Mass Timber Demonstration Fire Test Project (MTDFTP)

Literature Review

April 1, 2021

Prepared by

CHM FIRE CONSULTANTS LTD
103-858 Bank St.
Ottawa, Ontario
K1S 3W3

TABLE OF CONTENTS

INTRODUCTION

Developers and design teams in Canada are continuing to push the envelope with respect to the use of mass timber in tall building designs, including ones taller than 12 storeys. They also continue to want the majority of mass timber elements used to be exposed rather than protected and hidden. The technical basis to justify all such designs from available laboratory fire testing data may not be sufficient to convince regulatory authorities that these building designs meet the safety and property protection objectives needed to obtain building permit approval. As well, there have been concerns raised related to the level of fire safety of these buildings during construction – on the regulatory side, concerns related to severity of such fires are the primary focus, while on the developer/designer/constructor side, the concerns also include the costs associated with increased fire safety requirements imposed by regulations that may discourage the use of mass timber design and a need for technical justification of such increased fire safety requirements.

Increasing the potential for use of mass timber construction will require the various regulatory stakeholders, including municipal building departments and fire services, as well as the insurance industry, to be well-informed and confident in the expected fire performance of mass timber buildings.

To this end, the Mass Timber Demonstration Fire Test Project (MTDFTP) has been initiated to conduct a series of demonstration fire tests to assist in the education of stakeholders as to the performance of mass timber buildings in a variety of fire scenarios. *(See "Mass Timber Demonstration Fire Test Project (MTDFTP): Project Roadmap" document for more information on the project.)*

A large number of compartment fire tests on cross-laminated timber (CLT)-constructed rooms/suites have been conducted over the last decade. These CLT compartments have been used to better understand the impact of mass timber structural elements on fire safety in such constructed buildings. The majority of these fire tests have not been readily available and accessible to those involved in building approvals, such as building departments, fire departments, and other regulatory authorities, in a format that can be easily understood and processed. An important goal of the MTDFTP demonstration tests will be to demonstrate the performance of mass timber construction to these groups through invitation to tests, videos, and documentation that can be shared and easily understood. As well, it is expected that the MTDFTP series of tests will present some fire scenarios not addressed in previous research testing.

This literature review of available testing data and reports has been conducted by CHM Fire Consultants as part of the MTDFTP work to inform the Technical Working Group on the research completed to date in order to guide the design and testing process to yield the most meaningful and relevant results and to avoid, to the extent possible, redundancy in the research testing. This review focuses on full-scale compartment fire testing that includes various degrees of exposed mass timber, as they are the most relevant to both meeting the goals of the MTDFTP and many of the earliest ones are those that have most influenced design requirements and proposed code changes to date.

LITERATURE REVIEW

A large number of compartment fire tests on cross-laminated timber (CLT)-constructed rooms/suites have been conducted over the last decade. These CLT compartments have been used to better understand the impact of mass timber structural elements on fire dynamics in such constructed buildings. Some of the most recent tests completed, particularly those initiated in Canada, used CLT manufactured using a new, heat-resistant polyurethane adhesive that meets the new adhesive requirements of the revised PRG-320 CLT product standard, “Standard for Performance-Rated Cross-Laminated Timber” (2018 Edition).

The significant impact of exposed CLT on compartment fire dynamics has been shown to be caused by delamination, which occurs when a single CLT lamination is almost fully charred. The charred wood falls off at the adhesive bond line, exposing non-charred wood on both faces, providing fuel for the fire. This phenomenon has led to fire regrowth in some experiments, leading to a second flashover in some cases.

Recent changes to the North American CLT product standard, PRG-320-2018, includes the requirement for a full-scale compartment fire test that replicates a test that caused delamination in the effort to ensure that the CLT will not support delamination and subsequent fire regrowth. In tests conducted by the National Research Council Canada in 2018, this change has been demonstrated to significantly reduce the impact of the exposed CLT on fire severity. Specifically, the lack of delamination of the CLT means the fire will decay as the compartment’s combustible contents are consumed even with more exposed CLT than previously demonstrated. The tests also demonstrated that exposed mass timber columns, beams and CLT ceiling, in the tests conducted, were not enough to sustain a significant fire after the combustible room contents were consumed. In particular, the following testing discussed herein used CLT manufactured to PRG-320-2018, which requires the adhesive to demonstrate it is non-delaminating in fire when tested in the full-scale compartment test specified in the product standard:

- Two of the SwRI Tests (2017): one with a melamine formaldehyde (MF) adhesive and one with a new, heat-resistant polyurethane adhesive (HBX).
- NRC Tests (2018): polyurethane adhesive (HBX).
- Rise Testing – Research Institutes of Sweden (HBX).

The remainder of completed compartment fire tests with exposed mass timber used adhesives that do not meet the new PRG-320-2018 requirements. It is expected that current research testing will, for the most part, use compliant adhesives. However, the research reports for this testing will have to be consulted for this information once available.

The experiments discussed herein were largely conducted without sprinklers or intervention by the fire service to better understand what might happen in such an event where neither are able to control the fire, for one reason or another.

This literature review provides summaries of series of compartment fire testing completed to date for which information such as data, articles, or testing reports is available. This report summarizes key findings of reports and references to the full reports, where applicable, are provided.

Carleton University Tests

At Carleton University, two research projects on the contribution of CLT construction to room fire dynamics were completed by Cameron McGregor [1] and Alejandro Hevia [2], both as part of their Master's thesis research. The research was part of the Canadian research project NEWBuildS, which was funded by the Natural Sciences and Engineering Research Council (NSERC). The tests were conducted on rooms constructed with 3-ply CLT panels that were 3.5 m wide by 4.5 m long by 2.5 m high, with the door at one end on the 3.5-m-wide wall. The test results include heat release rate, temperature measurements in the room and CLT, and char depth at the conclusion of the test. A total of eight tests were conducted by McGregor and Hevia, two with propane fires and six with furnishings representing a bedroom. The fire tests were conducted with no sprinklers installed and no intervention until the end of the test. The heat release rate of the five most relevant tests conducted with furniture are compared in Figure 1 (Tests 4 and 5 from McGregor and Tests 1 - 3 from Hevia).

The following is a summary of the tests completed by McGregor [1]:

- McGregor – Test 1 – fully-protected room with propane fire: The room was lined with 2 layers of 12.7-mm-thick Type X gypsum board. The propane fire was left at the steady flow for approximately 35 minutes with a 3 MW output. The propane fire caused the first and second layers of gypsum board to fall from the ceiling and the CLT structure to become involved in the fire. After almost 2 hours with the gypsum protection lost and the first ply of CLT almost fully charred, delamination of the CLT led to the regrowth of the fire with a second flashover occurring, at which point the room was extinguished.
- McGregor – Test 2 – fully-protected room with furniture fire: The room was lined with 2 layers of 12.7-mm-thick Type X gypsum board. The fire resulted in no charring of the CLT for the duration of the fire exposure. Temperature data was lost due to hardware malfunction, so the test was repeated as Test 4.
- McGregor – Test 3 – fully-exposed CLT with propane fire: Interestingly, the CLT walls and ceiling self-extinguished after the burner was turned down/off between 17 and 25 minutes into the test. At 29 minutes into the test, the fire decayed, with only glowing combustion of the CLT surfaces. The glowing combustion quickly continued to go out leading to the temperature continuing to drop to approximately 180°C by 60 minutes after the start of the fire. This can happen when the fire exposure is not too severe, and delamination does not occur. In this case, delamination did not occur since the char depth did not approach the bond line.
- McGregor – Test 4 – fully-protected room with furniture fire: The room was fully lined with 2 layers of 12.7-mm-thick Type X gypsum board. The fire resulted in no charring of the CLT for the duration of the fire exposure. Test 4 was a repeat of Test 2.
- McGregor – Test 5 – fully-exposed CLT room with furniture fire: The fire quickly became fully developed and stayed above 5 MW for the 1-hour duration. Between 25 and 35 minutes, the fire seemed to be decaying; however, it is likely the first layer of CLT delaminated since there was regrowth of the fire, peaking again near 50 minutes before starting to decay again.

Tests 1 and 5 demonstrate what happens in CLT compartments when the adhesive used in manufacturing the panels allows for delamination of the CLT (when the lamination becomes almost fully charred). The result is a fresh source of fuel to allow the fire to regrow and possibly reach a second flashover. Test 3 is a demonstration of what happens if the CLT does not delaminate and the fire decays as it would in a noncombustible building. In this case, the delamination did not occur since the char front did not penetrate deep enough to cause failure of the adhesive. Test 3 also demonstrates how quickly the fire can decay relatively early in the fire exposure if the fuel has been consumed. This demonstrates that the structure itself could be extinguished (e.g., by fire services) relatively easily if the contents are either consumed or extinguished.

The following is a summary of the tests completed by Hevia [2]:

- Hevia – Test 1 – The CLT compartment was protected with 2 layers of 12.7-mm-thick Type X gypsum board with the exception of the rear and right-side walls as viewed from the doorway. The fire growth, peak and decay were very similar to that of the fully-protected room by McGregor [1], until approximately 70 minutes into the fire. The delamination of the CLT on the exposed walls led to regrowth of the fire, which caused the fire to reach flashover a second time, before decaying again.
- Hevia – Test 2 – The CLT compartment was protected with 2 layers of 12.7-mm-thick Type X gypsum board with the exception of the left- and right-side walls as viewed from the doorway. The fire growth was similar to the fully-protected room by McGregor [1], however the peak heat release rate was approximately 1.5 MW higher and decay was delayed by approximately 10 minutes. Unfortunately, when the room was constructed, joint sealant between panels was inadvertently left out, and therefore the fire burned through at the joints between panels leading to early termination of the test. It is likely a similar regrowth as witnessed in Test 1 would have occurred once the first ply of CLT delaminated.
- Hevia – Test 3 – The CLT compartment was protected with 2 layers of 12.7-mm-thick Type X gypsum board with the exception of the right-side wall as viewed from the doorway. The heat release rate was very close to that measured in the fully-protected room by McGregor [1] during the growth, peak and decay phases. Based on the performance of this test, it has led to building code proposals allowing for one wall to be exposed (in both Canada and the US).

It is important to recognize that the result in the first test conducted by Hevia, that the delamination of the CLT played a significant role in the fire performance of the CLT leading to regrowth of the fire after it had decayed significantly, even though the initial fire growth, peak and decay were similar to those for the fully-protected room. Since the fully-protected room test did not have any contribution from the CLT to the fire (i.e., the CLT structure did not begin to char), the heat release rate in that test is that which would be observed in noncombustible construction where there is no contribution from the structure. Therefore, based on Hevia's tests, it is possible to conclude the delamination of the CLT was the primary cause for a difference in performance between the CLT construction and noncombustible construction.

It should be noted that, based on more recent research (e.g., the NRC tests completed in 2018, summarized later in this report), it is expected that, with an adhesive that meets the PRG-320-2018 standard with the heat-resistant adhesive requirement, the complete tests would have been much more similar to the fully-protected room (Tests 2 and 4 from McGregor's research [1]).

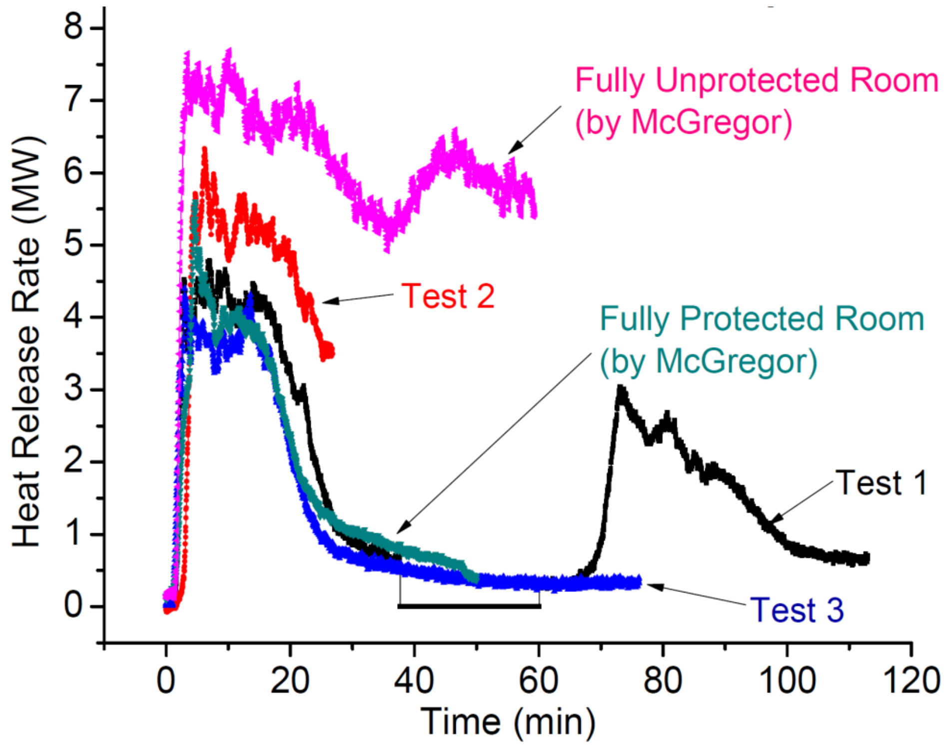


Figure 1. Heat release rate plots for Tests 4 and 5 completed by McGregor [1] and Tests 1 through 3 completed by Hevia [2], all with bedroom furniture as the fuel load.

FPRF TESTS

The Fire Protection Research Foundation (FPRF) initiated the "Fire Safety Challenges of Tall Wood Buildings – Phase 2" project [3] in 2016. This followed Phase 1 of the project [4], which included the results of a study collecting the available information on fire safety in timber structures and identifying knowledge gaps, as well as a Phase 2 study that consisted of a literature review on compartment fire tests [5]. As part of the FPRF Phase 2 research project, a total of six large-scale CLT compartment tests were conducted from February to April of 2017. The aim of the study was to quantify the contribution of the CLT structure to the fire severity of the compartment fire. To this end, the compartments were not equipped with sprinklers and there was no intervention (i.e., by the fire service) until the end of the test.

The test room was large in comparison to many of the other studies, measuring 9.1 m by 4.6 m by 2.7 m high. The fuel load in the room consisted of residential room furniture with a fire load density of 550 MJ/m^2. The fire tests were conducted without sprinklers to understand how the construction affects the fire severity. The six tests consisted of the following:

- Test 1-1: The first test represented the baseline test scenario in which the CLT compartment boundaries were protected with 3 layers of 15.9-mm-thick Type X gypsum board (walls and ceiling). The intent was to replicate a fire that would be expected to occur in a noncombustible building that is not lined with any combustible interior finishes. The compartment ventilation was provided with a 1.8 m wide by 2.0 m high opening (half the width of the opening in Test 1-2).
- Test 1-2: The second test represented the baseline test scenario in which the CLT compartment boundaries were protected with 2 layers of 15.9-mm-thick Type X gypsum board (walls and ceiling). The intent was to replicate a fire that would be expected to occur in a noncombustible building that is not lined with any combustible interior finishes. The compartment ventilation was provided with a 3.6 m wide by 2.0 m high opening (double the width of the opening in Test 1-1).
- Test 1-3: The third test employed the larger ventilation opening used in Test 1-2. The right-side 9.1-m-long wall was left exposed while the other walls were lined with 2 layers and the ceiling was lined with 3 layers of 15.9-mm-thick Type X gypsum board. The exposed wall surface was equal to 33% of the perimeter wall area.
- Test 1-4: The fourth test employed the smaller ventilation opening used in Test 1-1. The CLT ceiling was left exposed, with all walls lined with 3 layers of 15.9-mm-thick Type X gypsum board. The exposed ceiling surface represented 57% of the perimeter wall area.
- Test 1-5: The fifth test employed the smaller ventilation opening used in Test 1-1. The right-side 9.1-m-long wall was left exposed, while the other walls and ceiling were lined with 3 layers of 15.9-mm-thick Type X gypsum board. The exposed wall surface represented 33% of the perimeter wall area.
- Test 1-6: The sixth test employed the smaller ventilation opening used in Test 1-1. The right-side 9.1-m-long wall and ceiling were left exposed, while the other walls were lined with 3 layers of 15.9-mm-thick Type X gypsum board. The exposed wall surface represented 33% of the perimeter wall area. The exposed ceiling surface represented 57% of the perimeter wall area.

Tests 1-3 through 1-6 can be compared back to the two baseline tests, Test 1-1 and Test 1-2, in order to determine the impact of the combustible structure on the fire severity. The discussion below includes the figures included in the FPRF report comparing the heat release rate between each of those tests and the baseline test that uses the same ventilation opening size. These are included in Figure 2 through to Figure 5.

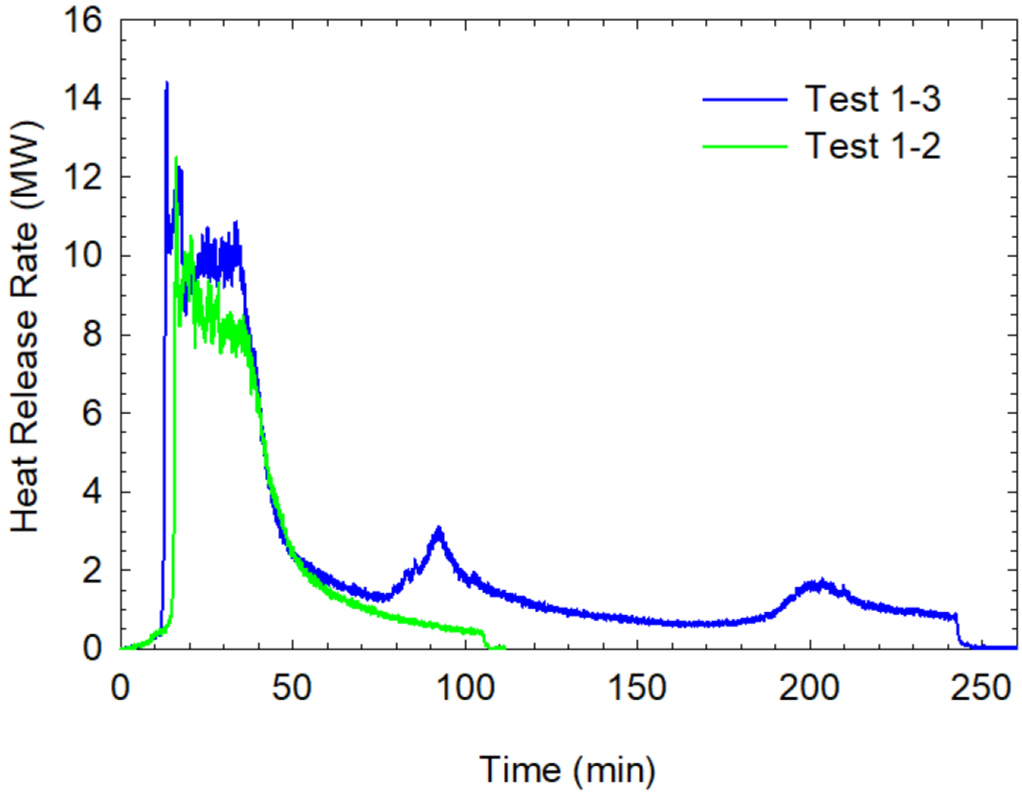


Figure 2. FPRF test series, comparison of heat release rate between Test 1-2 (fully-protected with gypsum board) and Test 1-3 (right-side wall of exposed CLT) [3].

Test 1-3 can be compared to the baseline Test 1-2, since both had the larger ventilation opening. The heat release rates between the two tests are very similar with two notable differences. First, the steady burning during the ventilation-controlled post-flashover fire phase from approximately 10 to 40 minutes are similar, with the exception that the exposed CLT wall contributes between 1 and 2 MW of additional heat release in the room (approximately 20% higher) during this stage of the fire. However, it should be noted that, if the Test 1-2 compartment was to be lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels) as is permitted in the NBC for noncombustible construction, it would be expected that the heat release rate in Test 1-2 would be the same or even greater in the ventilation-controlled post-flashover fire phase than was seen in Test 1-3, as Test 1-3 had only 33% of the perimeter wall of exposed CLT.

Interestingly, the two fires decay almost identically before seeing two small increases in heat release rate during the decay phase of the fire in Test 1-3, one at approximately 90 minutes and another at 190 minutes. These two increases were due to the char layer, first and second plies, respectively, falling off of the CLT, which has the result of providing additional fuel for the fire. Consequently, based on more recent research using non-delaminating CLT adhesives, if the CLT used in Test 1-3 had been one that used an adhesive that did not delaminate, it is expected that the decay phase would have been very similar to that seen in Test 1-2. As well, if the Test 1-2 compartment was to be lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, it would be expected that the decay phase in Test 1-2 would be longer than was seen as a result of the additional fuel.

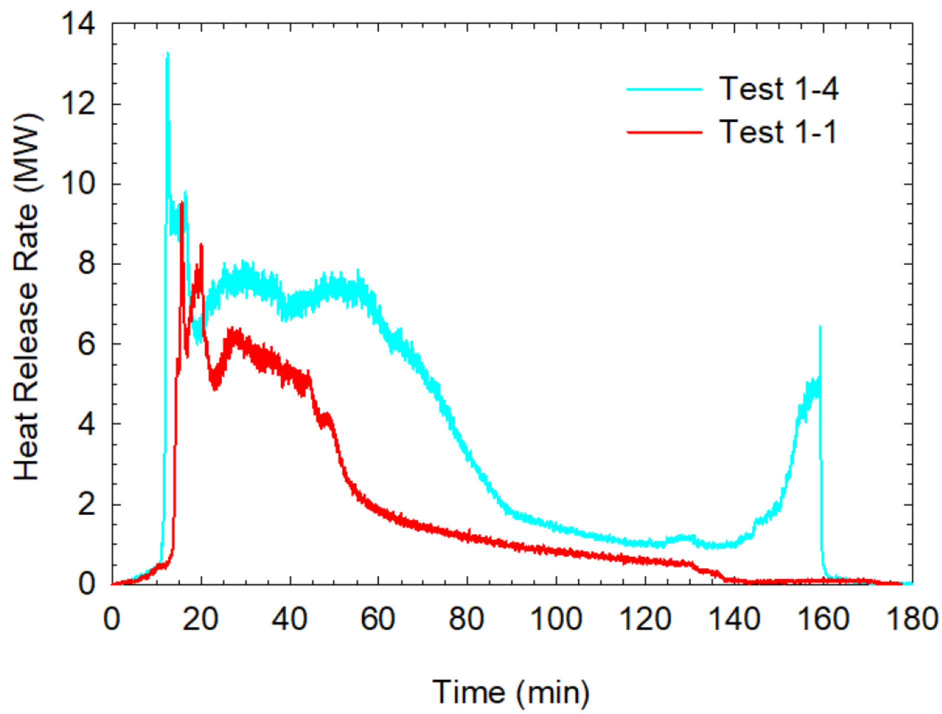


Figure 3. FPRF test series, comparison of heat release rate between Test 1-1 (fully-protected with gypsum board) and Test 1-4 (ceiling of exposed CLT) [3].

Test 1-4 can be compared to the baseline Test 1-1, since both had the smaller ventilation opening. The heat release rate in Test 1-4 with the exposed CLT ceiling is approximately 1/3 higher than the baseline scenario during the post-flashover steady burning period before decay begins. However, again it should be noted that, if the Test 1-1 compartment was to be lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g. wood panels) as is permitted in the NBC for noncombustible construction, it would be expected that the heat release rate in Test 1-1 would be the same or greater in the ventilation-controlled post-flashover fire phase than was seen in Test 1-4, as the fully exposed CLT ceiling in Test 1-4 was equivalent to only 57% of the perimeter wall area.

It appears that decay was delayed in Test 1-4 compared to the baseline test due to the fall-off of the char layer from the ceiling CLT. Decay of the fire continues after the additional fuel provided by the delamination is consumed. However, at 140 minutes, the second layer of CLT delaminates, causing a regrowth of the fire and leading to a second flashover. It is quite likely that without the falling off of the char layers, the fire would have decayed similar to the baseline test. As well, if the Test 1-1 compartment was to be lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, it would be expected that the decay phase in Test 1-1 would be even longer as a result of the additional fuel than the 2+ hours that was seen.

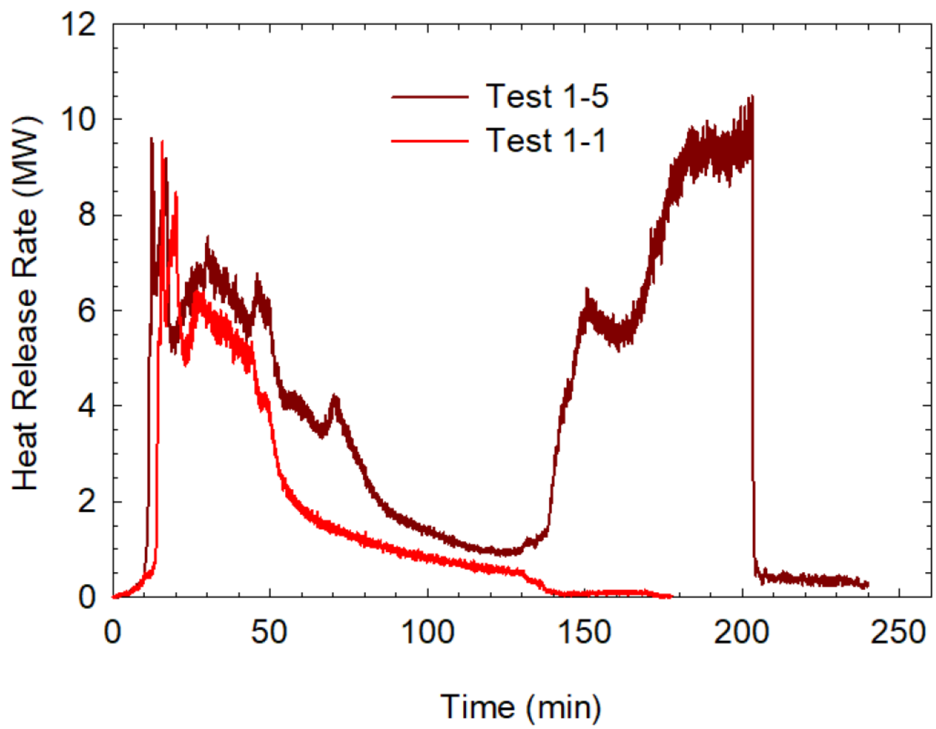


Figure 4. FPRF test series, comparison of heat release rate between Test 1-1 (fully-protected with gypsum board) and Test 1-5 (right-side wall of exposed CLT)[3].

Test 1-5 can also be compared to baseline Test 1-1, which had the same ventilation opening size. The impact of the exposed CLT wall results in approximately a 1-MW increase in heat release rate over the baseline test during the post-flashover phase from 10 to 40 minutes into the test. Again, if the Test 1-1 compartment was to be lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, it would be expected that the heat release rate in Test 1-1 would be the same or greater in the ventilation-controlled post-flashover fire phase than was seen in Test 1-5, as Test 1-5 had only 33% of the perimeter wall of exposed CLT.

At approximately 50 to 70 minutes, the heat release rate is greater due to the fall-off of the first ply of the CLT wall. At approximately 140 minutes, the second ply of the CLT falls off, providing additional fuel to the fire. The increase in the heat release rate and the temperatures in the room causes the gypsum board to fail on the ceiling and subsequently the walls, leading to full room involvement. This is an example where the exposed mass timber (with falling off of char layers) leads to the failure of the gypsum board protection and results in effectively a room with fully exposed mass timber walls and ceiling. Again, it is quite likely that without the falling off of the char layers, the fire would have decayed similar to the baseline test, particularly if the baseline test compartment would have been lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, such that it would be expected that the decay phase in Test 1-1 would be even longer as a result of the additional fuel than the 2+ hours that was seen.

Test 1-6 can also be compared to the baseline Test 1-1. The heat release rate is similarly higher during the post-flashover phase and shows no sign of decay until approximately 30 minutes after the baseline test begins decay. The burning of the exposed wall and ceiling in Test 1-6 is sufficient to support the fire for some time; due to the fully-involved fire, the observations recorded are not able to provide information on when fall-off of the charred CLT laminations occurred and when gypsum board was lost on the other walls in the compartment. It is difficult to say whether the fall-off of the CLT laminations had a significant role in this test, even though it appears to have occurred at approximately 90 minutes, which would most likely have been the second ply.

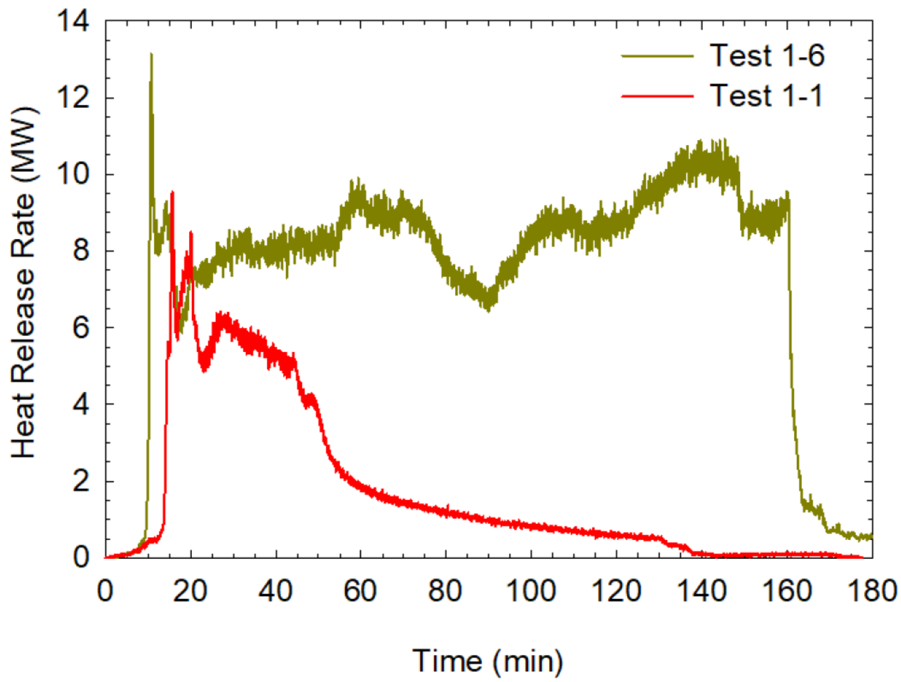


Figure 5. FPRF test series, comparison of heat release rate between Test 1-1 (fully-protected with gypsum board) and Test 1-6 (right-side wall and ceiling of exposed CLT) [3].

Overall, Tests 1-3, 1-4, and 1-5 showed promising results prior to the fall-off of charred CLT laminations, which then contributes additional fuel to the fire.

[Note that the new requirements in PRG-320-2018 are based on reproducing Test 1-4 above, while requiring that no fall-off of charred CLT laminations occurs during the 4-hour test.]

IBC AD HOC COMMITTEE/FPL TESTS

The US Forest Products Laboratory (FPL), in coordination with the IBC Ad Hoc Committee on Tall Wood Buildings, undertook a study on compartment fire behavior of mass timber construction with varying degrees of exposed mass timber [6]. A total of 5 tests were completed in a two-storey mass timber structure, complete with corridors and a stair shaft.

Of all the compartment tests completed, this test series used the largest compartment size at 9.14 m by 9.14 m by 2.74 m high. The corridor and stair shaft were on the exterior of the compartment. The tests were conducted under an oxygen consumption calorimetry hood allowing the heat release rate of the fire to be measured. The fuel load used consisted of furniture, kitchen cabinets and wood cribs, resulting in a fuel load of 550 MJ/m^2. The tests evaluated the impact of varying degrees of exposed mass timber as well as the effectiveness of sprinklers. The following is a brief summary of the tests completed:

- Test 1: The first test represented the baseline test scenario in which the CLT compartment boundaries were protected with 2 layers of 15.9-mm-thick Type X gypsum board (walls and ceiling). The fire was started on the first storey. The intent was to replicate the fire that would be expected to occur in a noncombustible building that is not lined with any combustible interior finishes. The compartment ventilation was provided with two 3.66 m by 2.44 m tall windows separated on the interior of the compartment by a non-rated partition of regular 12.7-mm-thick gypsum board.
- Test 2: In the second test, two areas of exposed CLT ceiling measuring 2.74 m by 3.05 m were left exposed in the living room and bedroom. This represented 30% of the total ceiling area. All other mass timber was protected with 2 layers of 15.9-mm-thick Type X gypsum board. Test 2 was conducted on the second storey.
- Test 3: In the third test, two CLT walls were left exposed, one in the living room and one in the bedroom, both on the perimeter of the apartment and facing one another. This represented approximately 30% of the perimeter wall area. All other mass timber was protected with 2 layers of 15.9-mm-thick Type X gypsum board. Test 3 was conducted on the second storey.
- Test 4: The fourth test consisted of all the CLT surfaces in the living room and bedroom left exposed, which included the ceilings and the perimeter walls. The beams and columns inside the apartment were also left exposed. A standard sprinkler system designed for light hazard in accordance with NFPA 13 was installed in the apartment for this test. The sprinkler system was charged at the beginning of the test. Unlike all other tests reported in this review, actual windows (1/4” tempered glass) were installed in the openings for this test and Test 5.
- Test 5: The fifth test reused the test configuration from Test 4, however the sprinkler system was not charged at the beginning of the test and was charged at approximately 23 minutes after the fire had started. To provide some ventilation at the beginning of the test, the apartment door was left open.

The heat release rates for the 5 tests are shown in Figure 6.

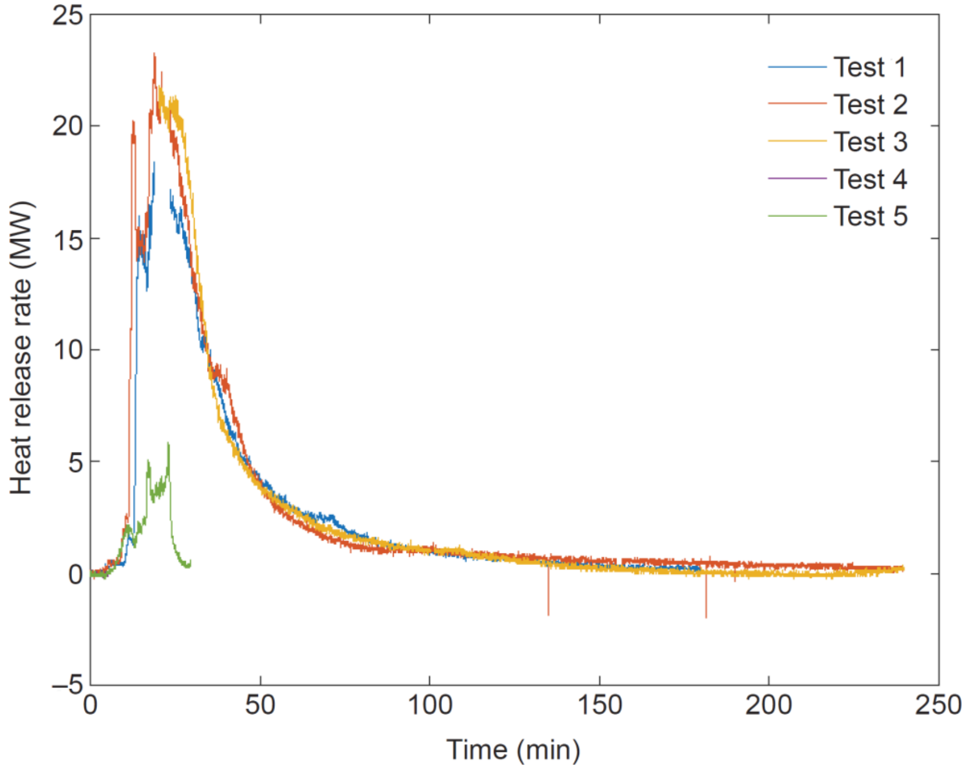


Figure 6. Heat release rate measurements during each of the 5 IBC Ad Hoc Committee/FPL tests [6].

The heat release rate in Test 1 represents a scenario where the combustible structure does not contribute to fire growth or severity; this is what would be expected in a building of noncombustible construction that is not lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), unlike what is permitted in the NBC for noncombustible construction. The peak heat release rate reached 18.5 MW and stayed above 15 MW for a little less than 20 minutes. The relatively short fully-developed post-flashover phase of the fire is due to the larger ventilation openings used in this test series compared to other research reported herein. It should be noted that some data was lost in this test near the time of peak HRR (for approximately 5 minutes during replacement of a gas filter). It is possible that the peak HRR was higher than 18.5 MW, but the data is not available.

Test 2, which included 30% exposed CLT ceiling, resulted in an apparent higher peak heat release rate (since the actual peak heat release rate for Test 1 is unknown). However, the duration of the fire was not significantly extended, indicating the ceiling did not continue to contribute to the fire significantly after the room contents were consumed. The peak heat release rate in this test was 23.3 MW, as opposed to the 18.5 MW reported in the baseline test (Test 1). The decay phase in Test 2 with 30% of the ceiling exposed was almost identical to that in Test 1, the baseline case representing a building of noncombustible construction with no combustible interior finishes, with respect to heat release rate over time. If the Test 1 compartment was to be lined on all walls (including interior partition walls) and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, it would be likely that the decay phase in Test 1 would be even longer, as a result of the additional fuel, than the 2+ hours that was seen. It is also possible that the heat release rate over time would be higher for longer as a result of the additional fuel, in comparison to Test 2.

Test 3 consisted of exposed CLT walls on either side of the apartment. Similar to Test 2, the heat release rate was apparently higher than in the baseline test (since the actual peak heat release rate for Test 1 is unknown), 20.9 MW compared to 18.5 MW, while the duration of the fire was not significantly increased. The decay phase in Test 3 with approximately 30% of the perimeter walls exposed was almost identical to that in Test 1, the baseline case representing a building of noncombustible construction with no combustible interior finishes, with respect to heat release rate over time. If the Test 1 compartment was to be lined on all walls (including interior partition walls) and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, it would be likely that the decay phase in Test 1 would be even longer, as a result of the additional fuel, than the 2+ hours that was seen. It is also possible that the heat release rate over time would be higher for longer as a result of the additional fuel, in comparison to Test 3. Again, this demonstrates that the CLT walls were not significantly contributing to the fire after the room contents were consumed.

The heat release rate from Test 4, which included a charged sprinkler system and all mass timber wall, ceiling, beam, and column surfaces exposed, shows no significant heat release prior to or after the activation of the sprinkler system. Note that in Figure 6 the HRR data for Test 4 is obscured by the data for the other 4 tests; the duration of the test was so short that there is only data for the first few minutes, as the sprinkler system quickly extinguished the fire.

Even though all mass timber wall, ceiling, beam, and column surfaces were exposed in Test 5, the heat release rate in Test 5 did not grow as quickly as the previous Tests 1 - 3 (with no or only limited exposed mass timber) since the openings included actual windows (e.g., a limited oxygen supply was available to the fire), despite there being significantly more exposed mass timber in this test compared to the others. From the test pictures, it appears that one of the windows in the bedroom breaks and falls out sometime between 14 and 17 minutes into the test. The windows resulted in slower growth even with the apartment door propped open to the corridor. At 23 minutes, the sprinkler activation quickly brought the fire under control despite 100% of all mass timber being exposed, and despite the delay, which was intended to replicate a system in which water is not available until the fire service arrives and is able to connect to the sprinkler system.

The tests conducted utilized the largest compartments out of the tests summarized in this report and also used the largest ventilation factor by having two large windows in the front wall. Since the CLT did not use a non-delaminating adhesive, the lack of fall-off of charred layers of CLT was likely a result of the larger ventilation factor, resulting in a less severe fire as the duration of the fire is shorter. While the ventilation factor was higher than in other test series, it is more realistic of what is likely to be built. The smaller ventilation openings used in other tests is clearly a worse case, resulting in a more severe fire exposure.

Since the CLT in these tests did not experience delamination, these tests can be considered representative of what would occur in the case of the use of CLT that uses an adhesive that meets the new non-delamination requirements in PRG-320-2018 – that is, while fires in compartments with some exposed mass timber that does not experience delamination may experience a slightly higher heat release rate during the ventilation-controlled post-flashover fire phase than would be in experienced in a compartment of noncombustible construction with no combustible interior finishes, they also can experience almost identical decay phases.

Also, if the compartment of noncombustible construction was to be lined on all walls (including interior partition walls) and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, rather than having no combustible interior finishes, it is likely that the decay phase would be even longer, as a result of the additional fuel, than was seen in the tests with some exposed mass timber in this testing. It is also possible that the heat release rate over time would be higher for longer in such a scenario meeting the noncombustible construction NBC requirements, as a result of the additional fuel, in comparison to the tests with some exposed mass timber in this testing.

SwRI Tests (2017)

In 2017, the American Wood Council contracted the Southwest Research Institute (SwRI) to conduct 3 full-scale compartment tests [7] that intended to replicate Test 1-4 of the FPRF tests described previously. FPRF Test 1-4 consisted of a CLT compartment with protected walls and an exposed ceiling. The fire experienced regrowth after a prolonged decay period. It was decided to use the fire exposure in that test to evaluate whether an adhesive used in the manufacturing of the CLT allows for delamination. Three tests were conducted, one with the same adhesive used in the FPRF tests, one with a melamine formaldehyde (MF) adhesive and one with a new, heat-resistant, polyurethane adhesive. The first test with the same adhesive as in the original FPRF test program behaved similarly to that in the original tests. Therefore, it was concluded that the fire exposure was similar enough to then be able to be used to evaluate other adhesives with respect to how they would have performed in that research. The MF adhesive performed as expected, with no delamination during the 4-h fire exposure. The heat-resistant PUR adhesive performed similar to the MF adhesive with no significant delamination during the more than 4-h exposure. These tests provided the methodology and necessary data to the Technical Committee that oversees the CLT product standard, PRG-320, for adoption of the compartment test method for qualifying adhesives in the 2018 edition of the standard.

NRC Tests (2018)

In 2018, the National Research Council of Canada (NRC) undertook a research project to further investigate the contribution of mass timber elements to fire [8]. The CLT panels used in the study utilized a polyurethane adhesive that meets the revised CLT product standard (PRG-320-2018) requirements that are intended to ensure that the fall-off of CLT laminations, once charred, does not occur. This was the first set of CLT compartment tests utilizing CLT panels manufactured using the new heat-resistant polyurethane adhesive, which was not yet being used in the commercial production of CLT panels at that time.

A total of five CLT compartment fire tests were completed that included varying amounts of exposed CLT surfaces; two of the tests also incorporated glulam columns and beams. The test rooms were relatively small at 4.5 m by 2.4 m by 2.7 m tall due to test laboratory constraints. This represents a severe scenario from the point of view of re-radiation of heat between surfaces within the compartment, which is a critical aspect in order to have the mass timber surfaces continue to burn once the movable fuel load is consumed. The room also had a door opening of 0.76 m x 2.0 m providing a ventilation factor of approximately 0.3 $m^{1/2}$. This provided for a slightly less severe ventilation condition than that used in the FPRF test series. In the FPRF test series, the smaller ventilation condition resulted in a longer duration of the ventilation-controlled post-flashover fire phase with similar maximum temperatures and heat fluxes than the larger ventilation condition, as well as a longer decay phase; therefore, there was a more severe fire exposure to the compartment boundaries (walls and ceiling) in terms of duration. The fuel load in the room consisted of wood cribs to simulate residential room contents with a fire load density of 550 MJ/m^2. The fire tests were conducted without sprinklers to understand how the construction affects the fire severity in the event that the sprinklers fail to operate and the fire service does not intervene. The five tests consisted of the following:

- Test 1: The first test represented the baseline test scenario in which the CLT compartment boundaries were protected with 3 layers of gypsum board (walls and ceiling). The intent was to replicate the fire that would be expected to occur in a noncombustible building that is not lined with any combustible interior finishes.
- Test 2: The second test consisted of one CLT wall exposed (33% of perimeter wall area) and 10% of the CLT ceiling exposed, representative of the 2020 NBC Encapsulated Mass Timber Construction code change proposal. All other surfaces were protected by two layers of 12.7-mm-thick Type X gypsum board, representative of the generic solution permitted in the 2020 NBC Encapsulated Mass Timber Construction code change proposal for the required 50-minute encapsulation rating of non-exposed mass timber elements.
- Test 3: The third test consisted of the CLT fire test compartment lined with 2 layers of 12.7-mm-thick Type X gypsum board and two exposed glulam columns and an exposed glulam beam that ran the 4.5 m length of the room between columns. The exposed surface area of the beam and columns was equal to 38% of the perimeter wall area, which is greater than the maximum exposed surface area of 10% permitted by the 2020 NBC Encapsulated Mass Timber Construction code change proposal. All other surfaces were protected by two layers of 12.7-mm-thick type X gypsum board, representative of the generic solution permitted in the 2020 NBC Encapsulated Mass Timber Construction code change proposal for the required 50-minute encapsulation rating of non-exposed mass timber elements.

Test 4: The fourth test consisted of a fully-exposed (100% exposed) CLT ceiling and a single exposed glulam column and beam. The exposed surface area of the beam and column represented 20% of the perimeter wall area, which is greater than the maximum exposed surface area of 10% permitted by the 2020 NBC Encapsulated Mass Timber Construction code change proposal, while the ceiling represented 29% of the perimeter wall area. The ceiling in this scenario is only permitted 25% exposure, rather than 100%, in accordance with the 2020 NBC Encapsulated Mass Timber Construction code change proposal. All other surfaces were protected by two layers of 12.7-mm-thick Type X gypsum board, representative of the generic solution permitted in the 2020 NBC Encapsulated Mass Timber Construction code change proposal for the required 50-minute encapsulation rating of non-exposed mass timber elements.

Test 5: The fifth test consisted of two exposed CLT walls at each side of the fire compartment and a fully-exposed (100% exposed) CLT ceiling. The two walls represented 35% of the perimeter wall area, while the ceiling represented 29% of the perimeter wall area. The ceiling in this scenario is only permitted 10% exposure, rather than 100%, in accordance with the 2020 NBC Encapsulated Mass Timber Construction code change proposal. Also, the 2020 NBC Encapsulated Mass Timber Construction code change proposal does not permit exposed mass timber walls to face each other, as was the case in this test. All other surfaces were protected by two layers of 12.7-mm-thick Type X gypsum board, representative of the generic solution permitted in the 2020 Encapsulated Mass Timber Construction code change proposal for the required 50-minute encapsulation rating of non-exposed mass timber elements.

The tests used the same fire load density as, and the smaller ventilation factor of, the FPRF tests, while using CLT with a more heat-resistant adhesive that satisfies the revised PRG-320-2018 standard. A greater amount of exposed mass timber and less encapsulation (less gypsum board) protection on the remaining mass timber was also used. The tests were also the first in Canada to include beams and columns in the fire compartments.

As expected, the peak temperatures in all tests were similar to the baseline test since the combustion that takes place in the room is limited by the amount of oxygen that can enter through the doorway (ventilation-controlled fire).

In Tests 2 and 4, the fire decayed somewhat similarly to that in the baseline test (Test 1) as the wood cribs were consumed, albeit at a slower rate. The slope of the temperature reduction during the decay phase was less than that in the baseline test due to some heat produced from the charred exposed mass timber, but also due to some contribution of heat from charring of the encapsulated mass timber within the compartment in Tests 2 and 4, in comparison to Test 1.

It should be noted that if the compartment in Test 1 was to be lined on all walls and on 10% the ceiling with 25-mm-thick combustible material (e.g., wood panels), as is permitted in the NBC for noncombustible construction, rather than having no combustible interior finishes, the decay phase would be longer as a result of the additional fuel, and therefore closer to what was seen with Test 2 and Test 4.

NRC NLT Tests (2019)

In early 2019, the NRC conducted a series of compartment fire tests using nail laminated timber (NLT) and glulam structural elements. The goal of this test series was to quantify the contribution of NLT elements to compartment fires and provide additional data for exposed mass timber elements [9].

Four tests were conducted in the same room configurations as the 2018 CLT testing (4.5 m x 2.4 m x 2.7 m high). The room had a door opening of 0.76 m x 2.0 m providing a ventilation factor of approximately 0.3 $m^{1/2}$.

NLT using dimension lumber of 38 mm x 140 mm (2 x 6), 38 mm x 184 mm (2 x 8), and 38 mm x 235 mm (2 x 10) were used. The 38 mm x 140 mm panels were used for encapsulated assemblies and the larger laminations for exposed assemblies.

The fuel load in the room consisted of wood cribs to simulate residential room contents with a fire load density of 550 MJ/m^2.

Table 1 below is a matrix of the tests completed.

Table 1. Test Matrix from NRC NLT Tests (Excerpt from [9])

NLT room test	Exposed surface	Dimension lumber for NLT ceiling	Dimension lumber and interior lining for NLT walls	NLT room exterior lining	Similar to prior CLT testing
Test NLT-1	Beam & column (=19% perimeter) + 100% ceiling	2 x 8	2 x 6 with 2GB	Walls - 1GB Roof - 2GB	Test CLT-4
Test NLT-2 (uneven ceiling)		2 x 8 + 2 x10	2 x 6 with 2GB	Walls - 1GB Roof - 2GB	Test CLT-4
Test NLT-3	Two end walls B&D (=35% perimeter) + 100% ceiling	2 x 8	2 x 8 exposed; 2 x 6 with 2GB	Walls A&C - 1GB Walls B&D - 2GB Roof - 2GB	Test CLT-5
Test NLT-4		2 x 8	2 x 8 exposed; 2 x 6 with 3GB	Walls A&C - 1GB Walls B&D - 2GB Roof - 2GB	Test CLT-5

1GB: one layer of 12.7 mm (½") thick Type X gypsum board lining
2GB: two layers of 12.7 mm (½") thick Type X gypsum board lining
3GB: three layers of 12.7 mm (½") thick Type X gypsum board lining

The figures below show the exposed NLT conditions for Tests 1 and 2, and Tests 3 and 4, respectively.

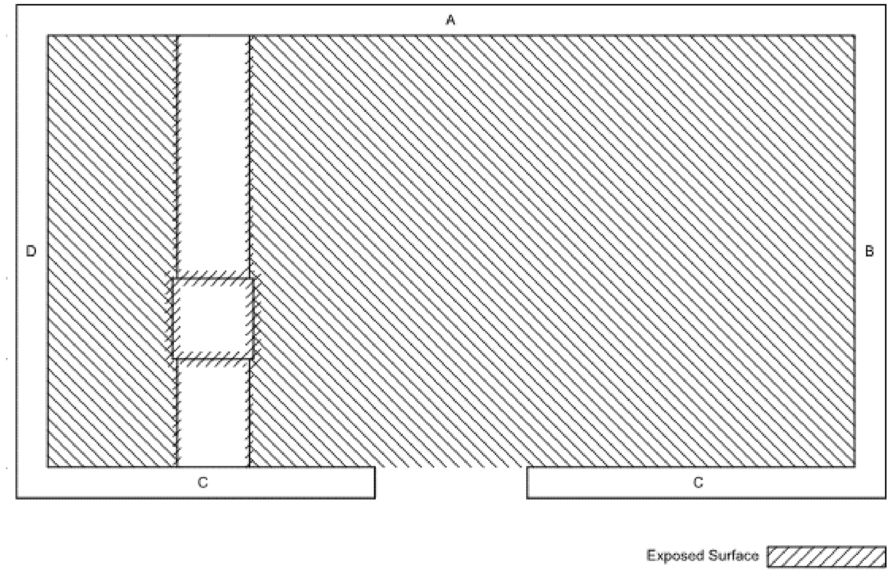


Figure 7. Exposed Mass Timber in NRC NLT Tests 1 and 2 (Figure 3 from [9]

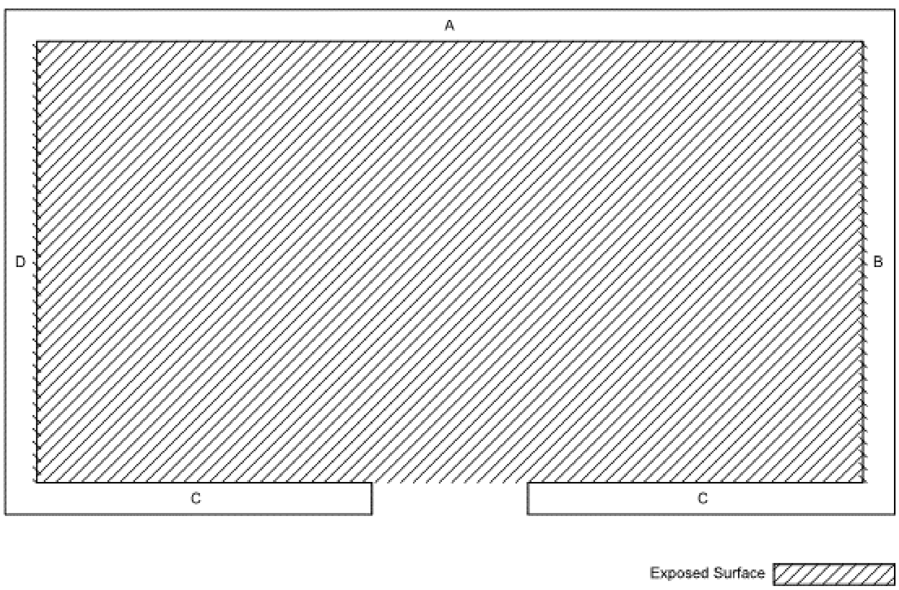


Figure 8. Exposed Mass Timber in NRC NLT Tests 3 and 4 (Figure 4 from [9]

The NLT tests showed times to flashover between 3.2 and 3.9 minutes in rooms with an exposed glulam beam, exposed glulam columns, and exposed NLT ceiling (Tests 1 and 2) and rooms with two exposed NLT walls and exposed NLT ceiling (Tests 3 and 4). The difference to time-to-flashover is low between the different rooms. These tests are evidence the time to flashover is not significantly affected by an exposed ceiling surface compared to an exposed wall surface. Specifically, in these tests, a scenario with an exposed ceiling, beam and column is compared to exposed walls with no significant difference.

In comparing the NLT tests to the CLT tests (see above and reference [8]), CLT was found to perform better due to tighter fitting lumber elements compared to NLT lumber elements with small gaps. Under certain conditions, these gaps were found to result in continued charring of NLT behind gypsum board keeping the room hot, and leading to deeper charring.

Test 4 was conducted with increased encapsulation of the protected walls compared to Test 3. This test demonstrated that it is feasible to have an increased area of exposed timber surfaces without causing undue contribution to the fire with this increased encapsulation.

RISE TESTING - RESEARCH INSTITUTES OF SWEDEN

A series of five full-scale compartment fire tests, constructed of CLT slabs and glulam beams and columns in accordance with current US product standards, were performed by the Research Institutes of Sweden (Rise) in 2020 [14]. The main funder of the project was the US Forest Service (USFS), US Department of Agriculture (USDA), and the project owner is the American Wood Council (AWC). Various other project partners and funders were also involved.

At the time of this writing, only the Summary Report [14] for this testing is available. The report indicates that the final project report will include full results and will be issued at a later date.

The purpose of this testing series was to assess possibilities for safe increases to US code-prescribed limits to exposed mass timber surface areas. As such, the tested structures had varying quantities of exposed mass timber. The unexposed surfaces were protected with either 2 or 3 layers of 15.9 mm (5/8”) Type X gypsum board. An iterative approach was used after each test to determine the quantity and locations of exposed mass timber in the next test that would yield the most useful information. A base assumption of the testing was the unlikely event that neither sprinkler protection nor the fire department were able to control or suppress the fire.

The compartments had surface areas of exposed mass timber equal to up to two times the area of the floor plan. The tests were each run for 4 hours and demonstrated that the quantities of exposed wood in the testing exhibited continuous decay to hot spots and embers after the fully-developed stage of the fire. The tests indicate that the presence of two exposed wall surfaces in one corner should be avoided to achieve decay.

The test compartments had internal dimensions of 7.0 m x 6.85 m x 2.73 m. Four of the compartments had two ventilation openings of 2.25 m wide by 2.10 m high, resulting in a ventilation factor of 0.062 $m^{1/2}$. The fifth compartment had six larger openings, resulting in a ventilation factor of 0.25 $m^{1/2}$. These ventilation factors are considerably larger than those in the FPRF and NRC tests. This results in a less challenging fire exposure to the structure.

The fuel load for the tests was a combination of typical apartment furniture, particle board sheets on the floor to represent a wood floor, and additional wood cribs representing fuel in storage spaces. The target fuel load density was 560 MJ/m^2. Photos of a typical fuel setup are in Figure 9 below (excerpt from research summary report).

Figure 9. Photos of the Furniture in Test 1 (Typical for Residential Tests) (Excerpt from [14]).

The compartments were constructed with ANSI/APA PRG 320, 2018-compliant, 175 mm thick 5-ply CLT (each ply 35 mm thick) and ANSI A 190.1-2017-compliant glued-laminated timber.

All tests had exposed CLT ceiling and a glulam beam and Tests 2-5 included different quantities of exposed mass timber wall surfaces. Of the small opening tests (Tests 1, 2, 3 and 5 - representative of dwellings), Test 1 had the least surface area of exposed wood surfaces 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 commercial occupancy) all internal walls except for the back wall were exposed.

The following Table 2 is an excerpt from the research summary report, indicating the quantities of exposed mass timber in each test.

Table 2. Test Matrix from RISE Tests (Excerpt from [14])

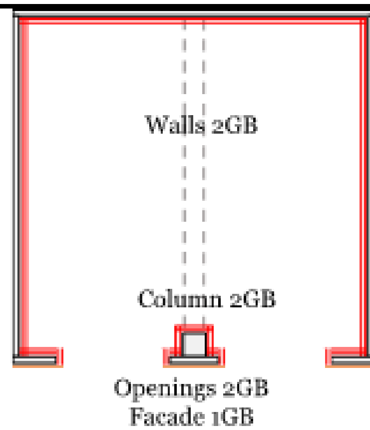
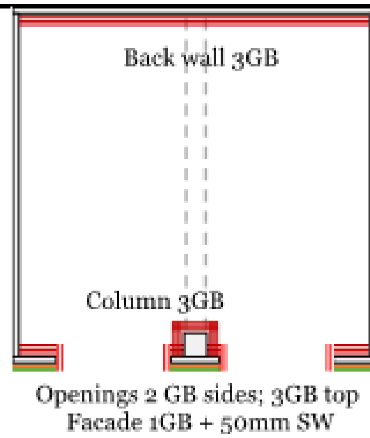
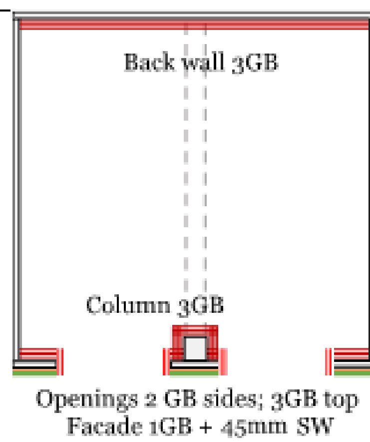
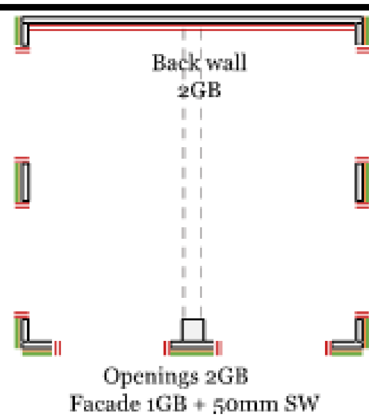
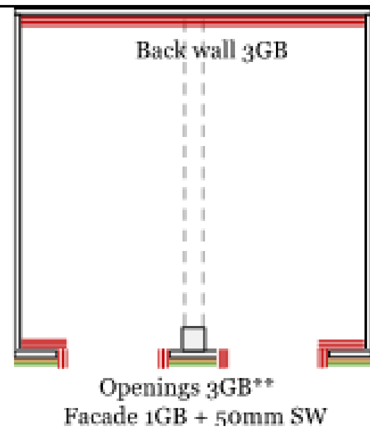
Test name Window Opening size	Gypsum Board (GB) Protected interior surfaces*	Exposed wood surfaces	Floor plan (schematic)***
Test 1 Two window openings 86 ft² (8.0 m²) of exterior wall open	- All walls and - Column protected by 2 layers of GB	100% of ceiling exposed and 100% of beam exposed No exposed 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	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)	

Table 1. (continued): Test Matrix from RISE Tests (Excerpt from [14])

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.*

Various measurements and observations were recorded for these tests, including temperatures, time to flashover, heat release rates, char depths, etc. Observations were also recorded about the intersections of mass timber elements, which were sealed with various different materials.

The following pass/fail criteria were put in place for the tests:

1. At 4 hours after ignition, the plate thermometer temperatures should be below 300°C (plate thermometers are located inside the compartment near the wall and ceiling surfaces at six locations in each test).
2. No secondary flashover should occur between 3 hours and 4 hours after ignition. Flashover is considered to occur when any two of the following conditions are attained:
    a. Heat release rate exceeds 0.12 MW/m^2 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.

In four of the five tests, the fires decayed until the test was terminated at 4 hours after ignition. At that time, there were some hot spots and embers remaining. In the test with larger openings (Test 4), the smouldering almost completely stopped by this time. In Test 3, radiative feedback from walls meeting at a corner resulted in increased flaming on the walls. As a result, Test 3 was the only test to fail the criteria put in place at the end of the 4-hour test. A summary of key events in each test is provided in Table 3 below.

Table 3. Significant Events After Ignition of Rise Tests (Table 3 from [14]).

	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.*

Note – references to Sections and Figures in Table 2 above refer to the Summary Report [14] and not this literature review.

EMBERLEY *ET AL.*

A full-scale fire test was conducted as part of a project investigating the feasibility of modular systems and construction methodologies for CLT [15]. The project was based on a case study of a proposed apartment building in Australia. For this project, there was a desire to have exposed CLT on one wall and the ceiling, and the testing was completed to demonstrate self-extinction for the proposed geometry as well as to demonstrate that de-lamination did not occur.

The full-scale test was conducted in conjunction with small-scale testing to identify criteria for self-extinction of the fire. The test room was 3.5 m x 3.5 m x 2.7 m high with a door opening measuring 0.85 m x 2.1 m (ventilation factor approximately 0.04 $m^{1/2}$). The fire load consisted of two wood cribs with a total of 80 kg of fuel located centrally in the room. This relatively low fire load (approximately 114 MJ/m^2) was selected to reduce the probability of de-lamination of the CLT. A similarly low fuel load was used in the testing by Hadden et al. [16], discussed below.

The CLT consisted of 5-ply Radiata Pine with a build-up of 45 x 20 x 20 x 20 x 45 mm.

Encapsulation of CLT walls was done with two 13 mm layers of Knauf FireShield plasterboard liners. One of the side walls and the ceiling were left exposed. Figure 10 below shows the test setup.

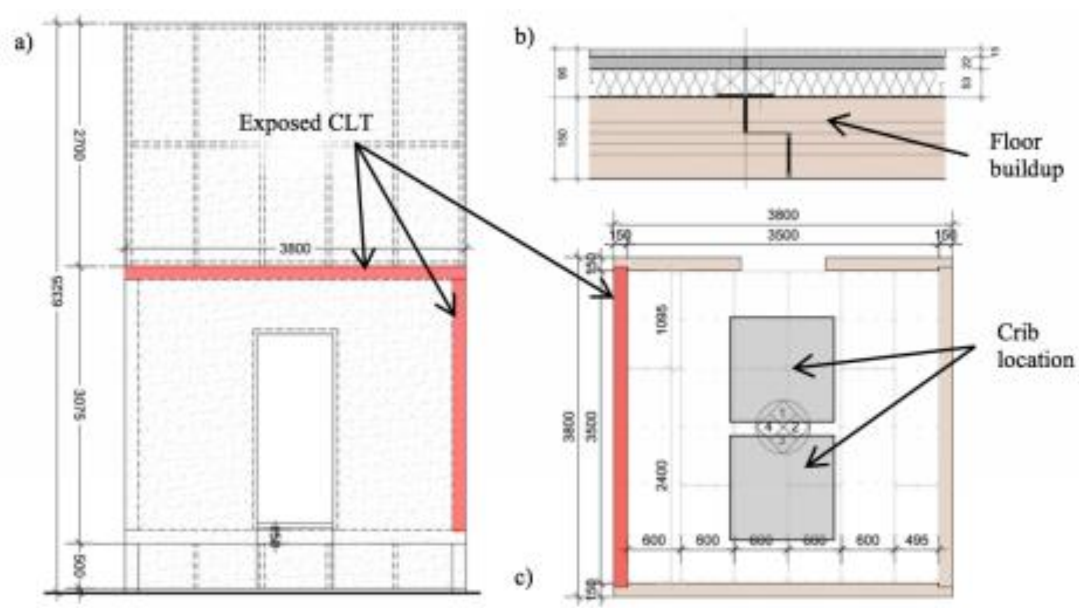


Figure 10. Test Setup by Emberley et al. (Figure 4 from [15])

During the test, the wood cribs became fully involved at approximately 10 minutes, and the CLT ceiling became involved at approximately 12 minutes, 15 seconds. The flames reached the base of the CLT wall shortly thereafter. As the cribs were consumed, the fire entered decay and full extinction of the wall and ceiling occurred at approximately 28 minutes. The test was continued for an extended period (approximately 5.5 hours) before being terminated.

During the test, no delamination of the CLT or failure of the fire protection occurred, and self-extinction was successful. It was found that when the maximum heat flux on the wall dropped below 45 kW/m^2, flaming on the CLT panel ceased within 30 seconds. This finding aligned well with the small-scale testing results. When self-extinction occurred, it began at the base of the wall and progressed to the ceiling.

It is noted that this test was designed to prevent delamination of the CLT and therefore a relatively low fuel load was used. As such, there are limitations to the conclusions that can be drawn from this test.

HADDEN *ET AL.*

A series of full-scale compartment fire tests were conducted to evaluate the impact of exposed CLT on compartment fire behaviour at the University of Edinburgh in the UK [16]. The room size was 2.72 m x 2.72 m x 2.77 m with a door opening 0.76 m x 1.84 m (ventilation factor approximately 0.04 $m^{1/2}$). A total of five tests were conducted with three different scenarios (see below and Figure 11).

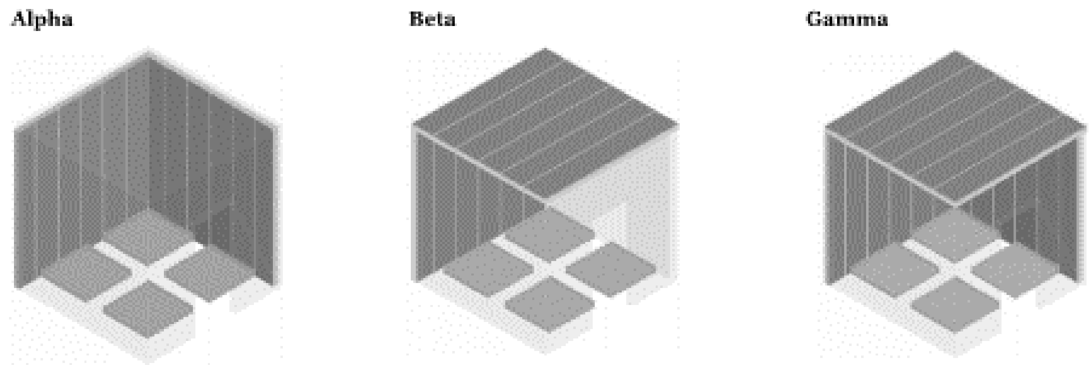


Figure 11. Test Scenarios by Hadden et al. (from Table 1 from [16])

Alpha scenario:

- Two tests conducted.
- Back wall and side wall exposed (total exposed area of 15 m^2).

Beta scenario:

- Two tests conducted.
- Back wall and ceiling exposed (total exposed area of 14 m^2).

Gamma scenario:

- One test conducted.
- Back wall, ceiling, and side wall exposed (total exposed area of 22 m^2).

The fuel load in all tests consisted of wood cribs. The fuel load was chosen based on the heat release rate required for flashover, and to ensure burnout of the cribs within a short period of time after flashover. Four cribs were used totalling 56 kg in each test (132 MJ/m^2). A similarly low fuel load was used by Emberley et al. [15], discussed above.

Encapsulated surfaces were protected using two layers of 12.5 mm Type F plasterboard. After the first test (Alpha-1), the encapsulated was increased to include 25 mm of high-density stone wool insulation as the plasterboard failed in the first test.

A summary of the test results is provided in Table 4 below.

Table 4. Summary of test results – Hadden *et al.* (Table 3 from [16])

Experiment	Time to flashover [min]	Total HRR at flashover [kW]	Time to peak HRR [min]	Peak total HRR [kW]	Maximum char depth in exposed timber after 60 min [mm]
Alpha-1	4.56	1709	6.27	5267	53
Alpha-2	5.13	1448	5.50	4677	53
Beta-1	8.55	1551	8.75	6213	11
Beta-2	4.23	1463	7.78	5248	44
Gamma-1	5.35	1171	5.55	6679	58

The testing identified two mechanisms associated with the CLT that will prevent auto-extinction: fall-off of the char exposing fresh timber beneath, and the critical heat flux being maintained for sustained burning. If the critical heat flux is maintained by radiative exchange between the linings, then the pyrolysis rate will be sufficiently high such that flaming will continue. In this case, the total heat release rate is a function of the ventilation providing oxygen and the exposed surface area of timber.

Auto-extinction was observed in testing with two surfaces of exposed timber, dependent on the char layer remaining and no delamination during combustion of the fuel load or decay phase. Auto-extinction was not observed in the test with three exposed mass timber surfaces.

The measured peak compartment temperatures were not substantially different from available correlations, suggesting that exposed timber surfaces have only a small influence on the compartment temperature. However, the heat release rate was increased as a result of the exposed mass timber.

Current/Ongoing Research

At the time of this writing, there are two major mass timber fire testing projects in the planning stages. Although there is limited information on these projects, the following is a summary of the information available for that current and ongoing research.

Proposed Full-scale Exposed Mass Timber Open Plan Free Burn Test Program – Australia

This project aims to conduct a full-scale fire demonstration tests on an open-plan, exposed mass timber post-and-beam structure, similar to many of the building currently proposed in Australia [17 and 18]. The tests aim to validate a set of design principles for mass timber buildings in Australia.

The current structure design includes a 3-bay, 27 m x 9 m structure, with 5 fire tests being planned. See Figure 12 below for the current proposed test structure.

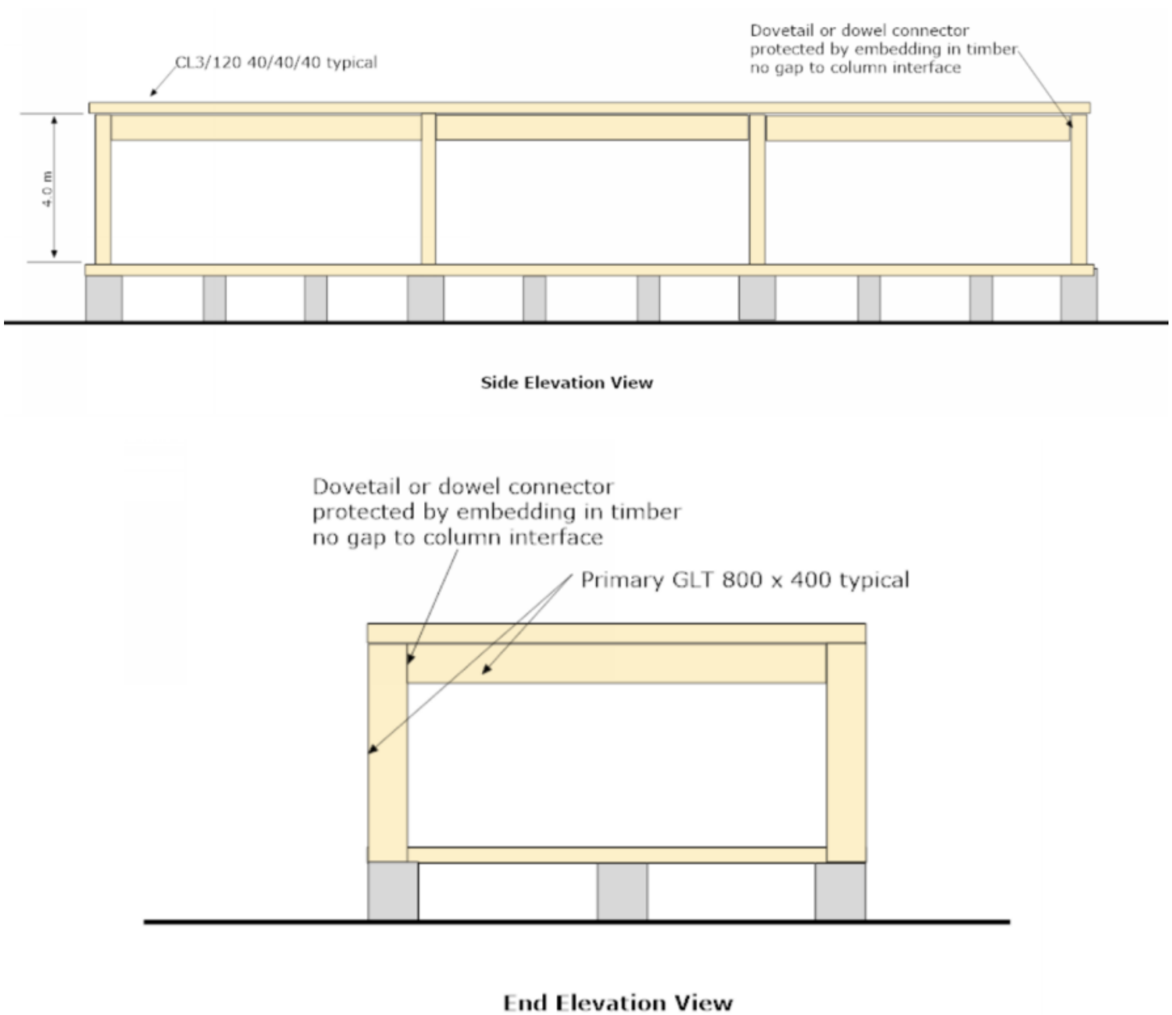


Figure 12. Proposed Tests Structure for Australia Testing (Excerpt from [18].

The proposed test program is as follows:

- Survey and modelling: Prior to testing, a survey will be conducted to determine an appropriate layout and fuel load and modelling of thermal conditions in the compartment will be conducted.
- Test 1: Control test with compliant combustible linings. This is proposed to be in one end bay (9.0 m x 9.0 m) with office furniture currently proposed to be 55 kg/m^2. No exposed mass timber. Test duration 4 hours.
- Test 2: Exposed Mass Timber Structure – Heat Release. This test is to establish the heat release rate of an exposed mass timber compartment. It will take place in one bay (9.0 m x 9.0 m) with the same fuel load as Test 1. In this test, primary beams and columns will have a sacrificial timber layer affixed to simulate exposed timber. The CLT ceiling and secondary beams will have no protection. Test duration 4 hours.
- Test 3: Fire Ignition and Temperature to Break Glazing. This test is to narrow down information regarding ventilation and glass breakage, as well as to gather information on sprinkler activation and secondary flashover. This will take place in the center bay (9.0 m x 9.0 m) with the same fuel load as Tests 1 and 2. Initially there will be no opening, and one glazed panel will be removed if the fire does not grow. In this test, primary beams and columns will have a sacrificial timber layer affixed to simulate exposed timber. The CLT ceiling and secondary beams will have no protection. Test duration 4 hours.
- Test 4: Performance Improvements. This test will aim to take lessons learned from the previous test to design a compartment with improved performance. It will take place in one bay (9.0 m x 9.0 m) with the same fuel load. The same exposed mass timber as previous tests is proposed and ventilation will consist of one glazed panel.
- Test 5: Full Compartment Test Demonstration. This test will be fully designed considering input from the previous tests. The test will take place in the full compartment (27.0 m x 9.0 m) with the same fuel load by area. At this time, one of the glazed openings is proposed to be open. There will be no protection of the mass timber beams, columns, and ceiling. Test duration 4 hours.

The anticipated outcomes of the research include engagement with regulatory authorities, technical information to inform design professionals, marketing to demonstrate performance to designers, the general public, and the construction industry, global exposure to mass timber construction, and education to professionals in the industry.

Several specific technical questions have been identified to be assessed in the testing.

The project is currently seeking funders and the testing is currently planned within the next year or so.

Structural Timber Association – UK

A series of fire compartment tests are planned for mass timber commercial and multi-family residential buildings in early 2021. These tests have the goal of clarifying routes to compliance and developing/promoting a safe working design envelope for mass timber buildings in the UK. These tests will be conducted in Poland.

Arup Testing in Paris, France

A series of large-scale tests are currently being undertaken by Arup in Paris, France with exposed CLT area of 380 m^2 in a large open configuration approximately 11 m wide and 36 m long. This testing is being conducted with the same size and ventilation conditions of testing that was previously conducted in Poland looking at travelling fires with a concrete slab (x-One and x-Two) [24] [25] [26]. The tests in Poland had the following ventilation conditions (see Figure 13):

- openings representing approximately 20% of the compartment walls.
- Total of 6 doors. Two of the doors are larger (approximately 2.5 m x 2.6 m opening at each end)
- 29 window openings (1 m x 1 m).
- Ventilation factor of 0.0621 $m^{1/2}$.

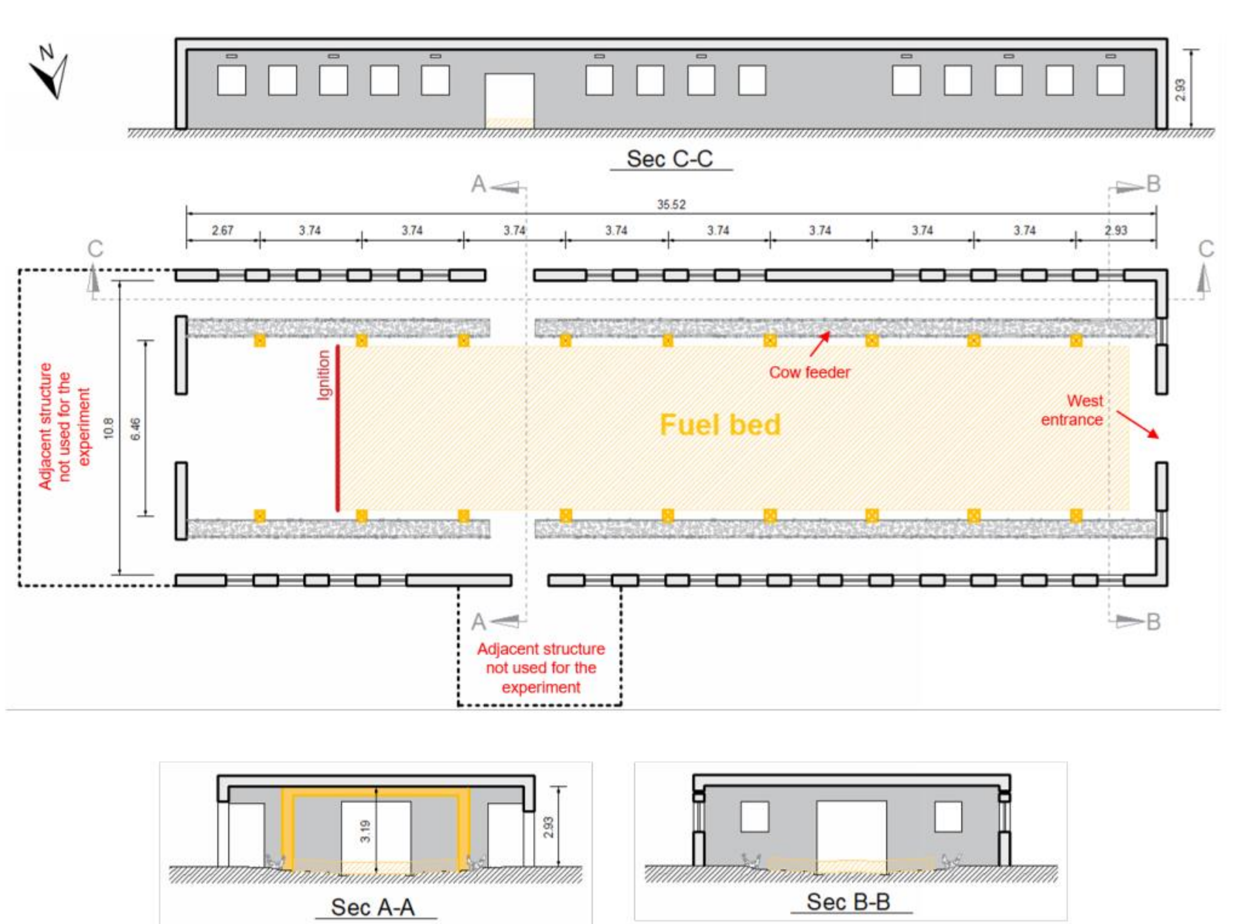


Figure 13. Floor Plan and Sections of the Compartment used for x-One and x-Two in Poland (excerpt from [26).

The purpose of the testing in Paris is to provide a direct comparison to between exposed mass timber open floor areas and concrete floor areas in large fire scenarios to better understand the fire dynamics. As of this writing, one of three tests has been conducted as a part of this project and two more tests are planned. However, no results have been published. This information is based on direct communication with Arup.

Technical University of Munich Testing in Germany

Recent full-scale mass timber compartment fire tests have been conducted in Germany at the Technical University of Munich (TUM) with the objective of allowing tall mass timber buildings in Germany.

There are some videos of the completed testing available online. However, most of the available information at this time is in German. The website for the testing is available at https://www.bgu.tum.de/timpuls/aktuelles/

The following Table 5 is a test matrix is from the website (translated from German). The fifth test (V4) was conducted in early February, 2021.

Table 5. Munich Testing Matrix

	V0	V1	V2	V3	V4
Room Dimensions (W x L x H)	4.5 m x 4.5 m x 2.4 m			4.5 m x 9.0 m x 2.4 m	
Room area	20.25 m^2			40.5 m^2	
Ventilation Factor	0.094 m$^{1/2}$				
Opening size (W x H)	2.4 m x 2.2 m			4.2 m x 2.2 m	
Fuel load	1085 MJ/m^2				
Wall 1	100 mm CLT 2 x 25 mm gypsum board	100 mm CLT 18 mm gypsum board	150 mm CLT -	140 mm wood frame 2 x 12.5 mm gypsum board	150 mm CLT -
Wall 2	100 mm CLT 2 x 25 mm gypsum board	100 mm CLT 18 mm gypsum board	140 mm wood frame 2 x 18 mm gypsum board	140 mm wood frame 2 x 12.5 mm gypsum board	140 mm wood frame 2 x 18 mm gypsum board
Wall 3	100 mm CLT 2 x 25 mm gypsum board	100 mm CLT 18 mm gypsum board	150 mm CLT -	140 mm wood frame 2 x 12.5 mm gypsum board	140 mm wood frame 2 x 18 mm gypsum board
Wall 4	100 mm CLT 2 x 25 mm gypsum board	100 mm CLT 18 mm gypsum board	140 mm wood frame 2 x 18 mm gypsum board	140 mm wood frame 2 x 12.5 mm gypsum board	140 mm wood frame 2 x 18 mm gypsum board
Ceiling	180 mm glulam 2x25 mm gypsum board	180 mm glulam -	200 mm wood frame 2 x 18 mm gypsum board	180 mm glulam -	180 mm glulam -
Structural members	-	-	-	-	2 x 300 mm x 300 mm column 1 x 300 mm x 320 mm beam

Other Mass Timber Compartment Fire Tests

There have been a number of other compartment fire tests for mass timber construction. However, the tests that are described briefly Table 6 below are not further summarized herein as they do not include exposed mass timber and are therefore of limited relevance to the proposed demonstration testing. However, it is considered appropriate to acknowledge and reference these tests for completeness.

Table 6. Other Mass Timber Compartment Fire Tests

Author	Number of tests	Fuel load	Room size	Openings	Notes
Frangi et al. [19]	1	Mattresses and wood cribs	3.34 m x 3.34 m x 2.95 m	Two windows approximately 1.0 m x 1.0 m. Door closed	No exposed mass timber.
Su & Lougheed [20]	1	Furniture	6.3 m x 8.3 m x 2.4 m	Two windows 1.5 m x 1.5 m	Simulates an apartment. No exposed mass timber.
Su & Muradori [21]	1	Furniture, wood cribs	4.58 m x 5.18 m x 2.70 m (apartment)	Window 2.50 m x 1.88 m.	Demonstration of mass timber exit stair performance. No exposed mass timber.
Janssens, M. [22]	2 (NLT ceiling and CLT ceiling)	Furniture	Test 1: 4.11 m x 3.60 m x 2.07 m Test 2: 4.46 m x 3.25 m x 2.07 m	Window 1.87 m x 2.07 m	No exposed mass timber.
Kolaitis et. al. [23]	1	Wood cribs	2.22 m x 2.22 m x 2.11 m	Window 0.43 m x 0.98 m	No exposed mass timber.

CONCLUSION

This review focuses on full-scale compartment fire testing that includes various degrees of exposed mass timber, as they are the most relevant to both meeting the goals of the MTDFTP and many of the earliest ones are those that have most influenced design requirements and proposed code changes to date. This literature review of available testing data and reports has been conducted as part of the Mass Timber Demonstration Fire Test Project (MTDFTP) to inform the Technical Working Group on the research completed to date in order to guide the design and testing process to yield the most meaningful and relevant results and to avoid, to the extent possible, redundancy in the research testing.

REFERENCES

1. McGregor, C., (2013), "Contribution of Cross Laminated Timber Panels to Room Fires", Thesis, Carleton University, Ottawa, Canada.
2. Hevia, A., (2014), "Fire Resistance of Partially Protected CLT Rooms", Thesis, Carleton University, Ottawa, Canada.
3. Su, J., Lafrance, P., Hoehler, M., Bundy, M., (2018), "Fire Safety Challenges of Tall Wood Buildings Phase 2: Tasks 2 & 3 – Development and Implementation of Cross Laminated Timber (CLT) Compartment Fire Tests", Fire Protection Research Foundation.
4. Gerard, R., Barber, D., (2013), "Fire Safety Challenges of Tall Wood Buildings", Fire Protection Research Foundation.
5. Brandon, D., Ostman, B., (2016), "Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 1 – Literature Review", Fire Protection Research Foundation.
6. Zelinka, S., Hasburgh, L., Bourne, K., Tucholski, D., Ouellette, J., (2018), "Compartment Fire Testing of a Two-Story Mass Timber Building", U.S. Forest Products Laboratory, General Technical Report FPL-GTR-247.
7. Janssens, M., (2017), "Development of a Fire Performance Assessment Methodology for Qualifying Cross-Laminated Timber Adhesives", Southwest Research Institute, Project No. 01.23086.01.001a.
8. Su, J., Leroux, P., Lafrance, P., Berzins, R., Gratton, K., Gibbs, E., Weinfurter, M., (2018), "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction", National Research Council Canada, Report No: A1-012710.1.
9. Su, J., Leroux, P., Leroux, P., Lafrance, P-S., Berzins, R., Gratton, K., Gibbs, E., Weinfurter, M., "Nail Laminated Timber Compartment Fire Tests", National Research Council Canada. Report No: A1-014149.1. May 30, 2019.
10. CAN/ULC-S146-2019, (2019), "Standard Method of Test for the Evaluation of Encapsulation Materials and Assemblies of Materials for the Protection of Structural Timber Elements", ULC Standards, Toronto, ON.
11. CAN/ULC-S101-2014, (2014), "Standard Methods of Fire Endurance Tests of Building Construction and Materials", ULC Standards, Toronto, ON.
12. CSA O86-14 (Including Updates 1 & 2), (2017), "Engineering Design in Wood", Canadian Standards Association, Mississauga, ON.
13. Barber, D., (2016), "Fire Safety Engineering of Tall Timber Buildings in the USA", Conference Proceedings of the 2016 World Conference on Timber Engineering.
14. Brandon, D. Summary Report: Fire Safe Implementation of Visible Mass Timber in Tall Buildings – Compartment Fire Testing. RISE Research Institutes of Sweden. RISE Report 2020:94. 2021.

15. Emberley, R., Emberley, R., Gorska, C., Bolanos, A., Lucherini, A., Solarte, A., Soriguer, D., Gonzalez, M. G., Humphreys, K., Hidalgo, J. P., Maluk, C., Law, A., & Torero, J. L. Description of small and large-scale cross laminated timber fire tests. Fire Safety Journal, 91, 327–335. 2017.
16. Hadden, R. M., Bartlett, A. I., Hidalgo, J. P., Santamaria, S., Wiesner, F., Bisby, L. A., Deeny, S., & Lane, B. Effects of exposed cross laminated timber on compartment fire dynamics. Fire Safety Journal, 91, 480–489. 2017.
17. Timber Development Association. Inter-National Fire Engineering Research Non-compliance Operation_INFERNO. Full-scale Open-plan Exposed Mass Timber Real Fire Research Project. V3. March 9, 2020.
18. No Author Indicated. Proposed Full-scale Exposed Mass Timber Open Plan Free Burn Test Program. Version 3 – For Discussion. December 16, 2020.
19. Frangi, A., Bochicchio, G., Ceccotti, A., Lauriola, M.P., . Natural Full-scale Fire Test on a 3 Storey XLam Timber Building. 10th World Conference on Timber Engineering 2008, 1, 529-535. 2008.
20. Su., J., Lougheed, G.D. Fire Safety Summary: Fire research conducted for the project on mid-rise wood construction (Report to research consortium for wood and wood-hybrid mid-rise buildings). National Research Council Canada. 2014.
21. Su, J., Muradori, S., Fire demonstration: cross-laminated timber stair/elevator shaft. National Research Council Canada. 2015.
22. Janssens, M. Full-scale tests in a furnished living room to evaluate the fire performance of protected cross-laminated and nail laminated timber construction. Prepared for American Wood Council. September 30, 2015.
23. Kolaitis, D. I., Asimakopoulou, E., Founti, M.A., Fire Protection of Light and Massive Timber Elements using Gypsum Plasterboards and Wood Based Panels: A Large-Scale Compartment Fire Test. Construction and Building Materials, 73, 163-170. 2014.
24. x-One Fire Experiment in a Very Large and Open-Plan Compartment. No Author. No Date.
25. Rackauskaite, E., Fernandez-Anez, N. x-One Fire Experiment in a Very Large and Open-Plan Compartment. Presentation Slides – 12th International Performance-Based Codes and Fire Safety Design Methods. Honolulu, Oahu. April 25-28, 2018. Imperial College London.
26. Heidari, M., Rackauskaite, E., Christensen, E., Bonner, M., Morat, S., Mitchell, H., Kotsovinos, P., Turkowski, P., Wegrzynski, W., Tofilo, P., Rein, G. Fire Experiments Inside a Very Large and Open-Plan Compartment: x-Two. SiF 2020 – The 11th International Conference on Structures in Fire. The University of Queensland, Brisbane, Australia. Nov 30 – Dec 2, 2020.