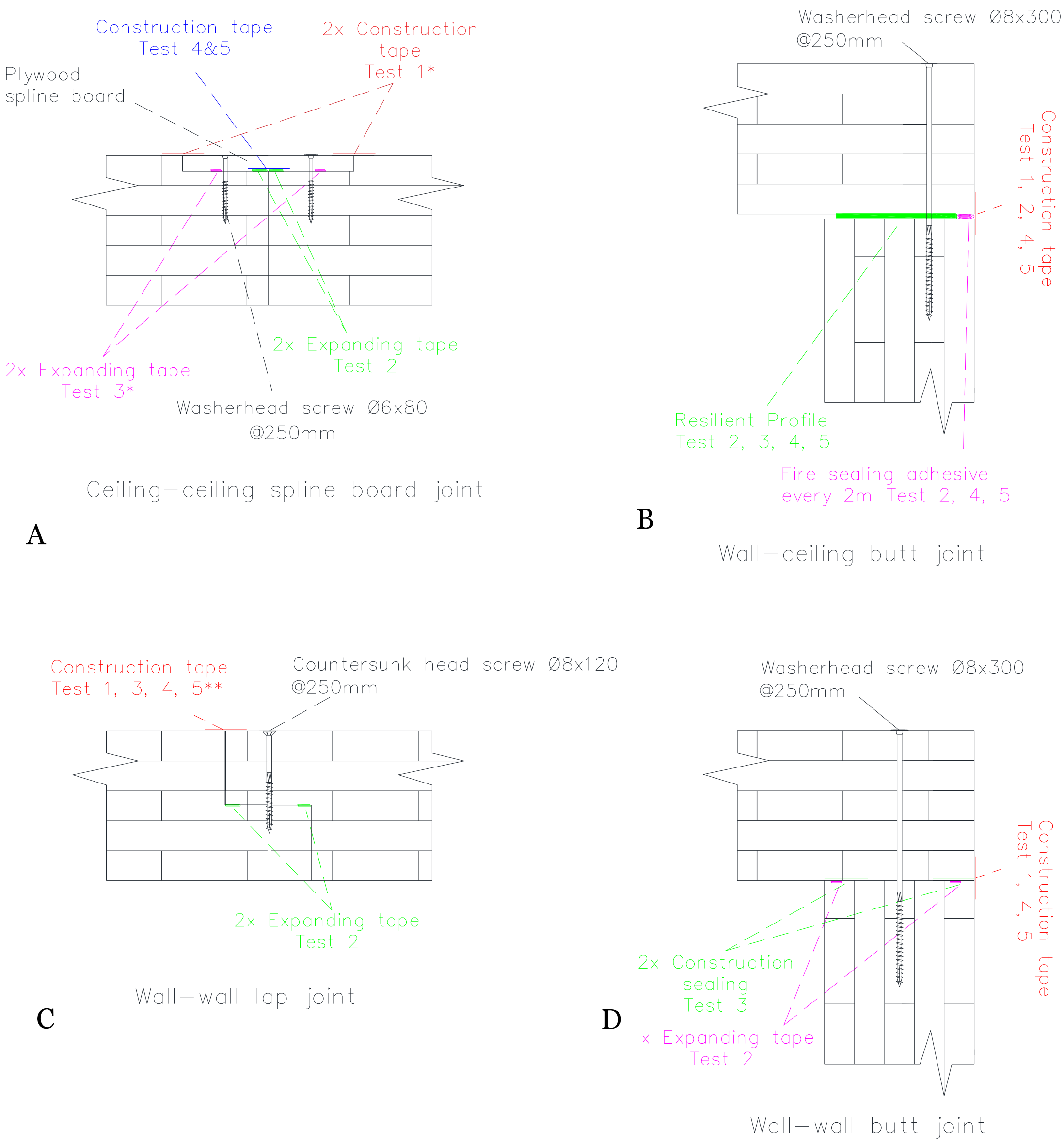


Figure 4: Variants of sealed CLT intersections and their sealing details (different colours represent different sealing types and/or locations)

** Construction tape was used to close potential voids between the spline board and the CLT at the end of the spline board, for Tests 1 and 3.*

*** Construction tape was not used for lap joints between gypsum protected walls in Test 3, 4 and 5.*

All configurations of CLT joints of Figure 4 were at least in one test implemented without any gypsum board protection, with the exception of the wall-ceiling joint of Test 1 and the wall-wall butt joint of Test 2. Those two configurations were subjected to less severe exposure because of the gypsum board protection. Therefore, the detail of these specific tests including gypsum boards is shown in Figure 5. In Test 1, no fire sealant was implemented between gypsum and abutting CLT members in corners. Before all subsequent tests, a small amount of fire sealing adhesive was used only in locations where a gap between gypsum and abutting CLT was visible.

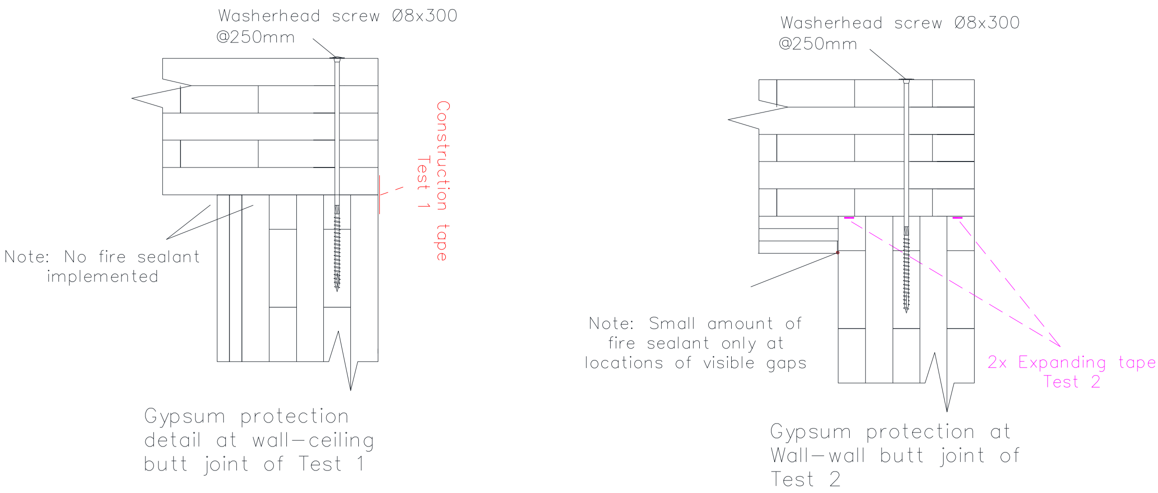


Figure 5: Variants of CLT intersections that only were implemented together with gypsum board protection.

2.2 Measurements

The test measurements were made before, during and for a period after the test. This summary report focusses only on basic measurements made during the tests that allow for identifying a decaying nature of a fire. In addition, charring depths measured after the tests have been included.

As such, the results presented in this report are limited to:

- Temperature measurements by plate thermometers at wall and ceiling surfaces that are directed into the compartment (Figure 6);
- Observations and measurements related to gypsum board protection;
- Heat release rates;
- Important observations during the tests;
- Observations regarding flame spread through intersections of mass timber members.

The final project report will include all measurements in either the main text or the Annex together with a more in-depth discussion of details. It will also include a description of locations where smoldering continued after the fires and a case study of repairing a part of the CLT after the fire.

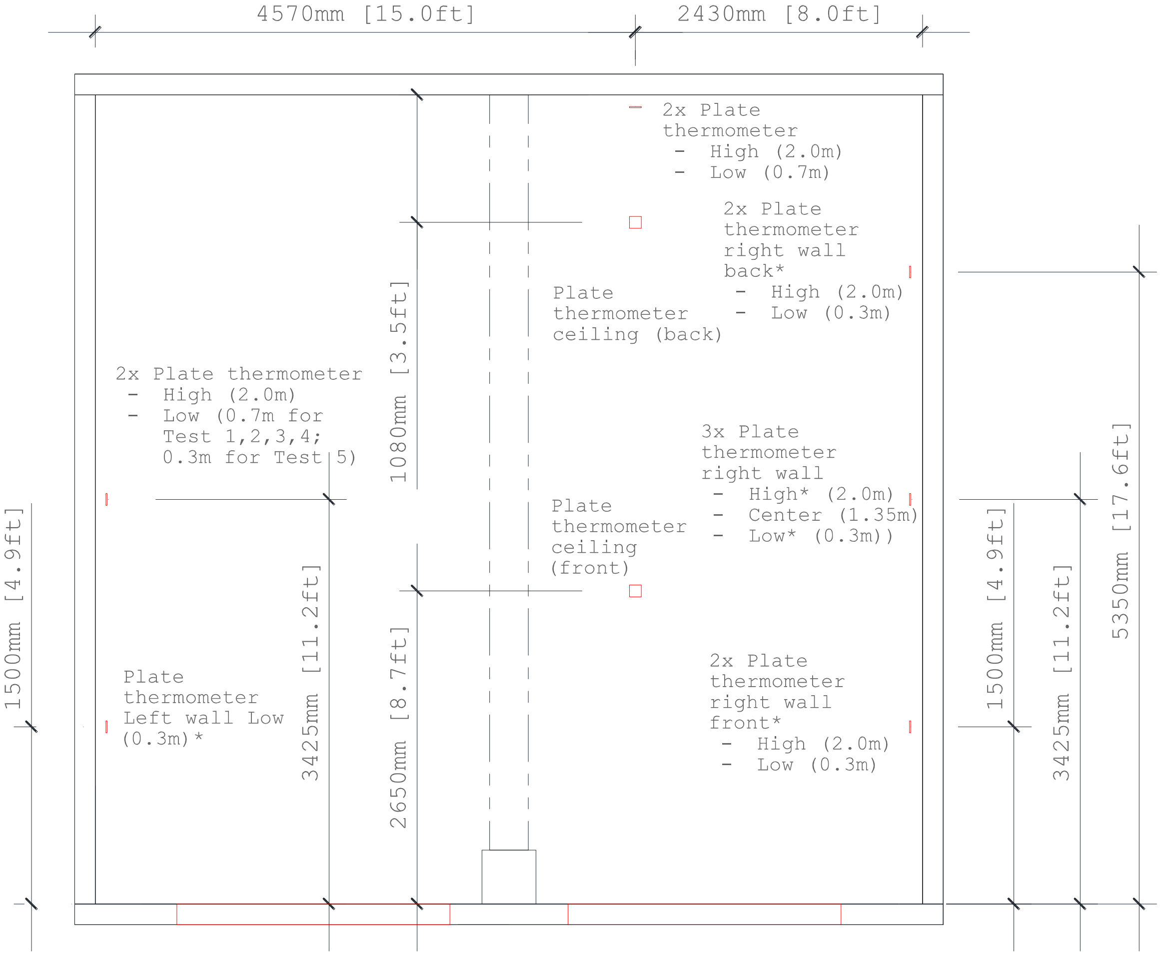


Figure 6: Locations of plate thermometers (includes only plates at surfaces that are directed away from the surface).

** indicates plates that are implemented in Test 5 only*

3 Pass/fail criteria – ICC TWB

The test matrix given in Table 1 was decided upon during the execution of the test series. Instead of planning the configurations of exposed surfaces, gypsum board protection and the number of protective layers before the execution of all tests, it was chosen to only plan the configuration of Test 1 and let the project steering group decide on the configuration of each subsequent test based on the test results. This approach was chosen aiming to find limits of surface areas of exposed mass timber and corresponding requirements for gypsum board protection (amount and location) iteratively. To support this procedure, the project steering group defined pass criteria to reach a common agreement of the desired outcome of the fire tests needed to justify fire safe changes of current code prescribed limits. These criteria are a quantifiable adaption of the criterion (where a compartment fire should continue to decay at 4 hours following fire initiation) used by the International Code Council Ad Hoc Committee on Tall Wood Building (ICC-TWB) to develop code change proposals for the International Building Code 2021 (IBC

2021), which were accepted in 2019. The criterion was used for the assessment of the results by Zelinka et al. (2018) and a comparable criterion is being used in the required CLT compartment fire test of Annex B in the ANSI/APA PRG 320 (2018), where temperatures should be equal to or below 510˚C after 4 hours of compartment fire testing.

The following quantifiable adaptation of the ICC pass criterion was developed by the project Steering Group at the outset and was included in the test plan:

- **At 4 hours after ignition the plate thermometer temperatures should be below 300 °C**. The corresponding incident radiant heat flux is roughly[4] 6 kW/m², which has previously been identified as one of the extinction criteria of smoldering in timber (Crielaard, 2019). Achieving a complete stop of all smoldering is, however, not an aim of this study. Instead, this study aims at assessing techniques for fire fighters of locating and extinguishing smoldering that is left after the fire through case studies, which will be included in the final project report.
- **No secondary flashover** (identified by absence of flashover criteria as specified in UL 1715, ASTM E2257, and ISO 9705**) should occur between 3 hours and 4 hours after ignition**. Flashover shall be considered to have occurred when any two of the following conditions have been attained:
    a. Heat release rate exceeds 0.12 MW/m² of floor area, which is determined from the mass loss rate)
    b. Average upper layer temperature exceeds 600°C.
    c. Flames exit one of the openings.

Exception:

In case the criteria above are locally not fulfilled caused by a detailing issue, that could be solved with a change of details, the results will be considered satisfactory (i.e. pass). In that case recommendations for further study of the fire performance of this detail will be made.

4 Summary of test results

This chapter gives an overview of the results of plate thermometer temperatures, char depth and heat release data. In addition, important observations regarding details are summarized. A full overview of all results will be provided in the final project report.

4.1 Events

Significant events that occurred during the tests are listed in Table 3 together with the corresponding time after ignition. The highly variable time to flashover is expected to be to some extent caused by the relatively high variability of the time it took for the ignited bin, to ignite the sofa cushions.

[4] The incident heat flux of roughly 6 kW/m² is based on the assumption that the gas temperature is equal or lower than the plate thermometer temperature, which is generally the case in a decaying fire.

The tests were stopped at the indicated times. In Test 1, 2, 4 and 5 the fires decayed until the test was stopped at 4 hours after ignition. At that time, there were some hot-spots and embers left in the compartment. In Test 4 (large opening) the smoldering almost completely stopped. In Tests, 2, 3 and 5 there were some occasional local flames at the wall surface during the final stages, but they had no significant effect on the global temperatures. In Test 3 increased flaming on the left wall starting at around 3:12 h which led to increased flaming on the right wall as well. Photos taken during the tests are shown in Annex E.

Table 3: Significant events and time after ignition (h:mm)

	Test 1	Test 2	Test 3	Test 4	Test 5
Flashover	0:14 h	0:08 h	0:12 h**	0:15 h	0:04 h*
Start of decay	0:36 h	0:36 h	0:43 h	0:29 h	0:34 h
Duration of the fully developed phase	0:22 h	0:28 h	0:31 h	0:14 h	0:30 h
Fall-off of exposed GB layer	-	0:32 h ~1-2 m² *Above 'A' of* Figure 2	-	-	0:36 h ~1 m² *Above 'A' of* Figure 2
Fall-off of other GB layers	-	-	-	-	-
Overall temperature increase during the decay phase	-	-	3:05 h and onwards	-	-
Smoldering/flaming through intersections	See Section 4.6	-	See Section 4.6	-	-
Stop of the test	4:00 h	4:00 h	3:31 h***	4:00 h	4:00 h

** The sofa cushions ignited significantly faster than in other tests, leading to a faster fire growth*

*** The pillow near the ignited bin did not ignite automatically. At approximately 5 minutes after the initial ignition, the fire brigade ignited that specific pillow manually.*

**** The test was stopped as it did not pass the criterion set by the project steering group to have continuous decay until 4 hours after ignition, as such, this level of mass timber surface exposure would not be recommended for high rise buildings, where there is possibility that an automatic sprinkler system could fail and that fire service intervention may not occur for 4 hours.*

Videos of the tests are available online at the web addresses listed below.

Test 1: https://youtu.be/V4VUF-FbraY

Test 2: https://youtu.be/UgtHJwfhaJs

Test 3: https://youtu.be/_R4EfKnQd2Q

Test 4: https://youtu.be/jOELM-cv-U8

Test 5: https://youtu.be/WUy-NEBLRoE

More videos will be made available through the RISE Fire Research YouTube account within weeks after publication of this report, at:

https://www.youtube.com/channel/UCi7ee3Rvuc1mZw-GsFjROgQ/videos

4.2 Interior plate thermometers

Measurements using plate thermometers inside the compartment, installed at a distance of 2.8 inch (10 cm) from wall or ceiling surfaces, facing away from the surface, are shown in this chapter together with the temperature criterion discussed in Chapter 3. Figure 7 to Figure 11 show the plate temperatures for Test 1 to 5, respectively. The plate thermometers were located as indicated in Figure 6. The front plate thermometer in the ceiling malfunctioned repeatedly and is, therefore, not visible in most of these figures.

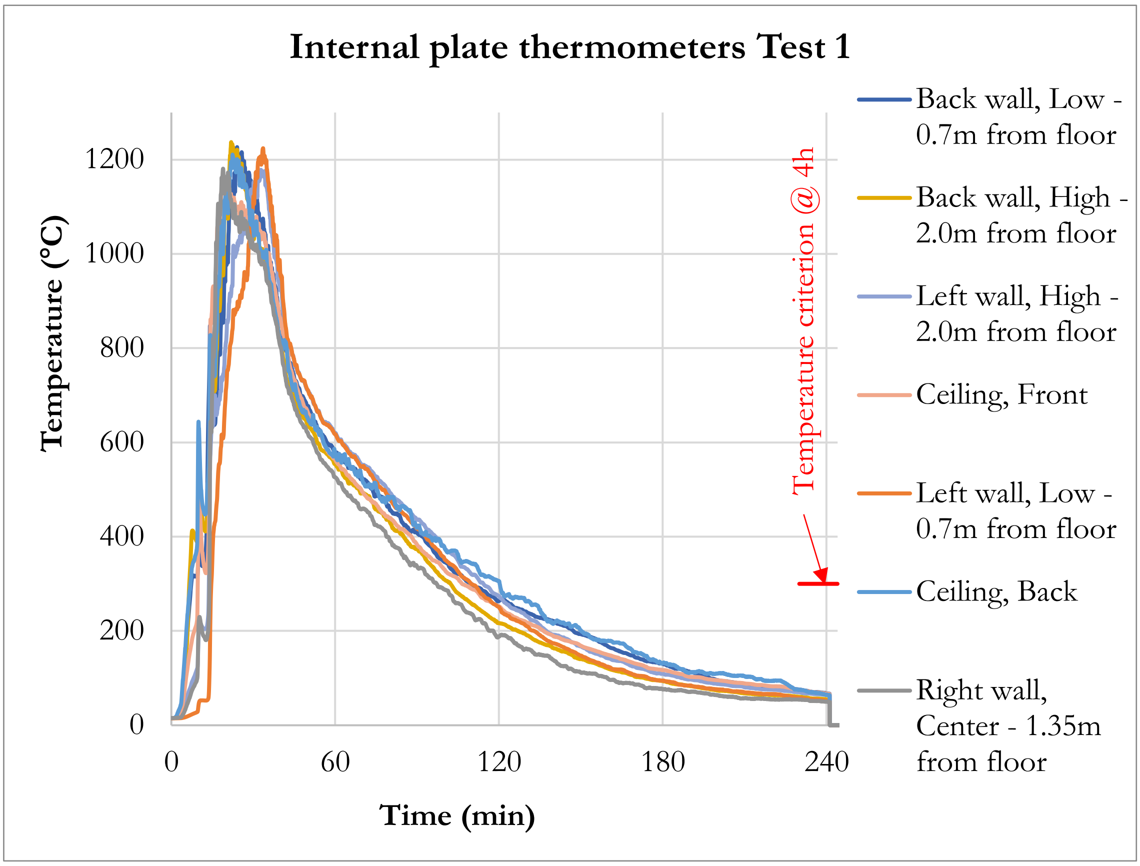


Figure 7: Internal plate thermometer measurements of Test 1

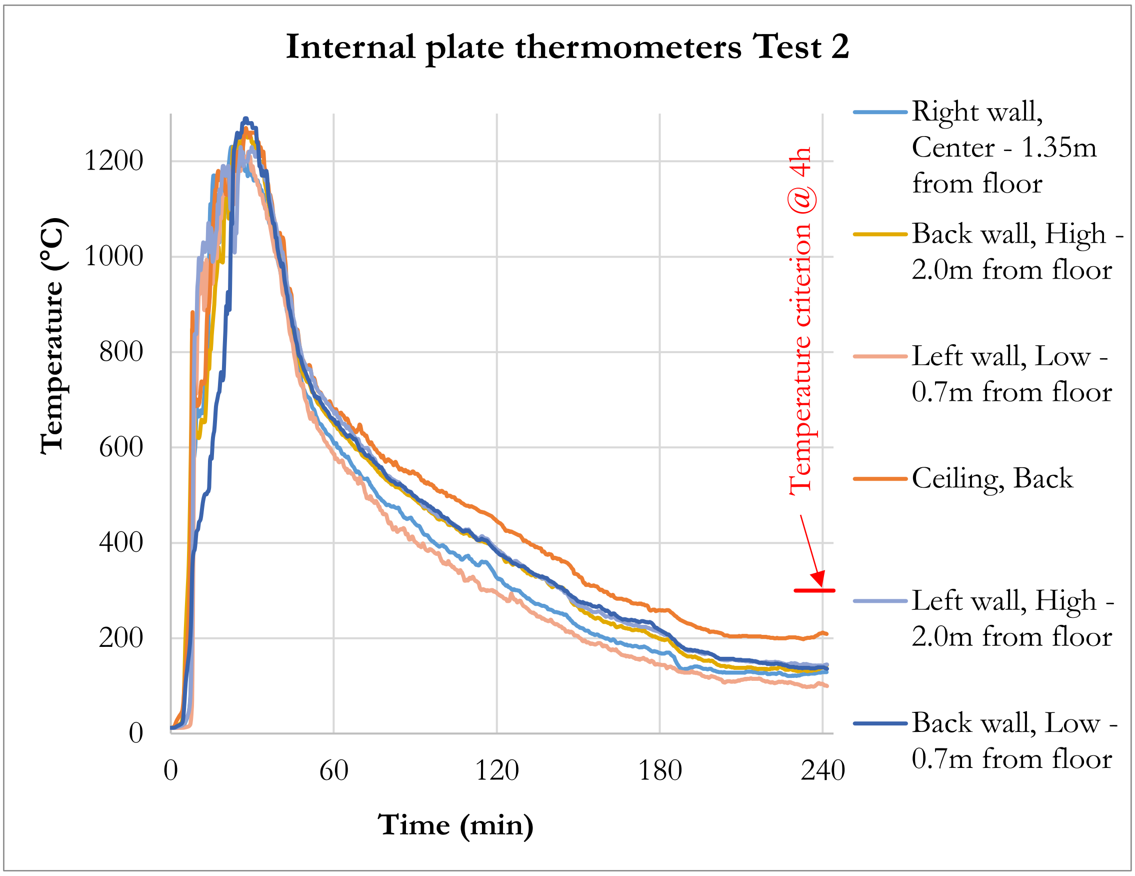


Figure 8: Internal plate thermometer measurements of Test 2

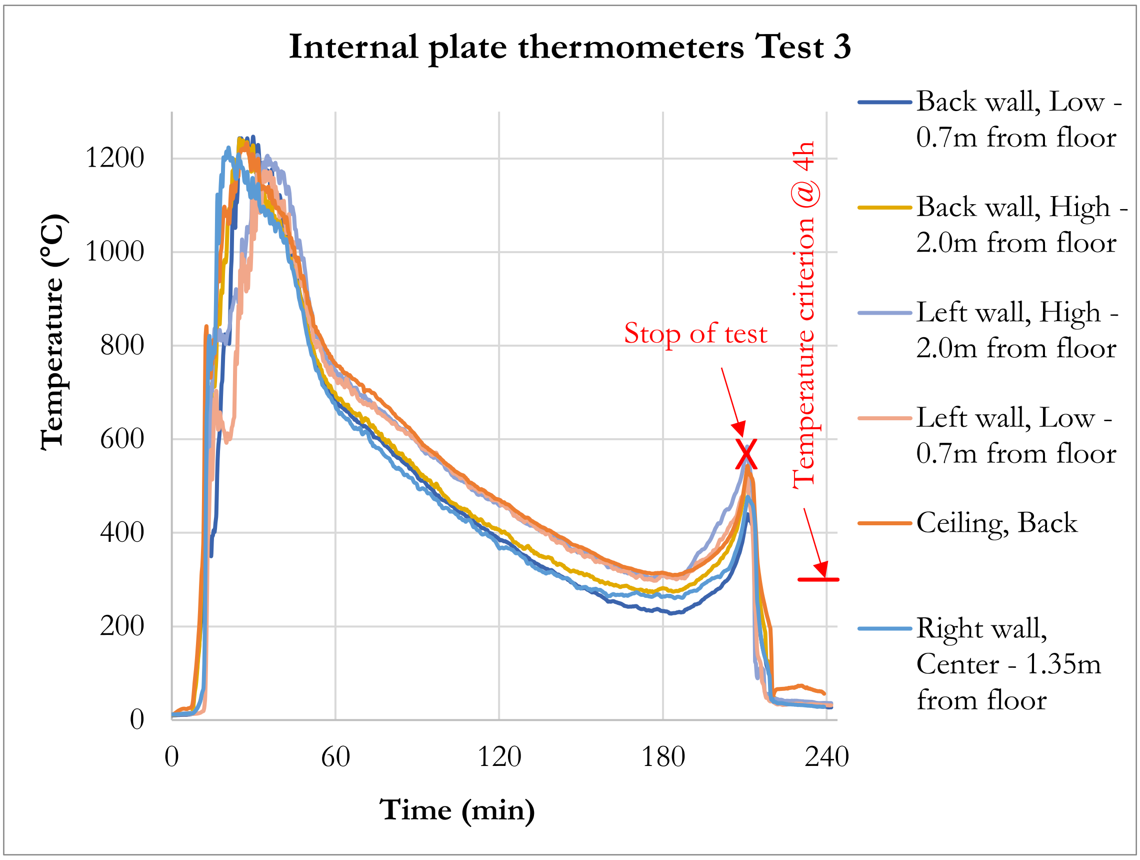


Figure 9: Internal plate thermometer measurements of Test 3

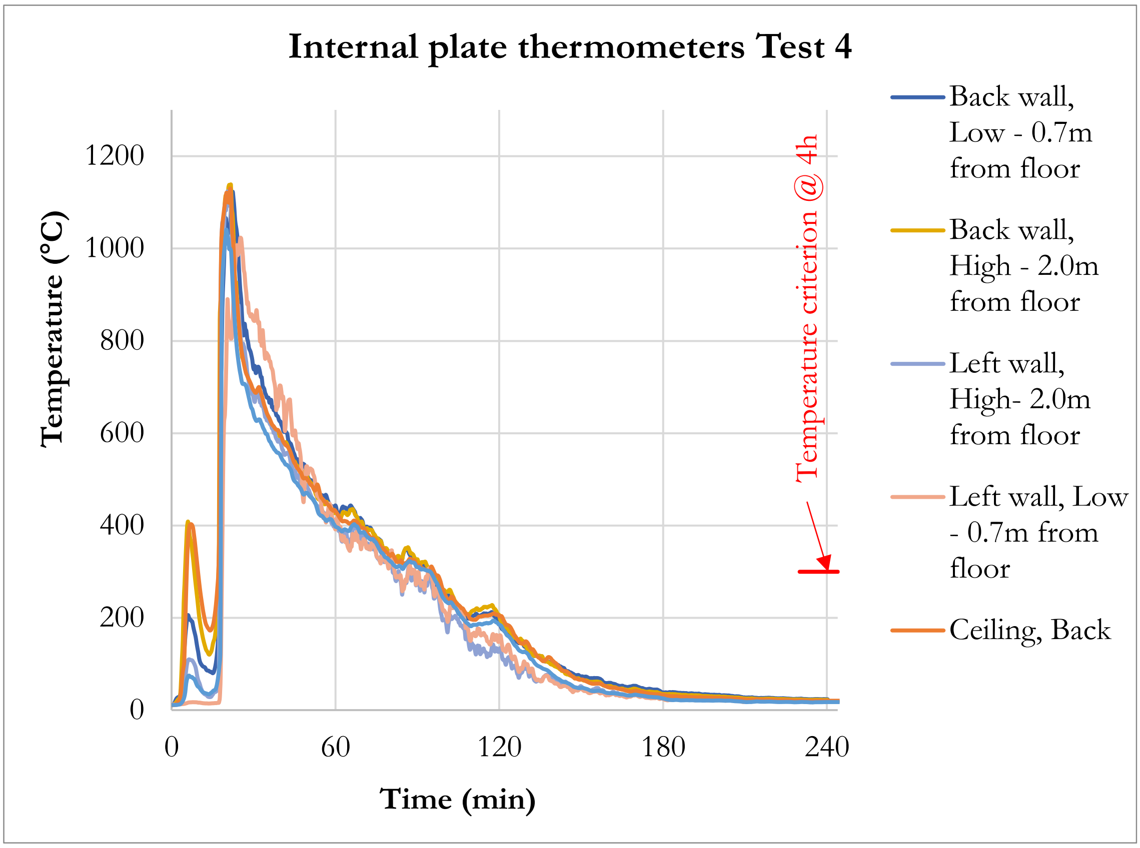


Figure 10: Internal plate thermometer measurements of Test 4

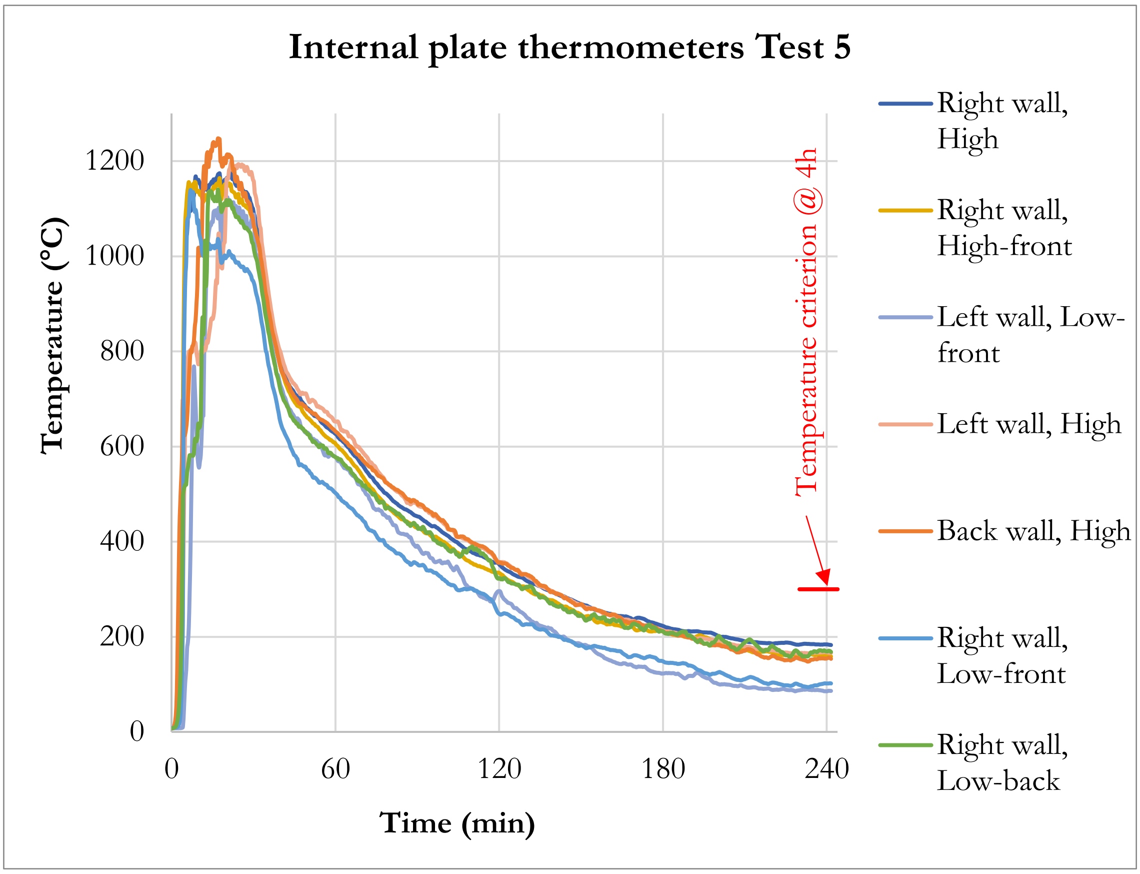


Figure 11: Internal plate thermometer measurements of Test 5

Figure 12 shows temperatures of the plate thermometers on the left wall 6.6ft (2.0m) from the floor of every test for comparative purposes. To improve the clarity of the figure for comparisons, the curves were time adjusted so that the moment of flashover is at 10 minutes on the x-axis.

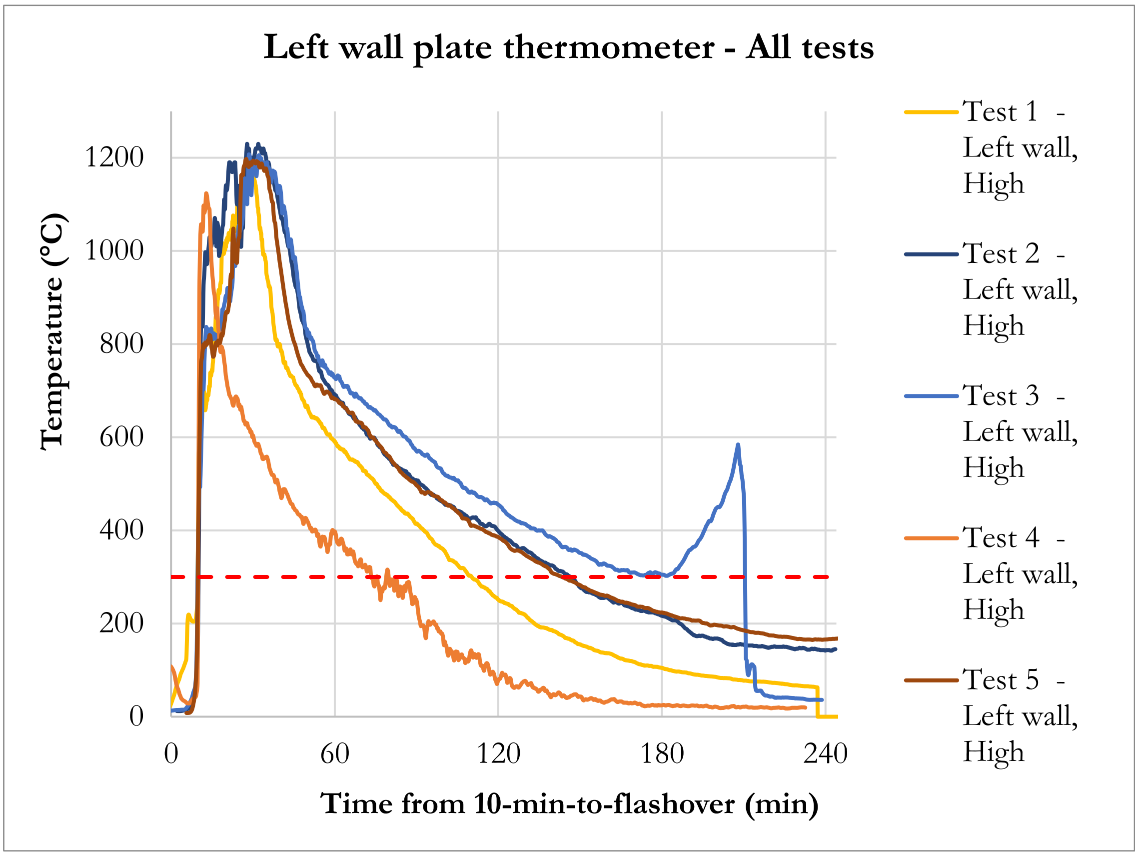


Figure 12: Left wall plate thermometer measurements at 2.0 meters (6.6ft) from the floor of all tests. The red dashed line indicates the 300 °C criterion at 4 hours.

4.3 Gypsum board protection

Temperatures were measured behind every layer of gypsum boards at different locations. The temperatures will be given in the final project report. In this report only an assessment of the involvement of protected CLT in the compartment fires is made. That assessment is made by temperatures measured at the interface between the CLT surface and the base layer of gypsum board protection. In Tests 2, 3, 4 and 5, all measured temperatures at the protected CLT or glulam surfaces were lower than 200˚C for the whole test duration, indicating no material decomposition and, therefore, no contribution to the heat release in the locations where temperatures were measured. In Test 1 the protected CLT or glulam surface temperatures were measured in seven locations of which one location had temperatures above 300˚C (but below 350˚C), indicating local charring at this location (Buchanan and Abu, 2017). In three other locations the temperatures exceeded 200˚C (but not 250˚C), indicating some local and minor material decomposition and contribution to the fuel load at the CLT surface.

Figure 13 and Figure 14 show photos of CLT surfaces after removal of the gypsum after Test 1 (2 gypsum board layers). Local charring was seen, especially in locations near the intersection of walls and the exposed ceiling and in some lap joints between two wall panels. Figure 15 shows the top of the back wall after removal of the ceiling. The right picture shows the location of the most significant charring that took place in a lap joint. As indicated before in Figure 5, there was no fire sealant applied at the interface between the gypsum boards and the ceiling of Test 1. In all other tests a fire sealant adhesive was used in this location only at locations were a gap was visible between the outer boards and the ceiling. The location of the local maximum char depths on gypsum protected surface after Test 1 was determined and indicated in the char diagram of Section 4.5. Figure 16 and Figure 17 show the CLT surface after removal of the gypsum boards for Test 2 to 5. It should be noted that the gypsum boards in Test 2 and 3 were removed by the local fire brigade with water mist, which left stains and some damage of wood grains. Water mist was used to identify alternative techniques to extinguish potential smoldering behind the gypsum boards using less water than conventional methods.

Figure 13: **Test 1,** Back wall (left) and right wall (right) after removal of the 2 gypsum board layers.

Figure 14: **Test 1,** Front wall (left) and left wall (right) after removal of the 2 gypsum board layers.

Figure 15: **Test 1,** Top of back wall after removal of ceiling.

Figure 16: Protected walls of **Test 2** (left) and **Test 3** (right) of left wall after removal of the 3 gypsum board layers.

Figure 17: Protected walls of **Test 4** (left, 2 GB layers) and **Test 5** (right, 3 GB layers) after removal of gypsum boards.

4.4 Heat release rates

Heat release rates were determined from load cell measurements of the floor and the structure separately. The method used is summarized in Annex D and includes corrections for the mass loss of the lightweight concrete floor structure (by drying out), the façade extension, and the gypsum boards. The movement of firefighters in the compartment at the beginning of the fire and in some instances at other times during the fire was identified using video recordings and the mass change caused by that was disregarded for the calculation of the heat release rates.

Heat release rates of all tests are shown in Figure 17. It should be noted that the first 9 minutes of Test 5 were lost due to a technical issue with the load cells. To increase the clarity of the figure, the heat release rate curves were time adjusted so that the moment of flashover is at 10 minutes on the x-axis. Additionally, after the peak heat release rate is reached, a moving average (of 5 datapoints) is plotted, which increased the visibility of the curves that are drawn behind other curves.

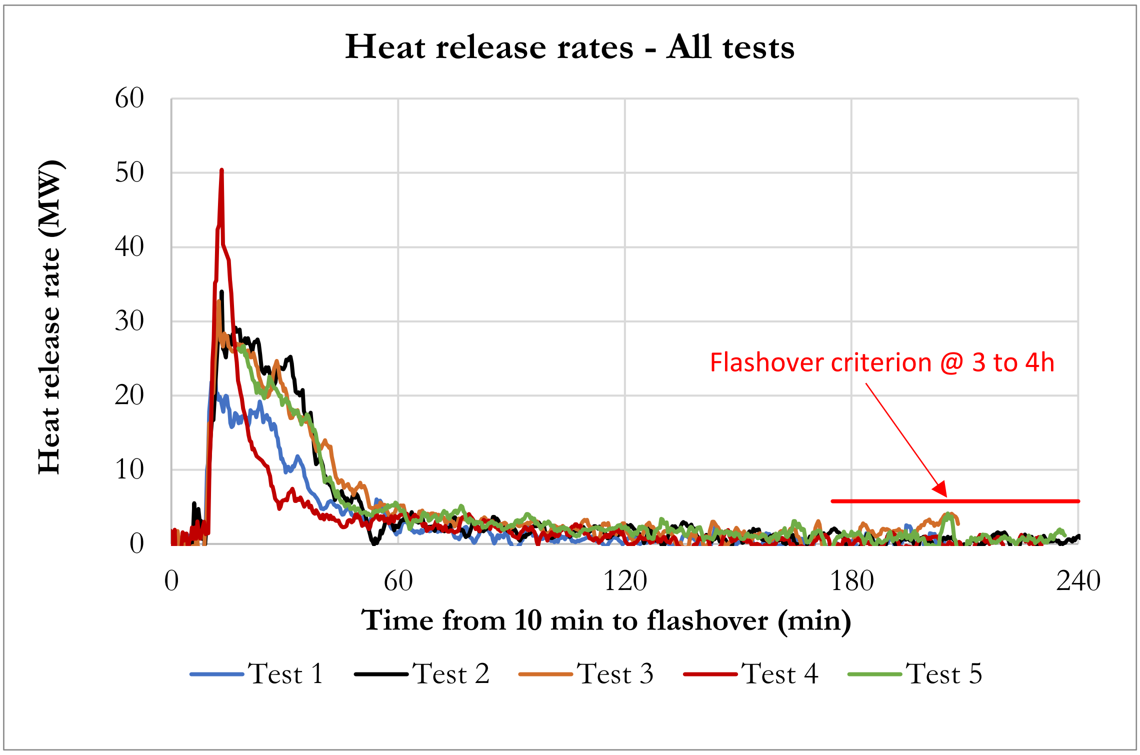


Figure 18: Heat release rates of all tests and the heat release rate flashover criterion of Chapter 3

4.5 Char depths

CLT char depths were measured after the test using a resistograph which is able to drill through the specimen while plotting the drill depth versus the torque resistance. The uncharred depth is identified as the depth at which the resistance drops significantly, as done previously by Brandon and Dagenais (2018) and Su et al. (2018b).

Figure 19 to Figure 23 show the depth of the char at the interior CLT surfaces of Test 1 to 5, respectively. The gypsum board protected surfaces are grey colored. After Test 1, the majority of the protected timber surface area was uncharred, but there were some locations with localized charring along CLT lap joints and gypsum board joints. There was no indication of any flaming as a result of this localized charring. Efforts were made to determine the deepest char depths at those locations as indicated in Figure 19. The protected surfaces of Tests 2 to 5 were mostly undamaged. Pictures of protected surfaces after removal of the gypsum boards, are shown in Section 4.3.

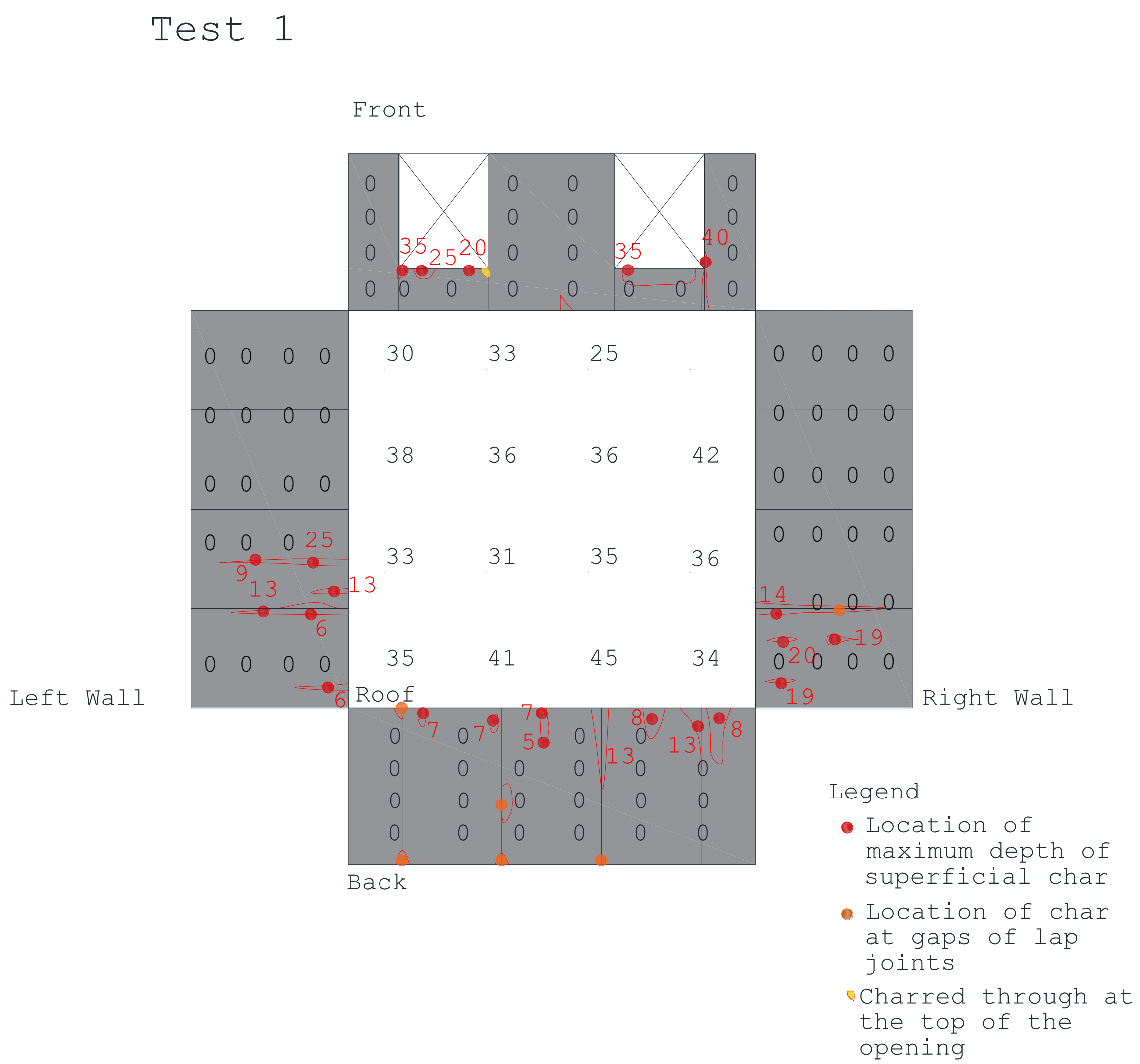
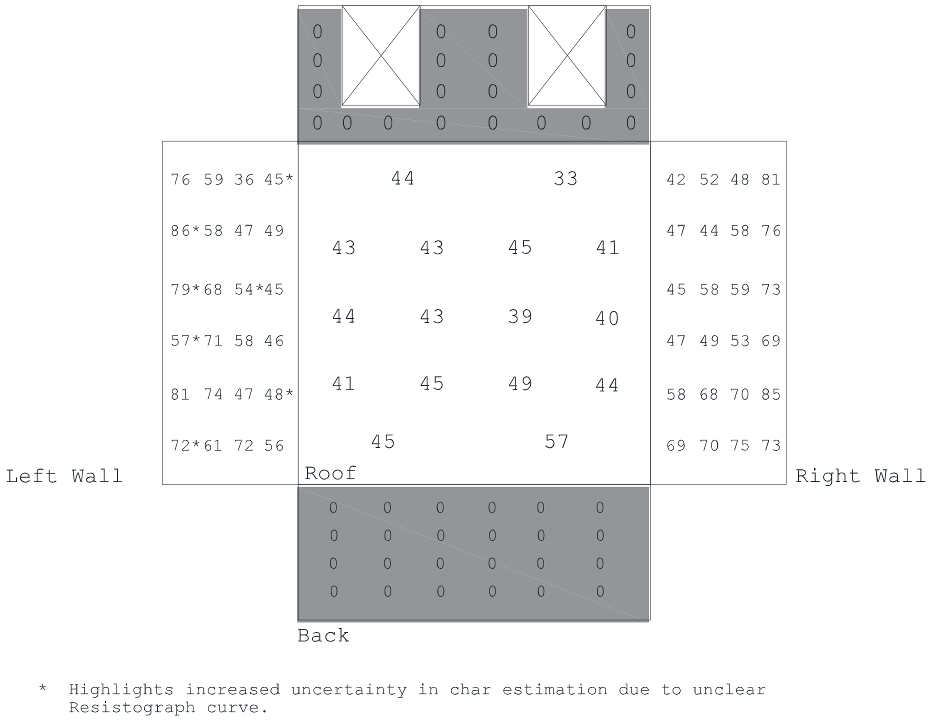


Figure 19: Char depths in mm measured after Test 1 (grey surfaces were protected)



** Indicates locations with an increased uncertainty of the char depth measurement*

Figure 20: Char depths in mm measured after Test 2 (grey surfaces were protected)

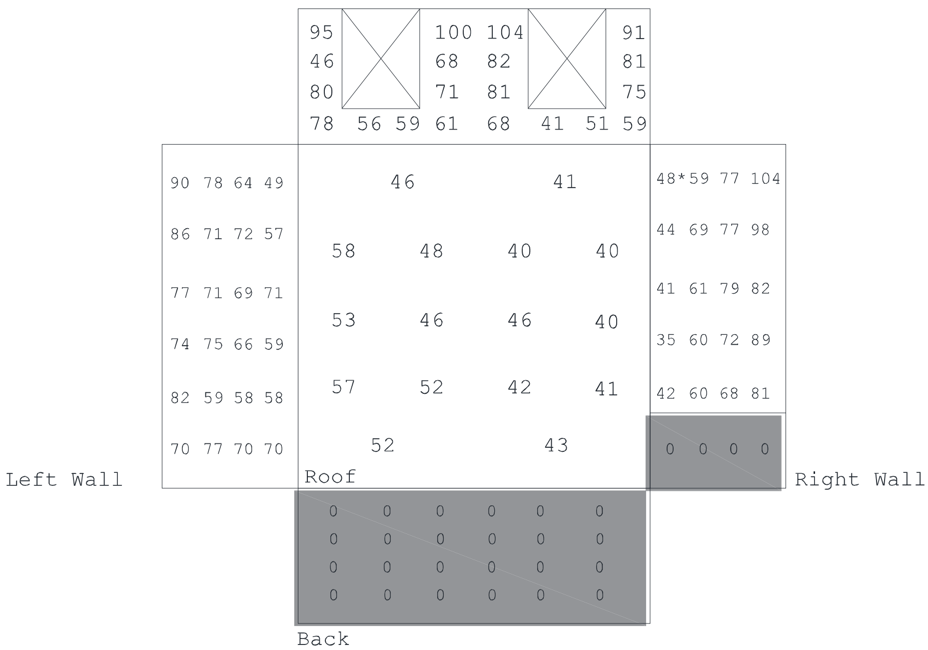


Figure 21: Char depths in mm measured after Test 3 (grey surfaces were protected)

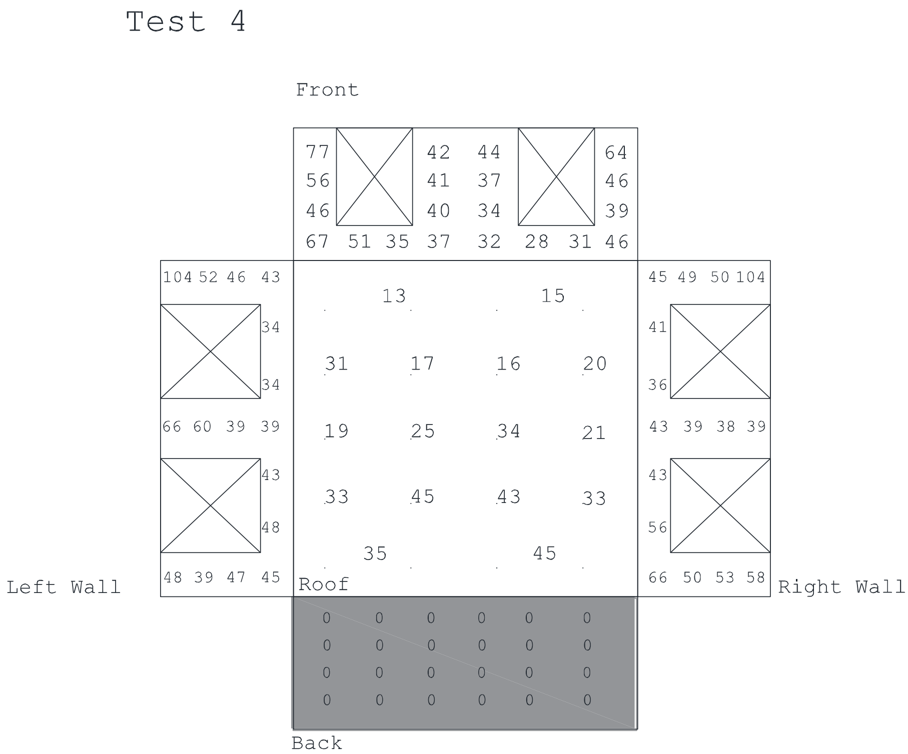


Figure 22: Char depths in mm measured after Test 4 (grey surfaces were protected)

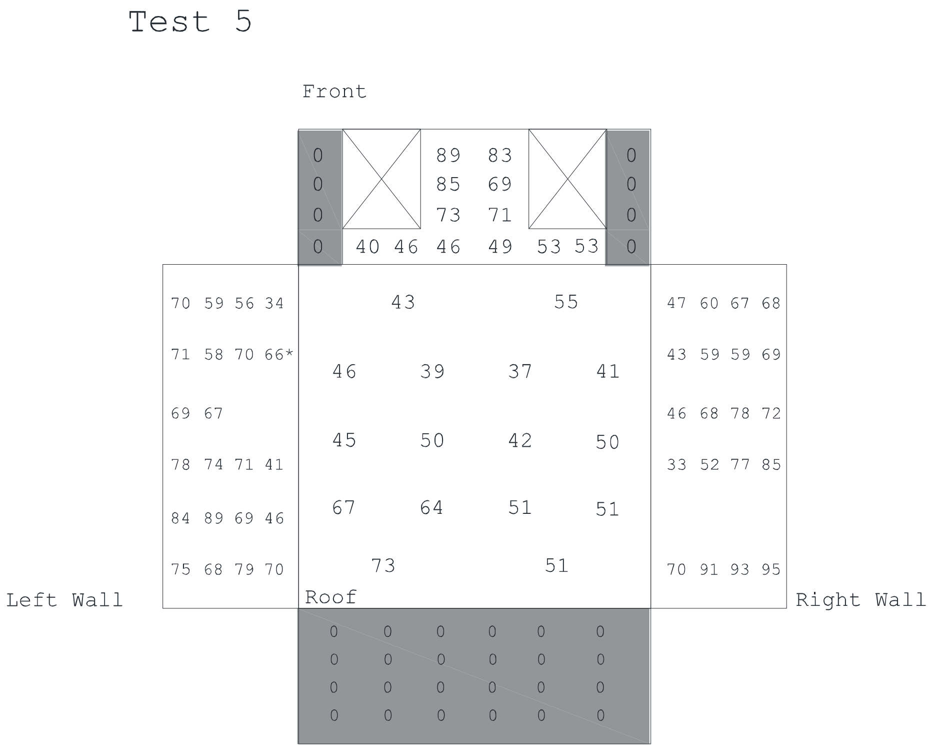


Figure 23: Char depths in mm measured after Test 5 (grey surfaces were protected)

The char depth during fire resistance tests (ASTM E119 and ISO 834) is generally used to calculate structural fire resistance of a load bearing assembly. Design standards, such as NDS (2018), use calculations of char depths to determine the load bearing capacity of mass timber elements to meet the fire resistance requirements.

These compartment tests are conducted to evaluate the safe limits of exposed mass timber surface areas, subject to a real fire. The time duration of 4 hours was chosen to assure that there is no reignition of mass timber elements after the real fire has decayed. The comparisons of char depths corresponding to a 4-hour real fire exposure to that of a 2-hour fire resistance test is not directly related to any U.S. code requirements. Nevertheless, this report provides a comparison for academic use. Please use caution in using the comparison for any regulatory requirements.

It should be noted that the NDS (2018) not only requires subtracting a char layer from the cross-section to calculate the load bearing capacity during fires, but also an additional 20% of the char layer thickness to account for damaged but uncharred wood. An appropriate size of this damaged layer to determine the structural capacity of a member exposed to fire, is dependent on the fire exposure which, in most cases, differs between standard fire tests and real fires. However, for a wide range of non-standard fire exposures, Lange et al. (2015) found that this layer was up to 16mm thick, which corresponds with the calculations of NDS (2018) for 2-hour fire resistance ratings. Therefore, the comparison of calculated char depth according to NDS and measured char depths is considered informative.

The CLT ceiling was exposed in all tests. Figure 24 shows box plots of the char depths measured after each test. It should be noted that Test 3 was stopped about 30 minutes earlier than all other tests[5], which means that the values would have been higher if the test lasted 4 hours instead. Test 4, which has a larger opening factor, had the lowest char depth. The char depths in the other compartments seem to show some correlation with the surface area of exposed timber. This agrees with predictions that were sent out to the project steering group and stake holders before the tests were performed. The predictions and the corresponding calculation model will be discussed in a separate report. It can be noted that all char depths measured in the ceiling after the fire were lower than the char depth for a 2 hour fire resistance rating, according to NDS (2018).

From the measurements it can be concluded that the char depths were lowest in the ceiling and at the top of walls and gradually increased towards the bottom of walls. Figure 25 shows the average char depth at different heights within the compartment. For comparison, the char depth according to NDS (2018) is indicated. It can be seen that the char depths are lower than the char depth for 2 hour fire resistance by NDS (2018), with the exception of the bottom of walls in Test 3[4].

[5] Test 3 was stopped at 3:30h as it did not pass the criterion set by the project steering group to have continuous decay until 4 hours after ignition, as such, this level of mass timber surface exposure would not be recommended for high rise buildings, where there is possibility that an automatic sprinkler system could fail and that fire service intervention may not occur for 4 hours.

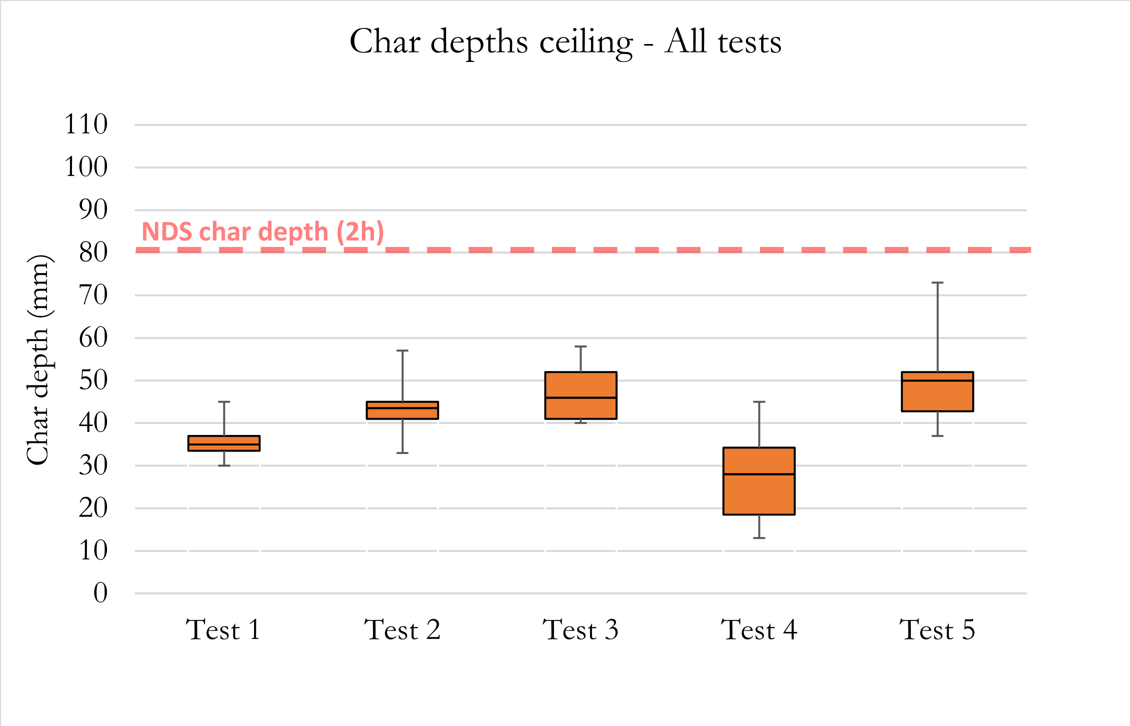


Figure 24: Box plots of char depths in the CLT surface of the ceiling

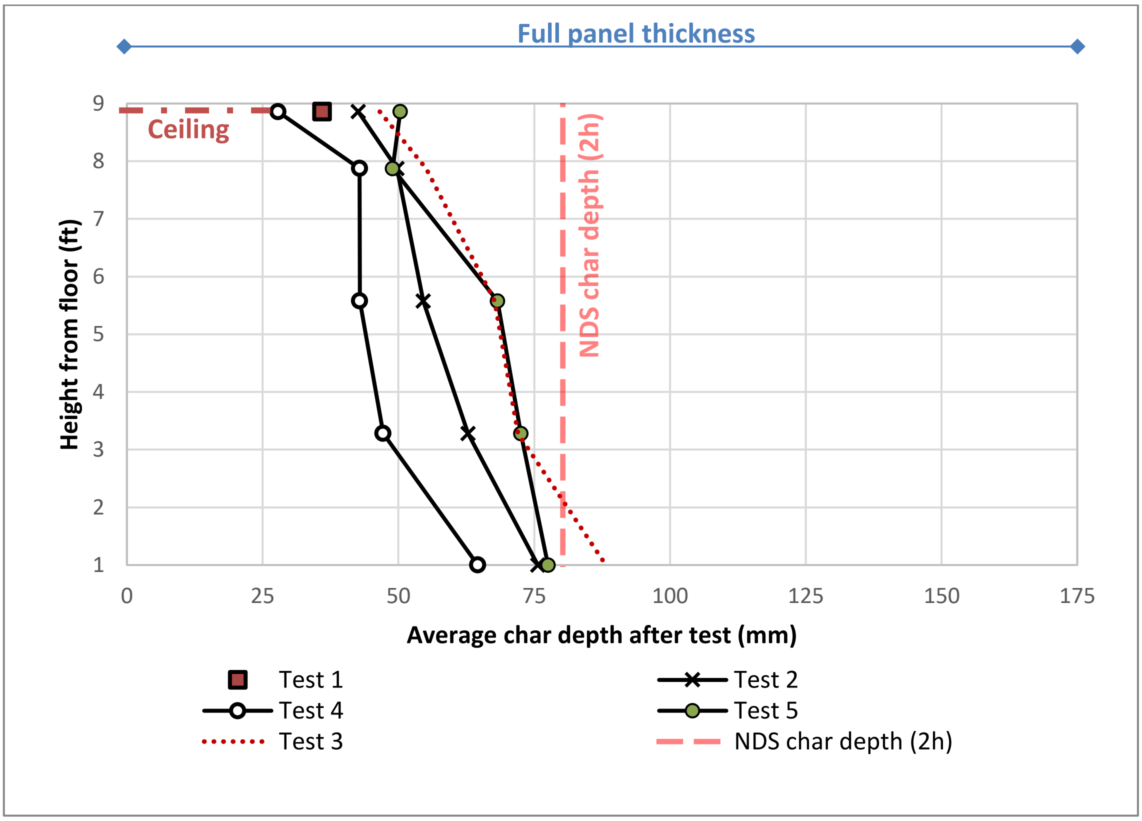


Figure 25: Average char depths in the walls and ceiling at different heights measured from the floor

In corners between two exposed timber members (CLT or glulam), the char depths were highest. Figure 26, shows box plots of the maximum measured char depth in corners of two exposed mass timber members and corners of one protected and one exposed member. As Test 4 had a different compartment design, its data is not included in the figure. The figure indicates a significantly higher char depth at the bottom of corners of two exposed members, indicating a significant influence of exchange of radiative heat between both combusting walls in the corner. At these locations the char depth exceeds the char depth of NDS (2018) for a fire rating of 2 hours. As Test 3 had a number of such corners, this significantly influenced the overall char depth. In corners where only one member was exposed, the measured char depth was significantly lower and only outliers (indicated by the whisker of the box plot) exceeded the char depth of NDS (2018).

In Test 4 a more significant difference was observed, as the maximum char depth at corners between two exposed walls was nearly twice as high as the maximum char depth in other wall corners.

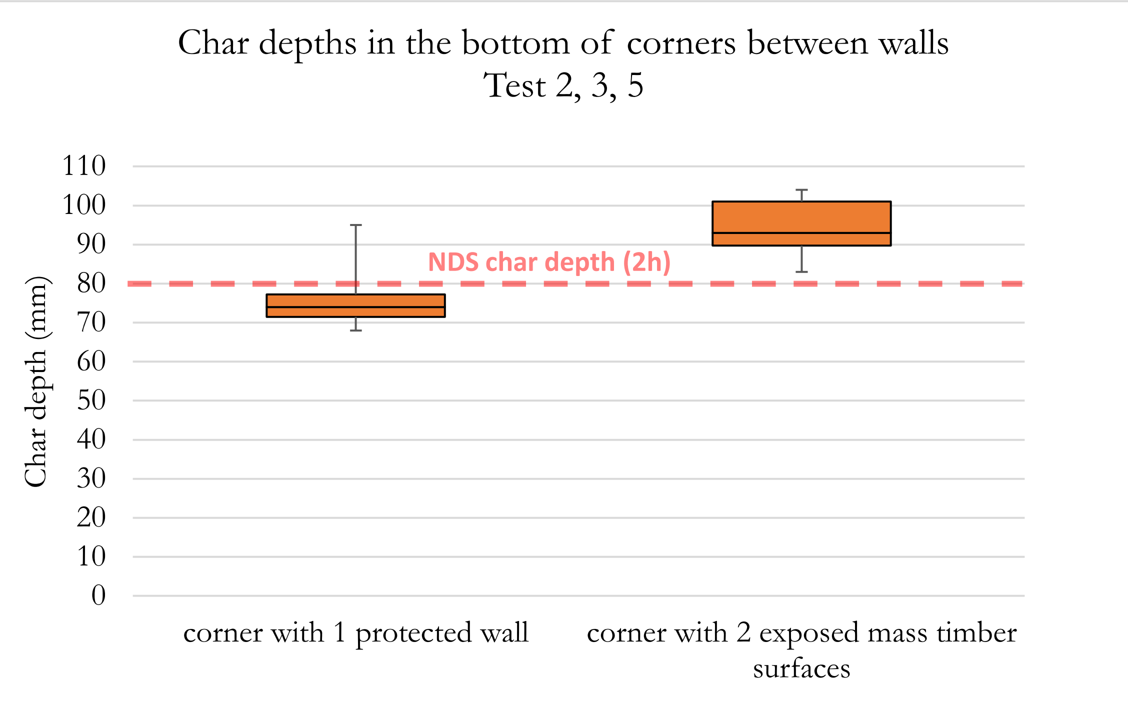


Figure 26: Box plots of measured char depths at the bottom of corners between walls (generally the most damaged location)

4.6 Intersections

With 2 exceptions no flaming occurred on the exterior side of the compartment. At (1) an intersection between the glued laminated timber beam and the back wall of Test 1, and (2) an intersection between the left wall and the ceiling at the front of the wall of Test 3, there was some flaming on the exterior side. Table 4 shows an overview of smoldering/flame spread through intersections of mass timber members.

Table 4: observed flames through joints or details

	Location	Description	Images
Test 1	Beam-wall joint at back wall	Minor flaming at one of the top corners of the beam at the location where the beam penetrated the back wall. ***Note:*** *the rectangular hole in the CLT was made on site using a hand-held reciprocating (tiger) saw. The geometrical imperfections are not representative for factory made cuts.* Some fire sealing adhesive, but no construction tape or expanding tape was used at this detail.	
Test 2	None	-	-
Test 3	Wall-ceiling joint at the front side of the left wall	Smoke exited the intersection at the top of the left wall on the front side directly after flashover, indicating the intersection was not sealed at this location. The smoke development took place at the location where several thermocouple wires were running (Note: these were moved before the photo was taken). To avoid loss of data, the stone wool was placed over the intersection (under the wires) to protect the wires. In extreme cases, small amounts of water on the external surface were used to minimize the exposure to the thermocouple wires.	 (Detail shown in Figure 4)
Test 4	None	-	-
Test 5	None	-	-

As mentioned in 2.1, the sealing materials used in the different tests varied. Table 5 gives an overview of these sealant materials (as also indicated before in Figure 4 of Section 2.2). Hereby, green shaded cells of the table indicate that connection details withstood the specific test without any occurrence of spread of smoldering or spread of flaming through the intersection. The orange shaded cell indicates local spread in one location, which was likely a result of compromised air tightness because of slight level differences between the top of connected wall members. Some of these locations were identified before the start of Test 3 (Figure 27) and fire sealing adhesive was applied to close the void under and above the resilient profile in those locations only. During the test, however, smoke left the intersection at the top of the left wall at an early stage in the fire, indicating lack of air tightness at that location.

Figure 28 and Figure 29 show the top of the wall in Test 3. The photo of Figure 28 is taken at a lap joint where the top faces of the wall panels were on the same level and showed no damage near the exterior side of the joint. Figure 30 and Figure 31 show typical photos of walls with the alternative wall-ceiling joints that were tested in other tests. No damage was observed near the exterior side of the joint.

Table 5: Sealing materials at intersections between CLT members (**green** indicates fire spread to the external surface; **orange** indicates spread of flames to the external surface in one location)

	Ceiling-ceiling spline board joint (see Figure 4 A)	Wall-ceiling joint (see Figure 4 B)	Wall-wall lap joint (see Figure 4 C)	Wall-wall corner butt-joint (see Figure 4 D)
Test 1	2x Construction tape	Construction tape	Construction tape	Construction tape*
Test 2	2x Expanding tape close together	Construction tape & Resilient profile	2x Expanding tape	2x Expanding tape*
Test 3	2x Expanding tape apart	Resilient profile	Construction tape	Construction sealant
Test 4	Construction tape under spline board	Construction tape & Resilient profile	Construction tape	Construction tape
Test 5	Construction tape under spline board	Construction tape & Resilient profile	Construction tape	Construction tape*

** All wall-wall corner joints in Test 1, 2 and 5 had at least one gypsum protected surface which reduced the challenge of sealing the connection*

Figure 27: Location of imperfect detail at wall-ceiling joint with a resilient profile identified before the test

Figure 28: Top of the wall lap joint after removal of the ceiling. Typical location without flame spread. Sealing method: resilient profile only (Test 3).

Figure 29: Top of the wall after removal of the ceiling and the resilient profile. Location of flame spread through intersection (front side of left wall) - Sealing method: resilient profile only (Test 3).

Figure 30: Top of the wall after removal of the ceiling. Typical location. Sealing method: construction tape only (Test 1).

Figure 31: Top of the wall after removal of the ceiling. Typical location. Sealing method: construction tape and resilient profile (Test 2).

Figure 32 to Figure 35 show the ceiling-ceiling spline board connection alternatives after the test. At most some discoloration of the CLT surface under the spline board was seen at some locations after Test 1 and Test 3. In the other tests, there was no sign of damage on the surface under the spline board.

Figure 32: Photo after removal of spline board. Sealing method: 2x construction tape on top of spline boards (Test 1)

Figure 33: Photo after removal of spline board. Sealing method: 2x expanding tape under spline board at CLT interface (Test 2)

Figure 34: Photo after removal of spline board. Sealing method: construction tape under spline boards at CLT interface (Test 4)

Figure 35: Photo after removal of spline board. Sealing method: 2x expanding tape at center of lap (Test 3). Note: the rain after the test cause additional discoloration

None of the corner joints between walls showed any sign of fire spread through the connection. Figure 36 shows the external side of typical wall-wall corner joints with construction sealant and Figure 37 shows the external side of typical wall-wall corner joints with construction tape (left) and expanding tape (right) after the test. Detail drawings of these connections are given in Figure 4 D.

Annex F includes details and pictures of the façade above openings, as that is a highly exposed location of the structure.

Figure 36: Typical wall-wall butt joint with construction sealing after the test.

Figure 37: Typical wall-wall butt joint with construction tape (left) and expanding tape (right) after the test.

4.7 Discussion

The data and analysis in Section 4.5 showed that the char depths at the end of the tests were higher in the bottom of corners with two exposed walls intercepting. It is expected that this is caused by a radiative feedback loop in the lower part of the corner located in a relatively oxygen rich environment (further analysis using oxygen measurements will be included in the final project report). The photo of Figure 38 shows such a corner at a late stage of decay of Test 4. At the time of this photo, smoldering combustion in most other surfaces started to extinguish as concluded using an infrared camera. However, the bottom corner was visibly smoldering more severely than other surfaces.

Figure 38: Photo at the final stage of Test 4

Tests 3, and 5 had approximately the same surface area of exposed wood and Test 2 had roughly 5 % less surface area of exposed wood, as is summarized in Table 6. Between the tests only one test parameter has changed, which is the location of the gypsum board protection. As indicated in Table 6 the gypsum boards of Test 2 and Test 5 were positioned in a way that one wall surface at each corner intersection between walls was protected, which was not the case for Test 3. The plate thermometer temperatures compiled in Figure 12 indicate that, despite the similar surface areas of exposed wood, the thermal radiation on the left wall in Test 3 was significantly higher for most of the decay phase compared to that of Test 2 and 5. An indication that radiative feedback played a role is the increased char depth in the bottom of those corners by roughly 40 % or 0.8 inch (30 mm) in Test 3, despite the fact that Test 3 was 30 minutes shorter than Test 5.

As indicated in Table 6, Test 3 did not pass the criteria defined in Chapter 3, while Test 5 (and all other tests) did fulfil these criteria. As there was only one test variable between Test 3 and Test 5 and because there are indications that radiative feedback between two exposed walls at the bottom of a corner is significant, the data indicates that the contrast between the outcome of (a) Test 3 and (b) Test 2 or 5 is a result of the presence of wall corners with two exposed CLT surfaces.

Table 6: Overview of tests with an opening factor of 0.062 $m^{1/2}$

Test	Opening factor $m^{1/2}$	Protection (interior). Number of 5/8 inch thick (15.9 mm) type X gypsum boards	Surface area of timber exposed			Presence of corner intersection between exposed walls	Pass criteria at 4 h
			m^2	ft^2	%*		
Test 1	0.062	2GB	53.8	579	44.2	No	Fulfilled
Test 2	0.062	3GB	91.2	981	75.0	No	Fulfilled
Test 3	0.062	3GB	96.2	1035	79.2	Yes	Not fulfilled
Test 5	0.062	3GB	97.2	1046	80.0	No	Fulfilled

** Percentage of all surface areas except the floor*

Test 4 fulfilled the criteria defined in Chapter 3, despite the presence of corners between two exposed walls. It can, however, be stated that the char damage to the mass timber structure becomes less with increasing opening factor (Su et al 2018a, Su et al 2018b, Brandon and Anderson, 2018). Thus, the large openings of Test 4, representing a building with mercantile occupancy (Annex B), lost significantly more heat through openings (by radiation and convection) and that despite the significantly larger HRR during flashover, the fire rapidly decayed to just a small number of very local hot-spots.

Table 7: Information of Test 4 with an opening factor of 0.25 $m^{1/2}$

Test	Opening factor $m^{1/2}$	Protection (interior)	Surface area of timber exposed			Presence of corner intersection between exposed walls	Pass criteria at 4h
			m^2	ft^2	%*		
Test 4	0.25	2GB type X 15.9 mm	77.9	838	80.2	Yes	Fulfilled

** Percentage of all surface areas except the floor*

5 Main conclusions

Five compartment fire tests were performed, that were designed to represent statistically severe and realistic fire scenarios. The tests were performed outside and, therefore, there were no laboratory restrictions regarding the heat release rates of the fires and the surface area of mass timber that could be exposed.

The conclusions of this study are only applicable for mass timber materials that have been demonstrated to withstand long duration compartment fires without the occurrence of delamination, such as required by ANSI/APA PRG 320 (2018).

The fire scenarios tested in this study correspond to the improbable event that (NFPA 13 compliant) sprinklers are not functioning, and fire service interference is not successful for the first 4 hours. Under those conditions a statistically severe fire scenario (with a statistically high fuel load density and low opening factor) is tested, aiming to make the conclusions more generally applicable, while limits of exposing mass timber have been investigated. More information of the statistical analysis can be found in Annex B.

From the compartments tested against the selected severe fire scenario, it can be concluded that:

(A) A flashover fire in a compartment with

(1) 100 % exposed (PRG 320, 2018 compliant) CLT ceiling
(2) 100 % exposed glulam beam under the ceiling
(3) two layers of 5/8 inch thick Type X gypsum board protection on all other mass timber surfaces,

decayed continuously until 4 hours after ignition and reached radiation temperatures that were significantly below 300˚C.

(B) Flashover fires in compartments with

(1) 100 % exposed (PRG 320, 2018 compliant) CLT ceiling
(2) 100 % exposed beam under the ceiling
(3) additional exposed surface areas of column and walls equal to 78 % or 90 % of the floor area
(4) 3 layers of 5/8 inch thick Type X gypsum board protection on all other mass timber surfaces,

decayed continuously until 4 hours after ignition and reached radiation temperatures that were significantly below 300˚C. A third test with similar surface areas of exposed mass timber walls indicate that the exposed CLT wall surfaces should not intersect in a corner in order to achieve a continuous decay phase for more than 3 hours after ignition.

(C) A post flashover fire in a similar compartment with a larger opening factor, which corresponds to the range of opening factors of office buildings, decayed relatively quickly and reached ambient temperature within 4 hours.

(D) In all tested compartments with walls and the ceiling surfaces exposed, the char depth in the ceiling and the top part of the wall was lower than the char depth at the bottom part of walls.

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Annex A - Façade drawings

This Annex includes drawings of the facades with openings. All tests, including Test 4 had a symmetrical structure. Therefore, only one of the side facades of Test 4 is included.

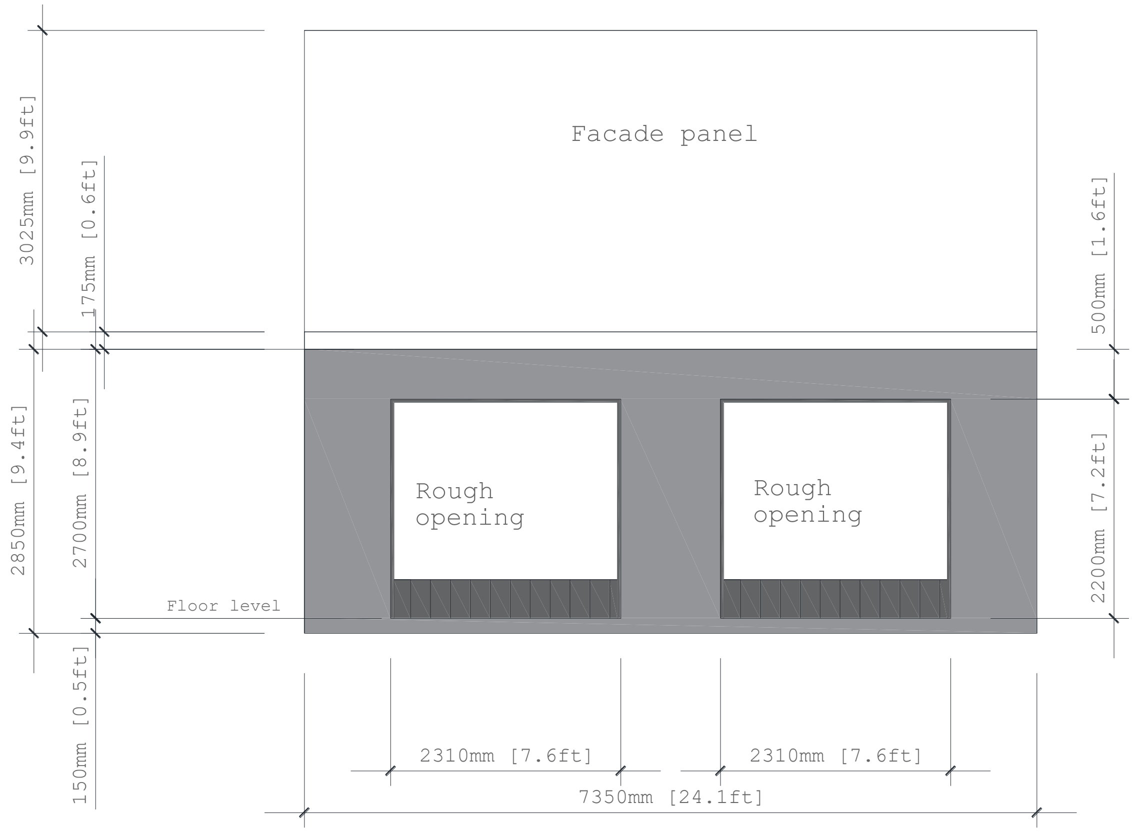

Figure A. 1: Front view of the compartments of Test 1, 2, 3 and 5

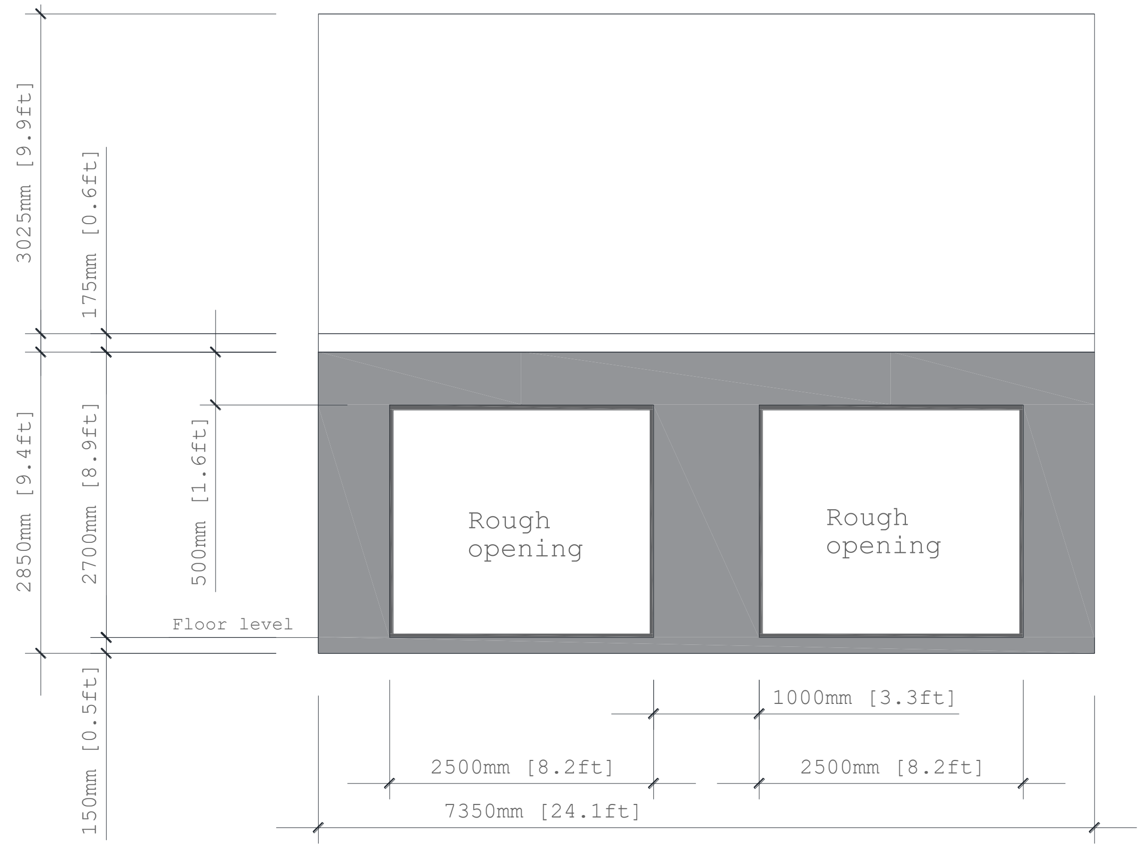

Figure A. 2: Front view of the compartment of Test 4

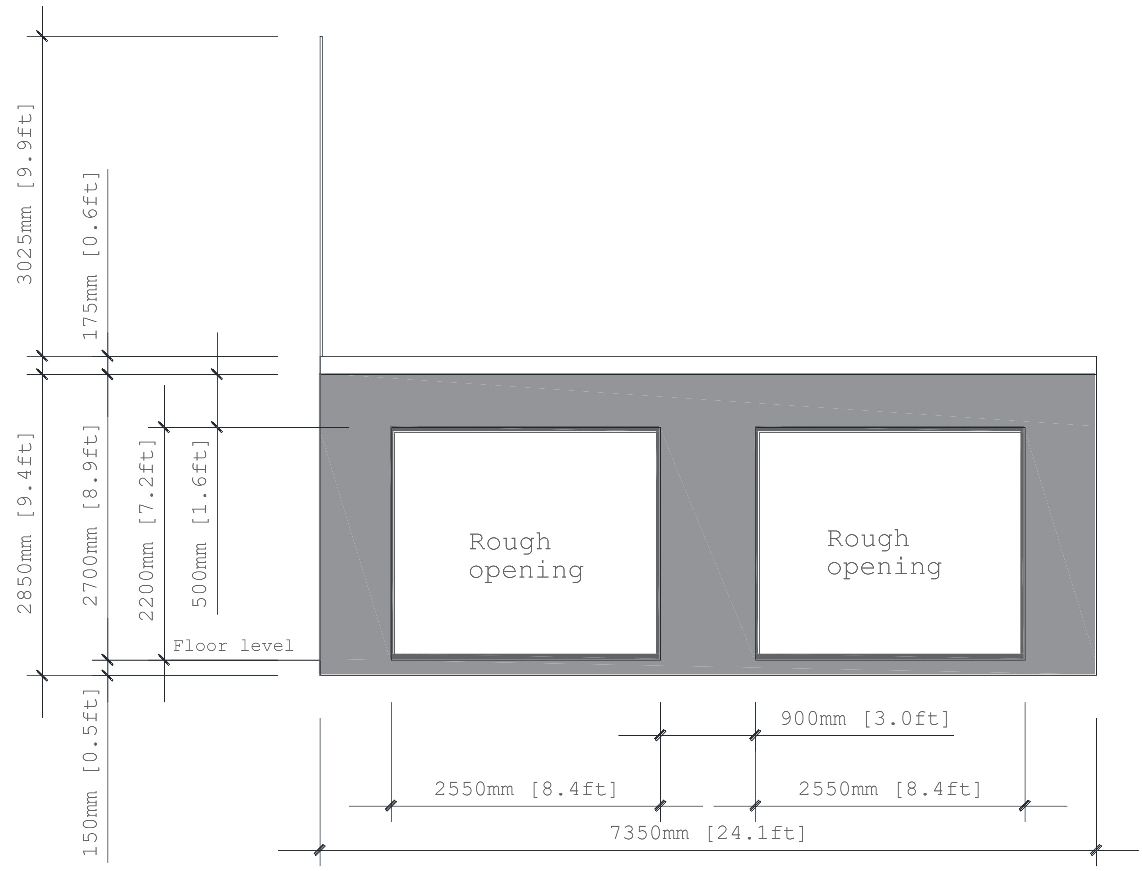

Figure A. 3: Side view of the compartment of Test 4

Annex B - Probabilistic study of compartments and fire scenarios

To ensure relevance of the compartment to real scenarios, a statistical approach has been utilized in the design of the test compartments. A review of the, publicly available, general arrangement, section, elevation and façade drawings, of 513 compartments in residential buildings constructed within the past decade in the UK, has been conducted to provide a statistical overview of modern apartment design, and specifically:

- The distribution of floor areas, and
- The distribution of opening factors (O)[6].

It has been indicated previously, for example by Zelinka et al. (2018) or Su and Lougheed (2014), that typical non-fire rated walls within enclosures provide limited impediment to the spread of fire. Therefore, when considering the floor area and perimeter of the apartments, the internal walls have been ignored, as shown in Figure B. 1 below.

Figure B. 1: Apartment showing measured floor area (blue) and assumed perimeter (red)

In order to confirm that buildings utilizing mass timber are not being designed in any significantly different manner, a review of 185 compartments in large residential mass timber buildings[7], has also been conducted. The distributions established for the compartment area and opening factors can be found in Figure B. 2 and Figure B. 3, respectively. Based on multiple studies (e.g. Hox, 2015 and Frangi and Fontana, 2005), it is presumed that windows will break before the post-flashover phase of the fire, if the

[6] Definition of opening factor: $O = A_0\sqrt{H_0}/A_t$, where $A_0 = \sum A_i$ is the sum of all opening areas, A_t is the total enclosing area (incl openings), $H_0 = \sum (A_i h_i)/A_0$, and h_i is the height of each opening

[7] The Cube, Dalston Lane and Stadthaus buildings, all of which are in London

fire has enough oxygen supply to develop to flashover. Therefore, windows and glass doors are counted as openings during flashover fires.

Lastly, drawings from 31 compartments in mass timber office buildings were collected and the distribution of corresponding opening factors are displayed alongside the ones for residential compartments in Figure B. 3. The opening factors of compartments in office buildings are in a range that is clearly higher than that of residential compartments.

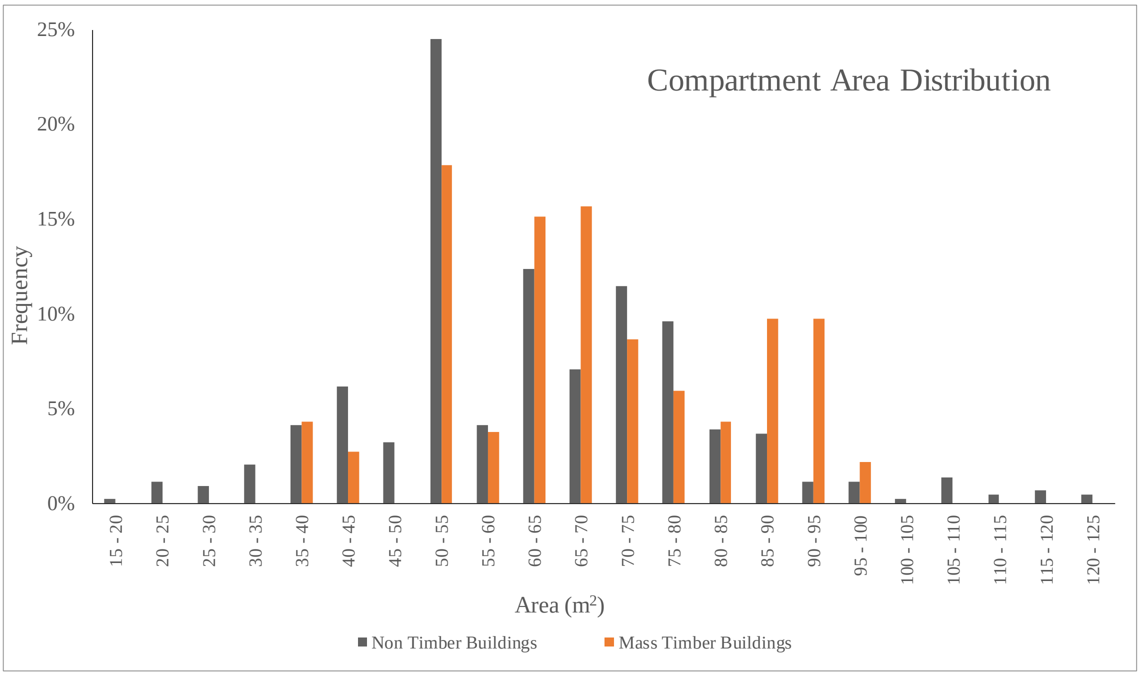

Figure B. 2: Compartment area frequencies from residential buildings (*n*=513 for non-timber buildings and *n*=185 for mass timber buildings)

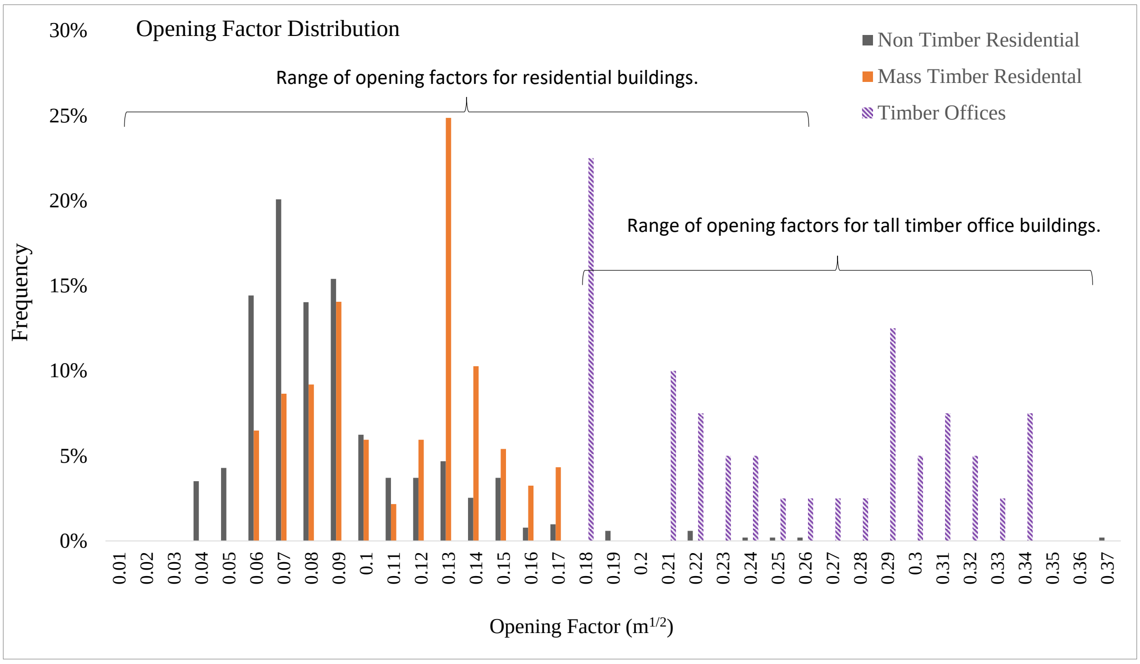

Figure B. 3: Opening factor frequencies for residential and office buildings. Note that the statistical basis for the office buildings is only 31 compartments. The results are, therefore, used as an indication of a range rather than a distribution

In addition to these distributions, results from a survey of combustible contents and floor areas in Canadian multi-family dwellings (Bwalya et al. 2010) were utilized. By combining the results and standard deviations, which are presented for different room types individually, the distribution of fuel load densities (FLD) of the total compartments are derived. These are normally distributed with an average FLD of 502 MJ/m² and a standard deviation of 92 MJ/m².

With the distributions of floor areas, opening factors and fuel loads in residential compartments we can estimate the damage, characterized by the final charring depth, from fires in timber buildings. The damage is assessed using the method specified by Brandon (2018) which is a conservative method to determine the char depth at the end of a decay phase, evaluated against most of the previously performed real compartment fire tests. The final charring depth after the cooling phase is modelled based on four characteristics of the compartment.

1. The opening factor
2. The moveable fuel load density
3. The area of exposed timber
4. The overall dimensions of the compartment

The model assumes that no charring occurs on the walls with unexposed timber. Thus, either they are incombustible or sufficiently protected by gypsum plaster boards or alike.

For the case shown here, we use the distribution of opening factors of all 698 residential compartments in Figure B. 3 (bearing in mind that, generally, residential buildings of mass timber structures had larger openings than non-timber buildings, which in turn would generally result in less fire damage). The floor area and FLD distributions are taken from the results of (Bwalya et al. 2010). The analysis corresponds to a compartment structure of mass timber and a ceiling that is 100 % exposed and walls that are sufficiently protected from charring by gypsum boards. 200 000 simulations have been run, randomly choosing the floor area, FLD and Opening factor according to the probability distributions described above and calculating the total damages described by the final char depth of the exposed timber, Figure B. 4.

The tests performed in this report were chosen to have the floor area of 49 m^2 which is the mean of floor areas of the 698 residential compartments reviewed here, and therefore realistic. The FLD should represent a high density of live fuel and is chosen to be 560 MJ/m^2 corresponding to the 74^{th} percentile of the values reported by Bwalya et al. Both of these design values are indicated in Figure B. 4.

Two different opening factors are decided to be used, one smaller opening factor characteristic for residential buildings and one larger opening factor representative for office buildings. The value for the residential buildings is chosen based on the estimated damage from the 200 000 simulations and represent the 85^{th} percentile of damage to the exposed surfaces. This opening factor, 0.062 $m^{1/2}$, its corresponding final char depth and how it relates to the distributions from the simulations are shown in Table 8. The design value is conservative for the residential buildings in general and in particular for the residential timber buildings in the survey above.

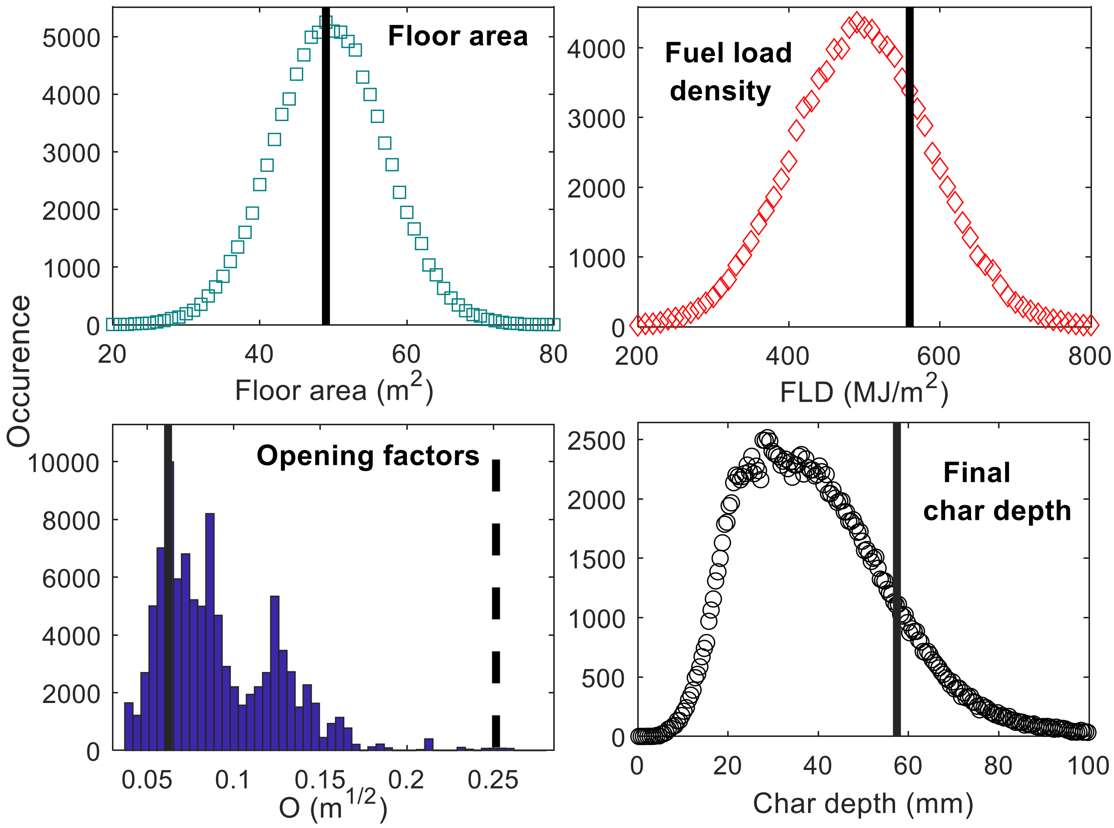

Figure B. 4: Results of the probabilistic study using the distributions for floor area and FLD according to Bwalya et al. (2010) and Opening factor from the 698 residential compartments in the survey described above. The simulations are done assuming that the ceiling is 100 % exposed timber and all other surfaces protected. The solid lines represent the design values chosen for the residential buildings and the dashed line that of the office building. The calculated damages are with a floor area of 49 m^2 and a FLD of 560 MJ/m^2 but variable opening factors.

Table 8. The opening factor highlighted in Figure B. 4, corresponding final char depth predicted percentile of the damage (char depth) after the fire.

Opening factor ($m^{1/2}$)	Percentile of all residential buildings	Percentile of timber residential buildings	Final char depth (mm)*	Percentile of damages for all residential buildings
0.062	25	7	57.4	85

* Assuming 49 m^2, full ceiling exposed and 560 MJ/m^2.

All previous experience show that larger openings will result in less damage. The design for the tests with a lager opening includes $O = 0.250$ $m^{1/2}$, which is right in the range of mass timber offices shown in Figure B. 4 and where the damage is expected to be less than for the small opening tests.

Annex C - Fuel load

Annex B discusses a probabilistic approach, concluding that a fuel load density of 560 MJ/m^2 would result in statistically severe scenarios, which was based on a statistical survey by NRC Canada (Bwayla et al 2010). To limit uncertainties introduced by using the NRC Canada survey based on one set of calorific values and using another set of calorific values to determine the fuel load density, this study also uses calorific values published by the same Unit at NRC Canada, involving partly the same researchers. Table C. 1 shows the calorific values of the NRC Canada study that are also used for this research.

Table C. 1: Calorific values from Su et al. (2018a)

Material	Calorific Value
Hardboard	19.9 MJ/kg
White pine	19.2 MJ/kg
Douglas Fir	21.0 MJ/kg
Polyurethane foam	29.0 MJ/kg
Cotton	20.3 MJ/kg
Paper	17.0 MJ/kg

In the compartments of this study several objects contained wood cribs of Norway Spruce for which a calorific value of 17.8 MJ/kg is calculated. The floor and several objects consist of particle board for which for which a calorific value of 21.2 MJ/kg is calculated based on data from *Phyllis 2*, a database of material properties performed according to relevant international test standards for the physico-chemical composition of lignocellulosic biomass, micro- and macroalgae, various feedstocks for biogas production and biochar, made available by TNO (the Netherlands). Some small amount of polypropylene (polyester) was used in the compartment, for which 47.3 MJ/kg is calculated based on the Phyllis 2 database. The weights of the object were individually determined and the total weight of the fuel on the floor was checked using load cell measurements before and after installation of the fuel. Table C. 2 shows the calculated calorific value per object. This excludes the energy of the exposed gypsum board paper, which is estimated to be between 2 and 5 MJ/m^2 depending on the area of gypsum board protection in each test.

Table C. 2: Calculated moveable fuel load density per test

	Brand	QTY	Material 1	(kg)	Material 2	(kg)	Material 3	(kg)	Total cal. value
Hemnes sofa bed	Ikea	2	Particle board	85	Spruce	9.8	Hardboard	8.2	4281
Friheten sofa bed	Ikea	1	Particle board	63	PU foam	40	Cotton	3	2557
Kleppstad wardrobe	Ikea	2	Particle board	74.1	Hardboard	4.8	none		3333
Göran table	Ikea	2	Particle board	8	Hardboard	2.5	none		439
Lack coffee table	Ikea	1	Particle board	18	none		none		382
Stefan chair	Ikea	8	White pine	4	none		none		614
Gersby book shelves	Ikea	6	Particle board	8	Hardboard	2.5	none		1316
Sköldblad cushions	Ikea	12	PU foam	0.37	none		none		129
Pärkla storage bags	Ikea	2	Polypropylene	0.14	none		none		13
Hemnes mattress	Ikea	4	PU foam	6.7	none		none		777
Fullkomlig Table cloth	Ikea	2	Polypropylene	0.57	none		none		54
Particle board floor		1	Particle board	289	none		none		6127
Wood cribs in total	Södra	1	Spruce	380	none		none		6802
Paper in bin		1	Paper	1	none		none		17
								Total fuel load (MJ)	**26840**
								Fuel load density (MJ/m²)	**560**

The wood cribs were positioned in storage spaces to correspond to a realistic distribution of fuel throughout the compartment. In addition, a wood crib was installed under the dinner table to more closely resemble a heavier table and set of chairs. Table C. 3 indicates mass of the wood cribs at the locations indicated with the letters A to J in Figure 2 and Figure 3 of the main text.

Table C. 3: Mass of spruce wood crib at locations indicated in Figure 2 and Figure 3

Location	**Type**	**Mass of wood crib (kg)**
A	Hemnes sofa bed	19.4
B	Lack coffee table	23.3
C	Gersby bookshelves (4x)	103.6
E1	Kleppstad wardrobe at back wall	36.3
E2	Kleppstad wardrobe towards center	41.5
F	Hemnes sofa bed	20.7
G	Göran dinner tables	66.1
H	Gersby bookshelf	25.9
I	Gersby bookshelf	25.9
J	Pärkla storage bags	17.3
	Total mass of wood cribs	380.0

Annex D - Mass loss measurements and heat release rate calculations

Mass loss rates of the floor and the mass loss of the structure were determined using load cells that were positioned under a steel frame that bared the floor or a steel frame that bared the remaining structure (walls, ceiling and external façade). The initial mass of the bare floor was determined before every test using load cell measurements. The mass of the movable fuel load was determined from load cell measurements before and after installation of the fuel. After each fire test, the material left on the floor was limited to some metallic parts of the furniture and some equipment, weighing 36 kg (79 lb) in total. The combustible material left on the floor is considered negligible and the mass of the floor after the test was determined from load cell measurements at the end of the test.

As the bare mass of the floor was determined before and after the test, the total mass loss, due to drying of the floor (175 mm (20.7 inch) CLT, 20 mm (2.4 inch) Stone Wool and 100 mm (11.8 inch) light weight concrete on top) could be determined. For the calculations of the mass loss rate, it is considered reasonable to assume that the ratio between mass loss rate of water in the floor and mass loss rate of the movable fuel was constant. This assumption will be further assessed using material temperature measurements of the floor and will be discussed in the final project report. By subtracting the mass loss rate of the floor structure from the total mass loss rate, the mass loss rate of the fuel load on the floor was determined.

The structure (walls, ceiling and glulam members) was weighed during the tests using load cells under a separate frame. The mass loss of the CLT and glulam of the structure is determined by subtracting an estimated mass loss of gypsum and the mass loss of the facade extension from the measured mass loss. The total mass loss of the lightweight concrete façade extension was determined by weighing the total structure before the façade extension was installed on top of the compartment before the test and after removing it. The mass loss of the façade extension was relatively small in comparison with the total mass loss (approximately 3%). Given the small overall influence on the total mass loss, for calculations of the mass loss rates of the combustible structure, it was considered reasonable to assume that the ratio between mass loss rate of the total structure and mass loss rate of the façade extension was constant. The mass loss rate of gypsum board protection was determined using temperature measurements and a heat transfer model described previously by Brandon and Andersson (2018, Annex A & B). The heat transfer model was used to estimate the temperatures in a large amount of locations in the gypsum board cross section. The calculation included the following steps:

1. Finite element calculation of the temperatures throughout the gypsum boards, using the average plate thermometer temperature curve measured during the test as boundary conditions for both radiation temperature and gas temperature. The gypsum thermal properties used are given by Brandon and Andersson (2018).
2. Comparison with measured temperature to assess the accuracy of the calculation.
3. Use Thermo Gravimetric Analysis (Figure D. 2) of the tested gypsum board to determine the mass loss throughout the gypsum board.

Step 2 mentioned above is a crucial step to assess the accuracy of the method. In order to have an indication of the accuracy, the total density loss corresponding to the predicted and measured temperatures of Figure D. 1 was calculated. The difference between the total mass loss determined from measurements and from predictions is ranging between 0 % and 11 % percent. This error translates in an error of approximately 0 to 1.3 % for the calculation of the mass loss of the combustible structure in Test 2 to 5.

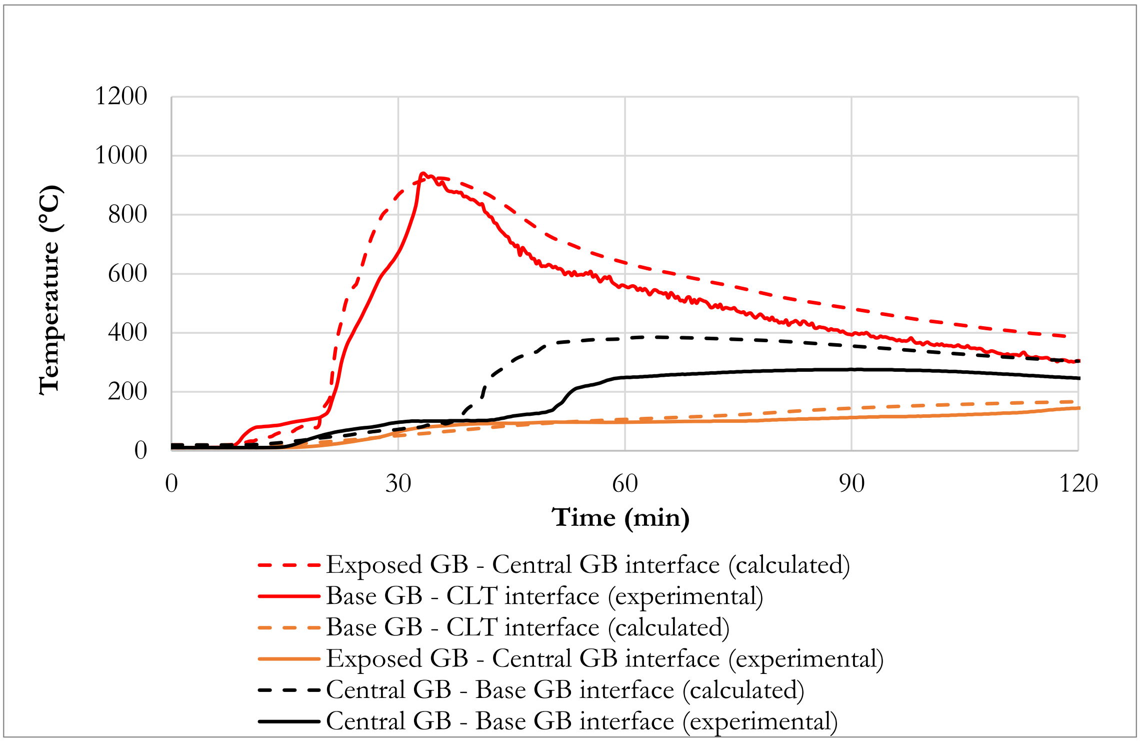

Figure D. 1: Measured and calculated temperatures at interfaces between gypsum boards (Example for Test 3).

Figure D. 3 shows the mass loss rate of the floor and the mass loss rate of the movable fuel of Test 2. The small difference between the two curves is explained by the relatively small mass loss due to drying of the floor during Test 2, most water was evaporated during Test 1. In the figure, three instances are indicated in which a fire fighter left the compartment. This happened at the beginning of every test and during Test 2 several times at around 145 and 160 minutes after ignition to fix a test-setup related problem[8]. For the calculation of the heat release rate the mass loss rate jumps caused by persons leaving the floor are disregarded.

[8] During Test 2, the fire fighter responsible for safety during the test added wet stone wool insulation in a gap between the floor and the right wall to avoid downward fire spread. It should be noted, that the floor and the walls were not mechanically connected to allow separate measurements of the mass of the floor and the mass of the rest of the structure. The detail is therefore not representative for the design of real buildings.

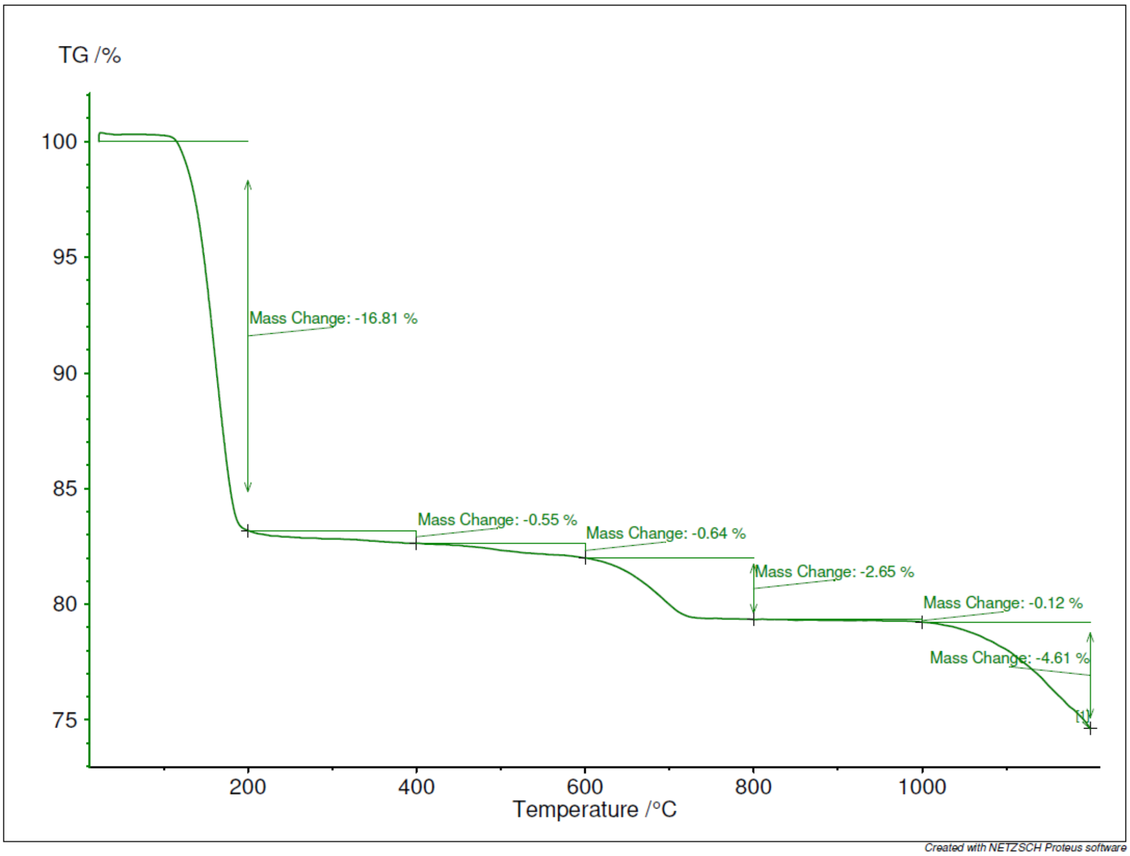

Figure D. 2: TGA results of Type X gypsum board conducted with a NETZSCH F3 Jupiter. Heating rate: 20˚C/min from 20 ˚C to 1200 ˚C in an N_2 atmosphere.

Figure D. 4 shows the mass loss rate of the structure excluding the floor and the fuel load on the floor together with the mass loss of the façade and the estimated mass loss of gypsum boards. The mass loss of the structural timber is determined by subtracting the mass loss of the gypsum boards and façade from the measured mass loss.

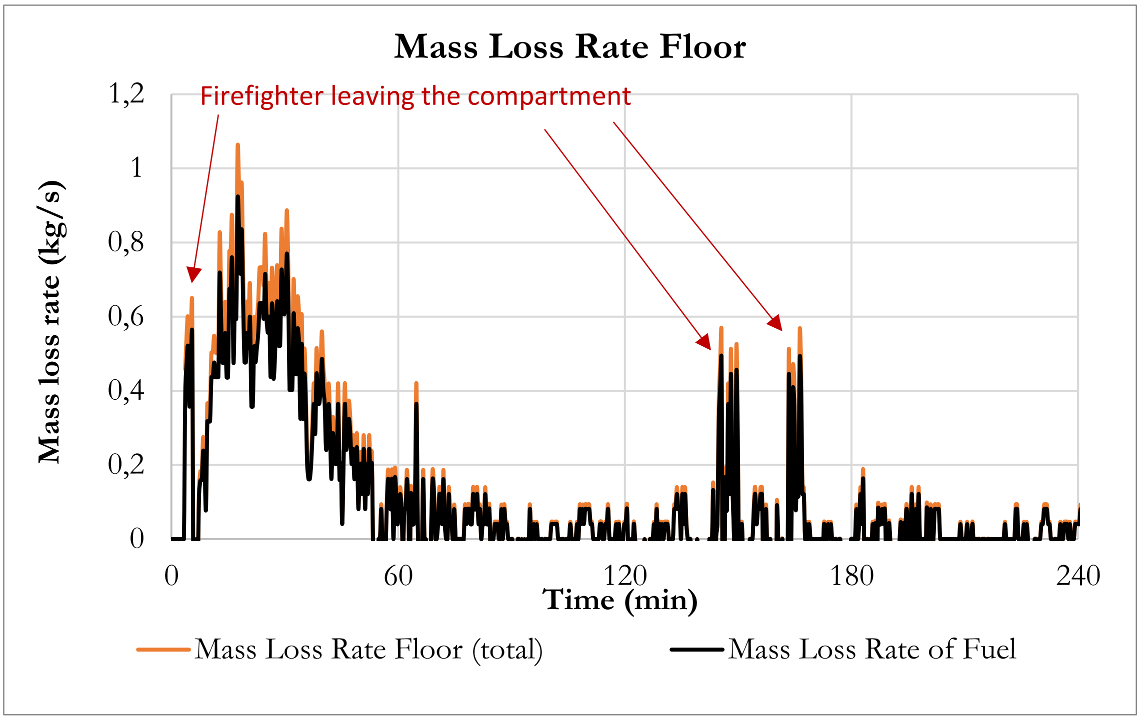

Figure D. 3: Mass loss rate of floor and mass loss rate of fuel of Test 2

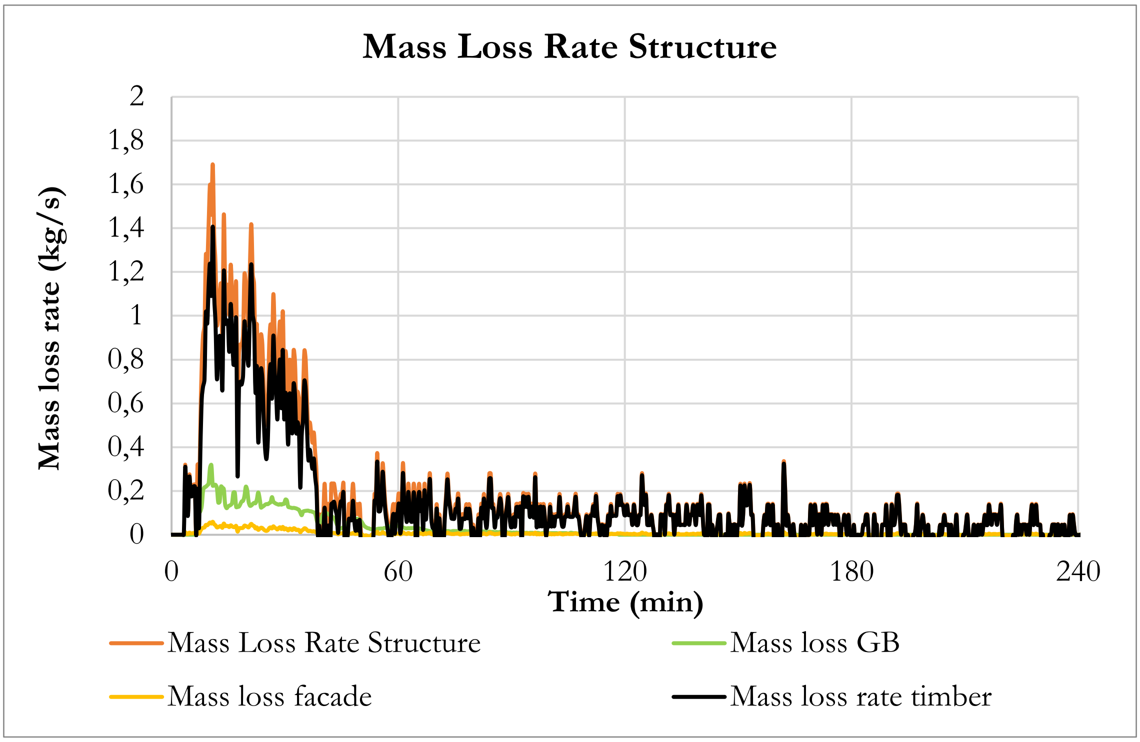

Figure D. 4: Mass loss rate of the structure (excluding floor), façade, gypsum boards and timber surfaces for Test 2.

From the mass loss rates the heat release rates are estimated using the calorific values summarized in Annex C - Fuel load (17.8 MJ/kg for the structural timber and 20.5 MJ/kg for the moveable fuel load). The heat release calculation assumes that all combustible volatiles that are released in the fire will combust. Figure D. 5 shows the heat release rates of Test 2. It was found that the floor and the structure clearly interacted in multiple tests, which is evidenced by simultaneous extreme values of the mass loss/mass gain rate in opposite direction. The total mass of both is however not affected by the pressure interaction between the floor and the ceiling. Therefore, only the total heat release rate is plotted in the in the main text of the report.

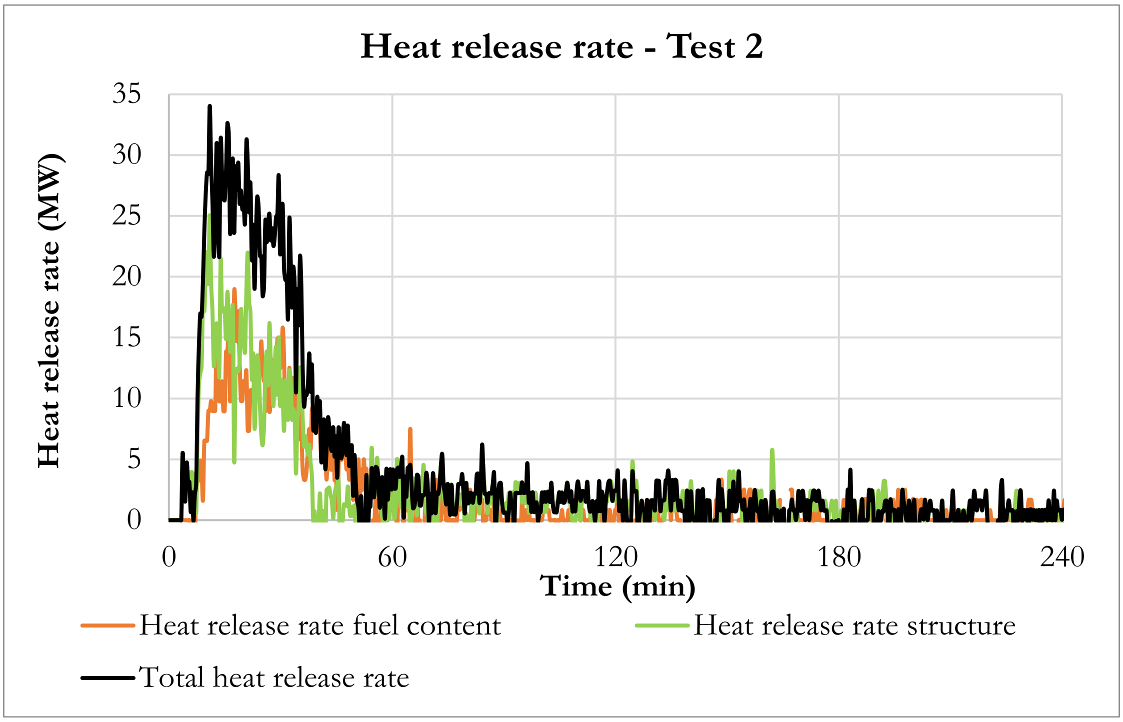

Figure D. 5: Heat release rate Test 2

Annex E - Photos

Photos of the fuel setup

Figure E. 1. Photos of the furniture in Test 1 (replicated for all three tests)

Photos of tests

Snapshots of videos taken at the opening of the tests are shown in this Annex. Snap shots are taken of the moment of flashover, 30 minutes after flashover and each whole hour after ignition. The videos can be accessed using the URLs below:

Test 1:

https://youtu.be/V4VUF-FbraY

Test 2:

https://youtu.be/UgtHJwfhaJs

Test 3:

https://youtu.be/_R4EfKnQd2Q

Test 4:

https://youtu.be/jOELM-cv-U8

Test 5:

https://youtu.be/WUy-NEBLRoE

Figure H. 1. Test 1 - Video snapshots at flashover (left) and 30 minutes after flashover (right)

Figure H. 2. Test 1 - Video snapshots at 1 hour (left) and 2 hours (right) after ignition

Figure H. 3. Test 1 - Video snapshots at 3 hours (left) and 4 hours (right) after ignition

Figure H. 4. Test 2 - Video snapshots at flashover (left) and 30 minutes after flashover (right)

Figure H. 5. Test 2 - Video snapshots at 1 hour (left) and 2 hours (right) after ignition

Figure H. 6. Test 2 - Video snapshots at 3 hours (left) and 4 hours (right) after ignition

Figure F. 1. Test 3 - Video snapshots at flashover (left) and 30 minutes after flashover (right)

Figure F. 2. Test 3 - Video snapshots at 1 hour (left) and 2 hours (right) after ignition

Figure F. 3. Test 3 - Video snapshots at 3 hours (left) and 4 hours (right) after ignition

Figure F. 4. Test 4 - Video snapshots at flashover (left) and 30 minutes after flashover (right)

Figure F. 5. Test 4 - Video snapshots at 1 hour (left) and 2 hours (right) after ignition

Figure F. 6. Test 4 - Video snapshots at 3 hours (left) and 4 hours (right) after ignition

Figure F. 7. Test 5 - Video snapshots at flashover (left) and 30 minutes after flashover (right)

Figure F. 8. Test 5 - Video snapshots at 1 hour (left) and 2 hours (right) after ignition

Figure F. 9. Test 5 - Video snapshots at 3 hours (left) and 4 hours (right) after ignition

Snapshots of videos taken at the opening of the tests are shown in this Annex. Snap shots are taken of the moment of flashover, 30 minutes after flashover and each whole hour

Annex F – Facade pictures and details

The detail above openings at the façade is a sensitive detail, which is subject to high gas velocities and thermal exposures. This study included different details for each test. Iteratively looking for an effective solution that leads to minor damage. It should be noted that Test 5 included cavities in the front façade as it was originally planned to have larger openings. The damage in the façade of Test 5 is therefore, considered not representative for real buildings.

Figure F. 10. Test 1 - Detail above opening (left) and front façade after removal of gypsum boards (right)

Figure F. 11. Test 2 - Detail above opening (left) and front façade after removal of gypsum boards. NOTE: the sides of the opening had 2 layers of gypsum boards.

Figure F. 12. Test 3 - Detail above opening (left) and front façade after removal of gypsum boards. NOTE: Stone wool B (1200 x 555 x 45) was thinner and had smaller batt dimensions than stone wool A, which was used in other tests (1200 x 2700 x 50mm). The stone wool batt above the right opening fell at an early stage.

Figure F. 13. Test 4 - Detail above opening (left) and front façade after removal of gypsum boards.

Figure F. 14. Test 4 – Left façade after removal of gypsum boards.

Figure F. 15. Test 4 – Right façade after removal of gypsum boards.

Figure F. 16. Test 5 - Detail above opening (left) and front façade after removal of gypsum boards. NOTE: Test 5 was originally planned to have larger openings. During the test series is was decided to perform a test with the same openings as Test 1, 2 and 3 and modify the opening width in the front façade. As a result an cavity existed between the external and internal gypsum boards at the outer side of both openings. It is expected that a smouldering fire entered the cavity on the right side of the right opening, which stayed behind the outer gypsum boards.

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