NRC·CNRC CONSTRUCTION

Nail Laminated Timber Compartment Fire Tests

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Executive Summary

In early 2019, with funding support from Natural Resources Canada, the National Research Council Canada conducted a series of room scale fire tests of *Encapsulated Mass Timber Construction* (EMTC) with nail laminated timber (NLT) and Glulam structural elements. The goal of this test series is to quantify the contribution of NLT mass timber elements to compartment fires and to provide additional data as the technical basis for the amount of exposed mass timber elements to be allowed in EMTC buildings without significantly increasing the fire severity and duration.

Four room fire tests were conducted, incorporating mass timber structural elements of Glulam beams and columns and NLT panels. The test rooms were 4.5 m long x 2.4 m wide x 2.7 m high, constructed using NLT structural panels. The NLT panels were fabricated using nails and 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) spruce-pine-fir lumber as laminations, respectively. The NLT panels with 38 mm x 140 mm (2 x 6) laminations were used for encapsulated assemblies. The NLT panels with 38 mm x 184 mm (2 x 8) laminations and/or 38 mm x 235 mm (2 x 10) laminations were used for exposed assemblies. Each test room had a rough opening of 0.76 m wide x 2.0 m high with a ventilation factor of 0.03 $m^{½}$.

The NLT ceiling surfaces in the test rooms were fully exposed. Two of the test rooms incorporated Glulam beams and columns. The columns were fully exposed from the four sides. The beams were fully exposed from the three sides, with the NLT ceiling assembly covering the top side of the beams. The Glulam cross sections were 327 mm x 457 mm for beams and 457 mm x 457 mm for columns, respectively. Depending on the tests, the NLT wall surfaces in the test rooms were fully or partially covered using multiple layers of 12.7 mm thick Type X gypsum board. Wood cribs were used to simulate residential room contents with a fire load density of 550 MJ/m^2 in the room. The fire tests were conducted without sprinklers in order to achieve the goal of the tests.

This series of NLT compartment fire tests utilized two test configurations similar to the previous fire test series conducted in 2018 for the second-generation CLT compartments with a thermal resistant adhesive [4].

One test configuration was similar to the configuration used in Test CLT-4, including a fully exposed NLT ceiling (100% ceiling), a fully exposed Glulam beam and column (the combined exposed surface area of the Glulam beam and column was equal to 19% of the perimeter walls), and four protected perimeter walls with two layers of 12.7 mm thick Type X gypsum board. The exposed mass timber surfaces used in this test configuration were much greater than the allowances proposed for exposed mass timber in EMTC buildings in the new fire safety provisions expected to be included in the National Building Code of Canada (NBCC) 2020. Proposed new NBCC (2020) provisions would permit exposed beams/columns/arches at 10% of total suite or fire compartment perimeter wall area, plus partially exposed ceilings at 10% or 25% of total suite ceiling area (provided that the ceiling flame-spread rating is not greater than 150 or 75, respectively). And for the latter case of where 25% of the ceiling is permitted to be exposed, no exposed walls would be permitted.

Test NLT-1 and Test NLT-2 were conducted using the same configuration as Test CLT-4, except that Test NLT-1 used an even NLT ceiling while Test NLT-2 used an uneven NLT ceiling. Similarly in Test NLT-1, Test NLT-2 and Test CLT-4, two layers of gypsum board remained on the walls until the end of the tests. Test NLT-1 and Test NLT-2 produced comparable fire performance, although Test NLT-2 with the uneven NLT ceiling had a slightly lower HRR, lower

temperatures in the room and inside the NLT assemblies, and less char depths in the NLT panels. However, unlike Test CLT-4 where the fire fully burned-out and completely self-extinguished, Test NLT-1 and Test NLT-2 had the protected NLT wall panels continuously charring behind the gypsum board with flames through some gypsum board cracks and joints after the exposed NLT ceiling ceased flaming combustion. The continued charring of the protected NLT walls behind the gypsum board prevented fire decaying to the full extent as in Test CLT-4. The two layers of gypsum board protection appeared to be borderline in limiting the contribution of the protected NLT walls to the fire. The char was much deeper in the NLT tests than in the CLT test.

The other test configuration was similar to the configuration used in Test CLT-5, including a fully exposed NLT ceiling (100% ceiling), two exposed short walls facing each other (equal to 35% of perimeter wall area), and two long walls protected with two to three layers of 12.7 mm thick Type X gypsum board. The exposed mass timber surfaces used in this test configuration were far greater than the allowances proposed for exposed mass timber in EMTC buildings in the new fire safety provisions expected to be included in the NBCC 2020, creating a more severe fire with a longer fully developed stage. Proposed new NBCC (2020) provisions would permit exposed walls (facing one same direction only) at 35% of total suite perimeter wall area plus a partially exposed portion of the ceiling at 10% of total suite ceiling area; or partially exposed ceiling at 25% of total suite ceiling area only with no exposed walls (provided that the ceiling flame-spread rating is not greater than 75).

Test NLT-3 and Test NLT-4 were conducted using the same configuration as Test CLT-5, except that three layers of gypsum board were used in Test NLT-4 while two layers were used in Test NLT-3 and Test CLT-5 to protect the two long walls. Test NLT-3 caused an intense fire without significant decay and had to be terminated just after two hours. In contrast, Test CLT-5 after a long period of gradual fire decay including flame self-extinguishing on the exposed CLT panels, had recurrent fire at 220 min. In both Test NLT-3 and CLT-5, two layers of gypsum board were insufficient in this test configuration to protect the long walls, which charred continuously behind the gypsum board and eventually became exposed to fully participate in the fire. On the other hand, Test NLT-4, with the same amount of exposed timber surface but enhanced encapsulation (three layers of gypsum board) on the two long walls, led to continuous decay of the fire and much reduced contributions of the timber to the fire during the four-hour long test. The flames on exposed NLT panels eventually self-extinguished in Test NLT-4. The char depths were much less in Test NLT-4 than in Test NLT-3 (although Test NLT-4 lasted twice as long as Test NLT-3) and Test CLT-5 in all areas.

The NLT panels typically have some small gaps between laminations. Efforts were made to minimize the gaps during the NLT panel fabrication and room construction for this NLT test series. However, small gaps still existed between NLT laminations. These small gaps provided passages for the flame and hot pyrolysis gas to travel in the NLT panels. Test NLT-3 and Test NLT-4 demonstrated that, in the absence of operationally effective sprinklers, to reach full decay of the fire three layers of 12.7 mm thick Type X gypsum board were necessary for NLT rooms with partially encapsulated walls and fully exposed ceilings to limit undue contributions of the protected NLT elements to the compartment fires, while still keeping the same total area of exposed surfaces as in the two test configurations. It is expected that with the scenarios in Test NLT-1 and Test NLT-2, a similar effect from using three layers of gypsum board would be seen and the fire would be expected to reach full decay.

It is important to note the lumber elements in the NLT panels were not as tightly fitted as the CLT panels, as the NLT had small gaps between laminations. All other variables being equal, the second generation CLT generally performed better than NLT in these compartment fire tests to limit contributions of timber to the fire. Therefore, it is reasonable to expect that, had the three-layer gypsum board protection been used on the two long walls in Test CLT-5, the recurrent fire at 220 minutes would not have occurred in that CLT test. The use of additional encapsulation, such as, three layers of 12.7 mm thick Type X gypsum board is necessary for the protected elements in this partially encapsulated CLT room configuration to prevent the regrowth of the fire. It is also reasonable to expect that, with greater encapsulation, e.g. three-layer gypsum board protection, on the two long walls, the second generation CLT in this partial protection configuration would likely perform significantly better than Test NLT-4 to reach full decay of the fire.

Nail Laminated Timber Compartment Fire Tests

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1. INTRODUCTION

Mass timber is increasingly used for tall wood buildings as sustainable development in the era of combating climate changes. Mass timber comprises of cross laminated timber (CLT), nail laminated timber (NLT), glued laminated timber (Glulam), dowel laminated timber (DLT) and structural composite timber (SCL), etc. as structural elements. To understand the fire performance of mass timber structural systems and provide scientific data for use in the fire safety design and regulation of tall wood buildings, potential contributions of mass timber elements to compartment fires need to be evaluated and quantified. A large amount of compartment fire test data on cross laminated timber (CLT) is available [1-4]. There are gaps for technical data on NLT fire performance and its contribution to compartment fires. With financial support from the Natural Resources Canada, the National Research Council Canada conducted a series of NLT compartment fire tests to help fill the knowledge gaps.

The objective of this test series is to quantify the contribution of NLT elements to compartment fires and the NLT surface area that could be exposed without significantly increasing the fire severity and duration. The fire tests also incorporated Glulam beams and columns in the NLT compartments. In order to achieve the objective, the NLT compartment fire tests were conducted without using sprinklers (note that the National Building Code of Canada requires that all buildings taller than six storeys be fully sprinklered in accordance with NFPA 13 [5]). This report describes the NLT compartment fire tests and documents the test results.

2. TEST SETUP AND PROCEDURE

2.1 Test Matrix and Materials

Table 1 shows a matrix of the NLT compartment fire tests. The test matrix was determined in consideration of the testing configuration used for other mass timber products, combinations of NLT (walls, floor and ceiling) and Glulam (beams and columns) structural elements, and various amounts of exposed mass timber elements.

Table 1. Matrix of NLT compartment fire tests.

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 [4]
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

2.1.1 NLT enclosure of test compartments

NLT panels were fabricated at the NRC fire lab as shown in **Figure 1**, 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) spruce-pine-fir lumber as laminations, respectively. A heavy steel working platform was used for making the NLT panels. The panels were constructed horizontally on the platform using pneumatic nailers. All NLT panels were fabricated to the same size of 2.4 m x 2.8 m. As illustrated in **Figure 2**, the lamination-to-lamination nailing used 82 mm long nails (3¼ in. x .120 paper tape strip nails, smooth shank) at 450 mm (18 in.) spacing in two rows, and the nailing positions were staggered from layer to layer. Pressure was applied using quick grip clamps and bar clamps when nailing the lumber to minimize gaps.

The NLT panels with 38 mm x 140 mm (2 x 6) laminations were used for fully encapsulated assemblies. The NLT panels with 38 mm x 184 mm (2 x 8) laminations and/or 38 mm x 235 mm (2 x 10) laminations were used for fully exposed assemblies. The ceiling panels for Test NLT-2 were made using the 38 mm x 184 mm (2 x 8) laminations and 38 mm x 235 mm (2 x 10) laminations alternately to form an uneven surface.

Figure 1. Photographs of NLT panel fabrication.

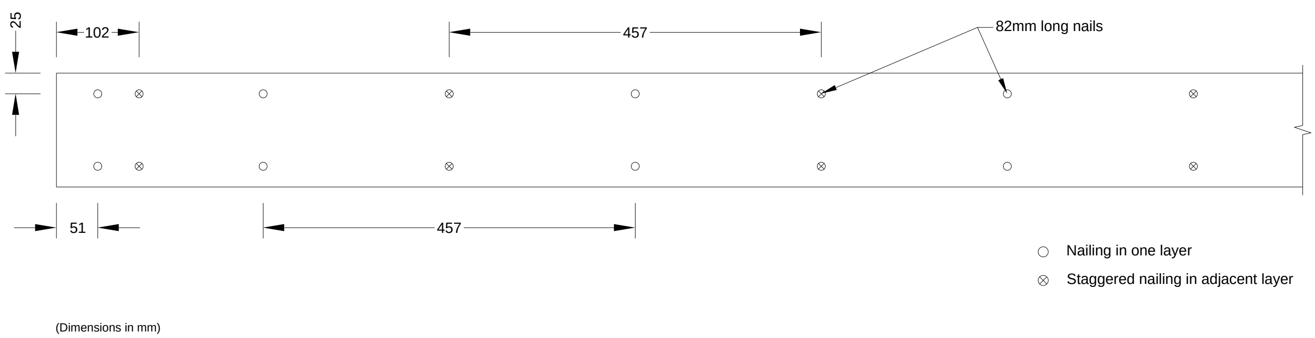


Figure 2. NLT lamination to lamination nailing.

Figure 3 and **Figure 4** show the schematics of four NLT compartments erected on a concrete slab floor for the fire tests. Each test compartment consisted of eight NLT panels. For the ceiling, Wall A and Wall C assemblies, each assembly consisted of two NLT panels connected using 180 mm long screws at 45° on each panel every 300 mm. Wall B and Wall D assemblies consisted of a single NLT panel. The perpendicular connections of the adjacent walls and ceiling to walls were butt joints with 280 mm long screws at 300 mm spacing. (Both were SWG screws made of steel with zinc coating, CSK head and partial thread). **Figure 5** illustrates the details of the NLT connections. **Figure 6** shows photographs of the NLT enclosure during construction. The interior dimension of the NLT enclosure was 4.5 m long x 2.4 m wide x 2.8 m high. No structural load was used other than the self-weight of the NLT assemblies.

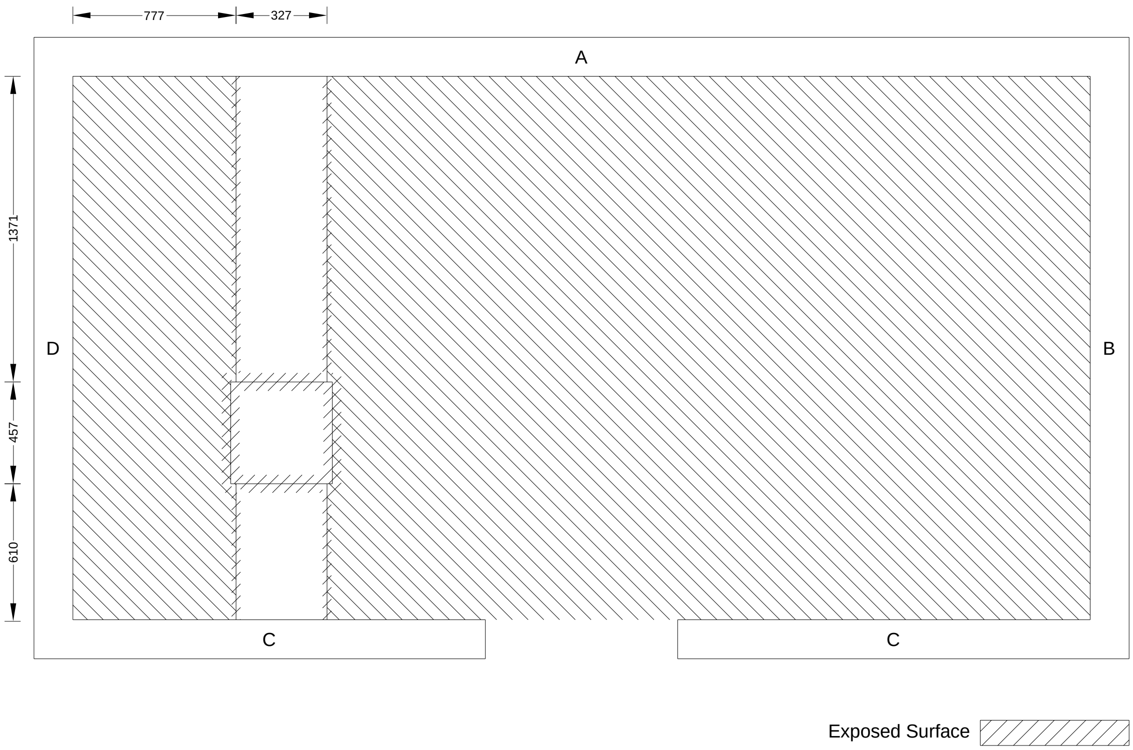


Figure 3. Schematic – fully exposed ceiling, column (4 sides) and beam (3 sides) for Test NLT-1 (even ceiling) and Test NLT-2 (uneven ceiling).

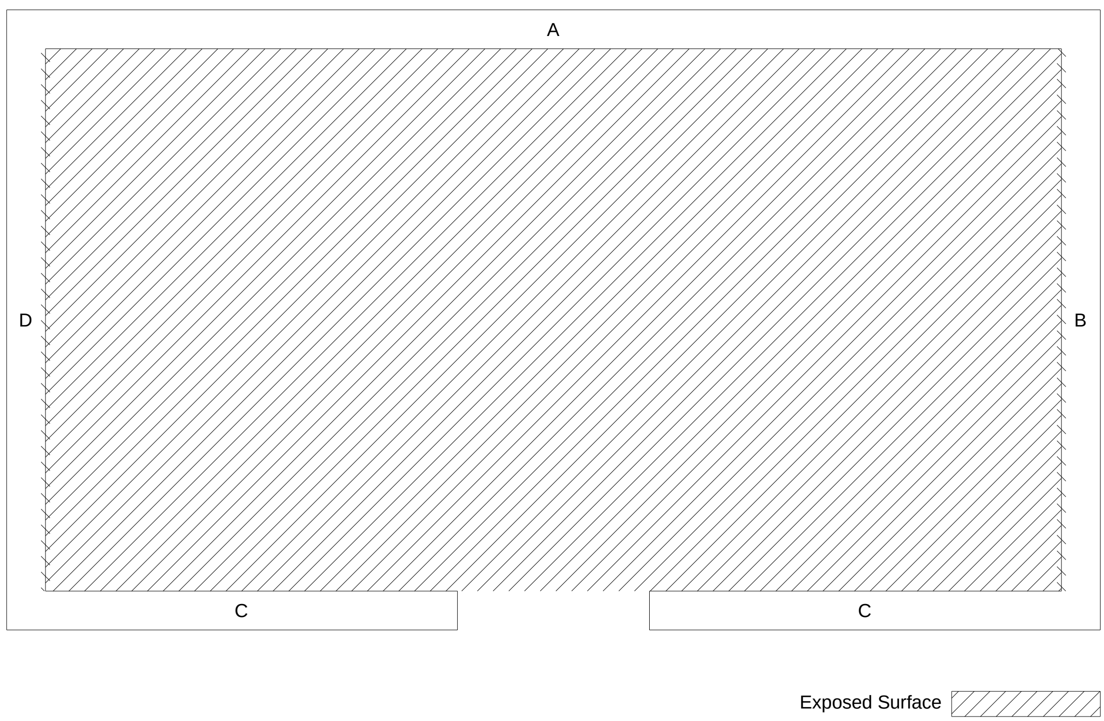
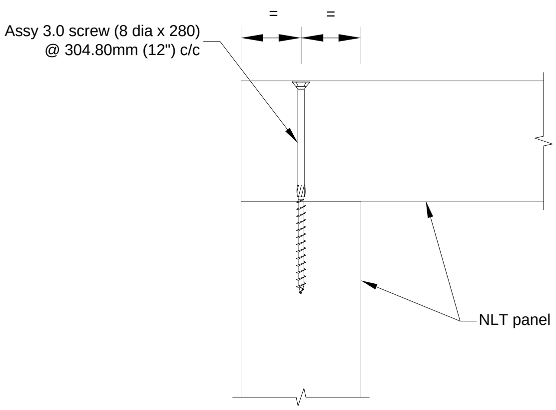
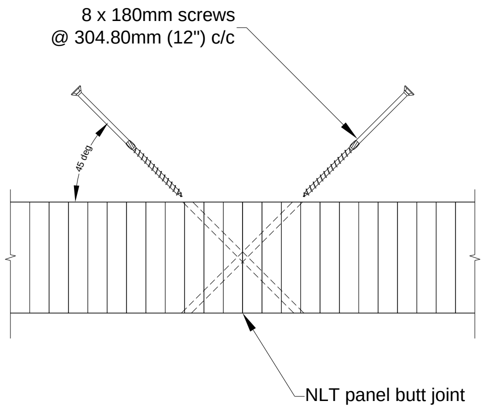


Figure 4. Schematic – fully exposed ceiling, Wall B and Wall D for Test NLT-3 and Test NLT-4.



(a) butt joint



(b) in-plane panel-to-panel joint

Figure 5. Details of NLT panel connections.

(a) outside view of NLT Walls A and D

(b) outside view of NLT Walls B and C

(c) outside view of NLT ceiling, Walls A and B

(d)) inside view of NLT compartment with Glulam beam/column

Figure 6. Photographs of test compartment construction.

2.1.2 Glulam beams and columns in test compartments

Two of the test compartments incorporated Glulam beams and columns. The laminae were made with multiple pieces of 38 mm × 38 mm lumber. The face bonding and end joints are bonded with a polyurethane adhesive (for end-joints: Ashland UX-100/WD3-A322, CCMC 13512-L; for edge and face laminations: Ashland WD3-A322/CX-47, CCMC 13591-L). The Glulam cross sections were 327 mm x 457 mm for beams and 457 mm x 457 mm for columns, respectively. The beams were connected to the sides of the columns. The connection details of the Glulam beams and columns and NLT panels are shown in **Figure 7**. The columns were fully exposed from the four sides. The beams were fully exposed from the three sides with the NLT ceiling assembly covering the top side of the beams.

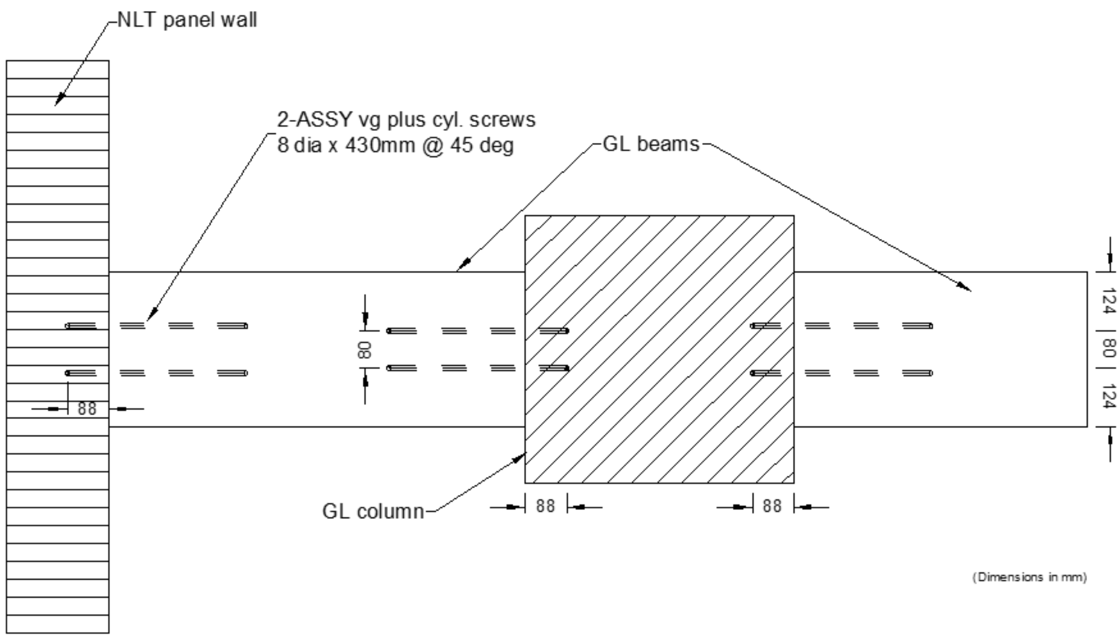


Figure 7. Connection details of Glulam beams and columns and NLT panels.

2.1.3 Ventilation opening

A rough doorway opening was created in the center of Wall C. After wrapped with gypsum board and ceramic fibre, the finished opening size was 0.76 m wide x 2.0 m high to give a ventilation factor of 0.03 $m^{1/2}$ in this series of the tests. The ventilation factor is calculated using $A_0\sqrt{H_0}\ / A_t$, where A_o and H_o are the area and height of the opening and A_t the total area of the boundary surfaces. (The ventilation factor was the same as the one used in the second generation CLT compartment tests [4]). This relatively small opening was expected to result in a long fully developed fire stage, creating a severe fire exposure to the mass timber elements inside the compartment.

2.1.4 Encapsulation materials

The interior of the NLT compartments was partially encapsulated using two or three layers of 12.7 mm (1/2 in.) thick Type X gypsum board, as shown in **Table 1**. The ceiling was fully exposed in all the tests. In Test NLT-1 and Test NLT-2, all the walls were protected using two layers of the gypsum board but the columns were exposed from four sides and the beams exposed from three sides (equivalent to 19% of perimeter wall surfaces). In Test NLT-3 and Test NLT-4, Wall B and Wall D were fully exposed (equivalent to 35% of perimeter wall surfaces) while Wall A and Wall C were protected using multiple layers of the gypsum board (two layers in Test NLT-3 and three layers in Test NLT-4). **Table 2** shows details of the screws used to fasten the gypsum board.

Table 2. Type X gypsum board and screws used for NLT encapsulation.

Gypsum board and screw	Tests NLT-1, NLT-2, NLT-3		Test NLT-4	
	Thickness of gypsum board	Length of screws (406 mm or 16 in. spacing o.c.)	Thickness of gypsum board	Length of screws (406 mm or 16 in. spacing o.c.)
Base layer	12.7 mm (1/2 in.)	41.3 mm (1-5/8 in.)	12.7 mm (1/2 in.)	41.3 mm (1-5/8 in.)
Middle layer	none	none	12.7 mm (1/2 in.)	50.8 mm (2 in.)
Face layer	12.7 mm (1/2 in.)	50.8 mm (2 in.)	12.7 mm (1/2 in.)	63.5 mm (2-1/2 in.)

Where used, the gypsum board was fastened directly on the NLT wall panels in a staggered fashion such that no joint would line up with any joint of the other gypsum board layer. Type W drywall screws were spaced at 406 mm (16 in.) on centre and 38 mm (1½ in.) from the edges of the gypsum board sections. Care was taken not to overdrive the screw head into the gypsum board (to prevent damaging the board surface). On the face layer, the joints between gypsum board sections were covered with tape and joint compound and the screw heads were also covered with joint compound.

The floor was protected using three layers of 12.7 mm (1/2 in.) thick Type X gypsum board.

The NLT surfaces outside the fire compartments were covered with either one layer or two layers of 12.7 mm (1/2 in.) thick Type X gypsum board, as shown in **Table 1** (depending on whether the NLT interior surfaces were exposed). The edges of the rough opening were also lined with two layers of 12.7 mm (1/2 in.) thick Type X gypsum board followed by a layer of 25 mm thick ceramic fiber insulation wrapped around.

2.1.5 Moisture content of timber elements

Prior to installation of the gypsum board, the moisture content of each NLT panel, Glulam column and beam was sampled at multiple locations using a handheld moisture meter. The moisture contents were in the range of 7.5 - 8.3 for the NLT panels, 7.1 - 8.9 for the Glulam columns and 6.1 - 7.8 for the Glulam beams.

2.2 Fire Load and Ignition Scenario

Three wood cribs, made of 38 mm x 89 mm x 900 mm spruce pieces with a total weight of 360 kg, were used as the fuel load for each test. Each wood crib had ten layers with eight spruce pieces per layer. The wood cribs provided a fire load density (FLD) of 550 MJ/m^2 in the room. This value is identical to recent CLT compartment fire tests [1, 4].

Three small plates which contained a total of 600 mL methyl hydrate were placed underneath the middle crib as the ignition source. A torch was used to ignite the methyl hydrate which ignited the wood crib (see **Figure 8**).

(a) (b)

Figure 8. Photographs of (a) wood cribs and (b) middle crib ignition.

2.3 Instrumentation and Measurements

Figure 9 to **Figure 12** illustrate the instrumentation plans for the tests. Various cameras were used to obtain videos and still pictures as well as thermal imaging during the experiments.

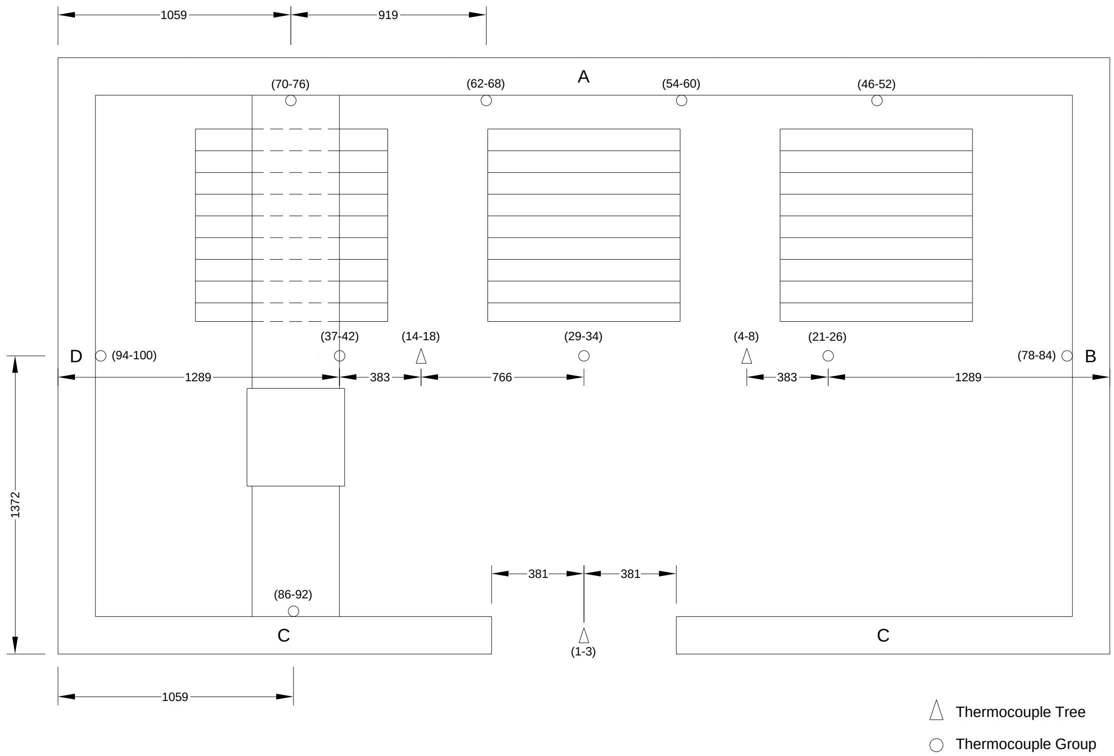


Figure 9. Thermocouple trees and embedded thermocouples in Test NLT-1 and Test NLT-2.

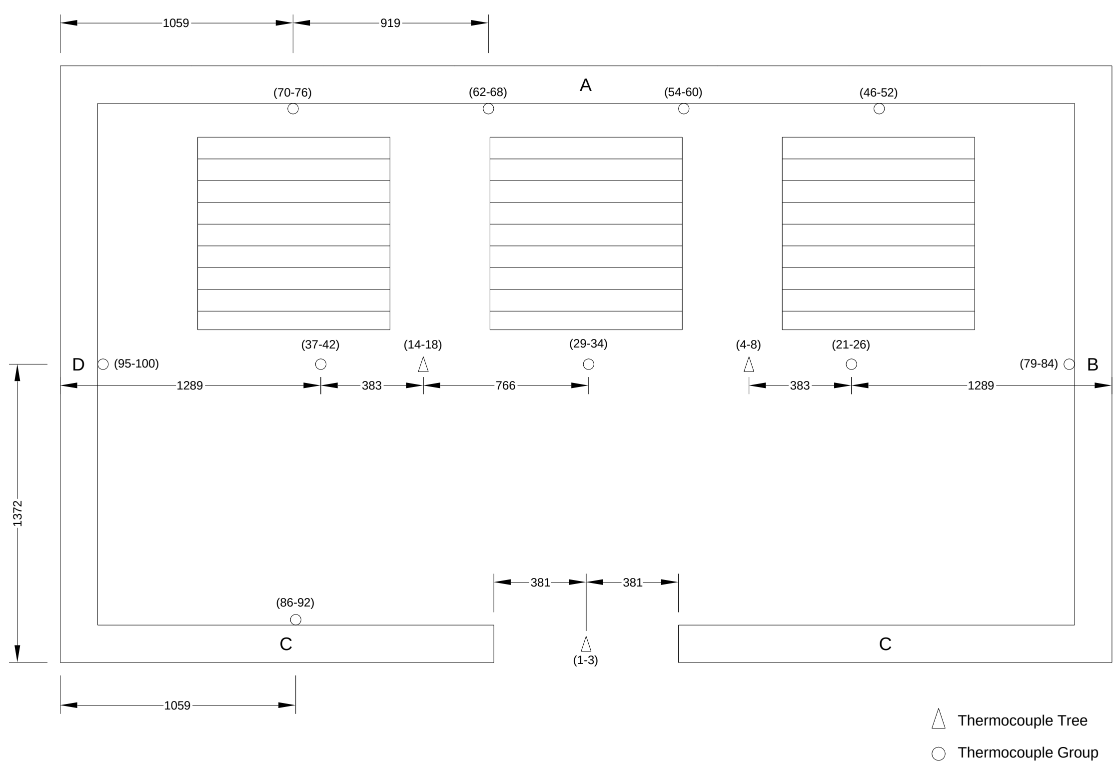


Figure 10. Thermocouple trees and embedded thermocouples in Test NLT-3 and Test NLT-4.

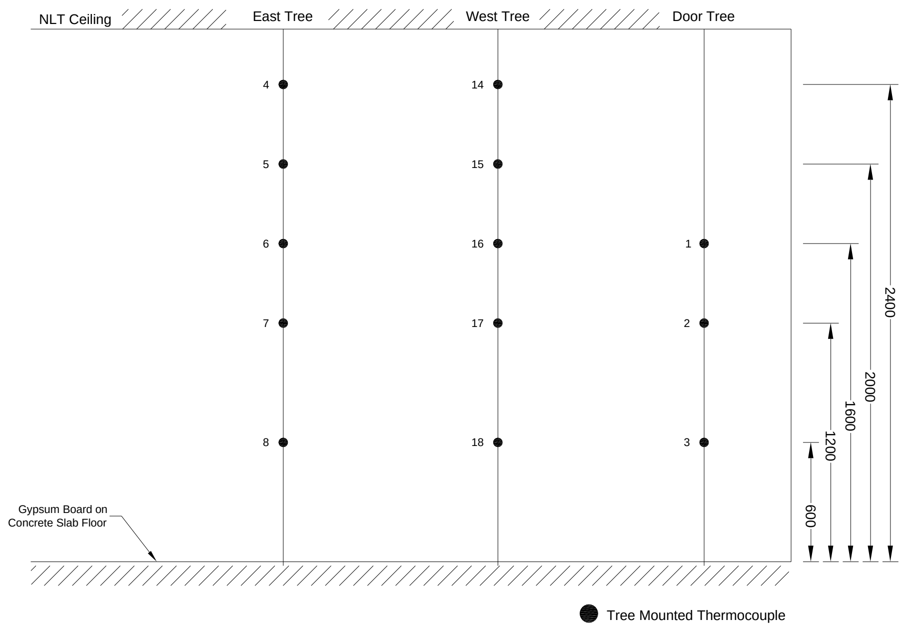


Figure 11. Heights of thermocouples on the thermocouple trees in test compartments.

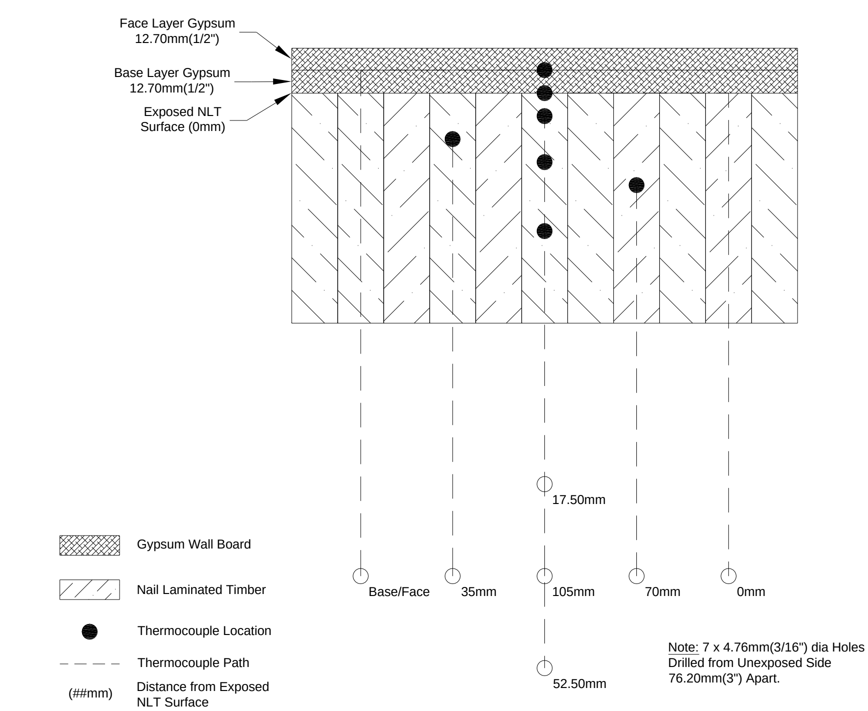


Figure 12. One of the thermocouple groups embedded in the NLT panels (gypsum board layer varied from 2 layers to none).

2.3.1 Room temperatures

As shown in **Figure 9** to **Figure 11**, two thermocouple trees were installed in the fire compartment to measure the room temperatures. Each thermocouple tree had five thermocouples at the 0.6, 1.2, 1.6, 2.0 and 2.4 m heights from floor. These thermocouples were Type K, stainless steel sheathed, 3.175-mm (1/8 in.) diameter, grounded junction thermocouples (Model HKQSS-18G-400 from Omega), shielded for radiation.

Another thermocouple tree was located at the centreline of the rough opening to measure the temperature of the flame and smoke exiting the fire compartment. Three thermocouples were installed at heights of 0.6, 1.2, 1.6 m from floor in the opening. These thermocouples were Type K, Inconel sheathed, grounded junction thermocouples (Model HKQIN-18G-300 from Omega).

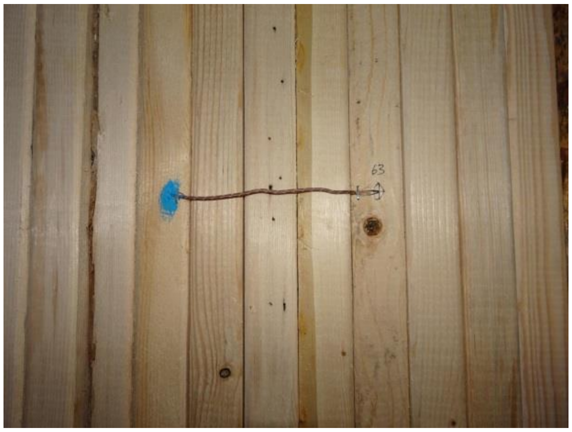
2.3.2 Temperatures inside NLT panels and at gypsum board interfaces

As shown in **Figure 9** and **Figure 10**, thermocouples were embedded at various locations inside the NLT wall and ceiling assemblies to measure the temperatures at the interface between gypsum layers and inside NLT panels. Each location included a group of embedded thermocouples. There were four locations in Wall A spaced at 0.9 m apart and at 1.8 m height, three locations in ceiling near the centre and two quarter points, and one location in each of Wall B, Wall C and Wall D at 1.8 m height.

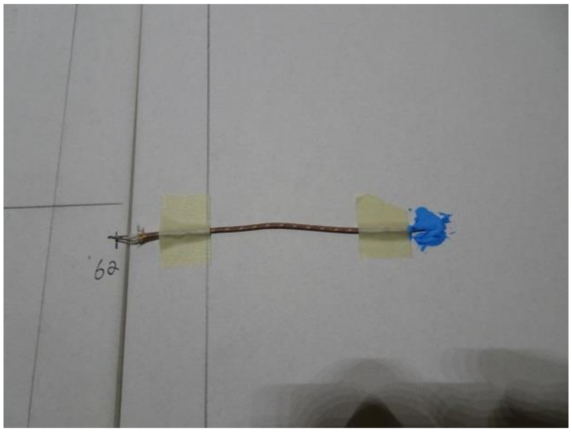
As shown in **Figure 12**, at each location, the thermocouples were embedded at each interface between two adjacent gypsum board layers and between the base layer gypsum board and the NLT panel. Thermocouples were also embedded inside NLT at the depths of 17.5, 35, 52.5, 70 and 105 mm from the interior NLT surface (interior side as 0). Depending on the tests and locations, the number of the gypsum board layers varied from three layers to none thus the interface thermocouples varied in number as well. (For Test NLT-4 where three layers of the gypsum board were used, no interface thermocouples were installed between the face layer and middle layer of gypsum board). The temperatures measured from the embedded thermocouples were used to determine the fall-off time of gypsum board, the effect of encapsulation on delaying ignition and/or preventing involvement of NLT in the fire, NLT charring depth and charring rate.

Figure 13 shows photographs of a group of embedded thermocouples. The embedded thermocouples were type K, glass-sheathed, 20-gauge, bare-bead thermocouples (Model GG-K-20-SLE-1000 from Omega). All holes drilled to install the embedded thermocouples were sealed with 3M Fire Barrier sealant FD150+ to maintain the integrity of the NLT panels and gypsum board. The thermocouples installed between layers of gypsum board and between gypsum board and NLT were run such that a length of approximately 150 mm ran along the surface of the NLT or gypsum board. This was to reduce the impact of heat transfer along the wire and minimize the effect of the holes drilled for installation.

(a) Holes drilled from exterior side of NLT and sealed with 3M Fire Barrier sealant



(b) 150 mm wire run along NLT interior surface



(c) 150 mm wire run along gypsum board surface

Figure 13. A group of embedded thermocouples.

2.3.3 Heat release rate measurements

Heat release rate (HRR) measurements were performed using an oxygen consumption fire calorimeter. A 1.9 m x 4.9 m canopy was installed above the compartment opening as the smoke collection hood which connected to an exhaust duct with a cross section of 0.4065 m^2. The exhaust duct was instrumented for mass flow measurements and CO, CO_2 and O_2 measurements of the exhausted gas. The HRR measurement system was calibrated using propane gas burner reference fires at 0.5 MW, 1 MW, 2 MW, 3 MW and 3.5 MW. To lead smoke flow into the collection hood, a structural extension was added on top of Wall C.

2.3.4 Char measurements

After each fire test, the charring depths in various areas of the NLT ceiling and wall assemblies as well as Glulam columns and beams were measured. The Resistograph R650-SC was used to determine the char depth of the mass timber after the fire tests. The Resistograph is an electronically controlled device that drills a long needle drill bit into wood. The drilling resistance is then recorded and interpreted to determine the remaining wood depth. By subtracting the remaining wood depth from the original wood dimension, the char depth can be determined.

2.4 Test Procedure

The following procedure was used for the fire tests.

(1) Start data acquisition and instrumentation system;
(2) Ignite the wood cribs;
(3) Let the fire continue to a total burnout where possible;
(4) Terminate the test based on the following criteria:
    a. Total burnout to self-extinguishment, or
    b. An elapsed time of 4 hours, or
    c. Safety threat to personnel or facility; and
(5) Examine debris and take necessary measurements (photographs, charring depth, etc.) after the fire tests.

3. RESULTS AND DISCUSSIONS

Four NLT compartment fire tests were conducted to produce technical data, including temperatures inside and outside the compartment and through the ceiling and wall assemblies, heat release rate and char depth, etc. for quantifying the contribution of the mass timber structural elements to the compartment fires. Key results of the tests and analysis are presented in this section. **Table 3** shows some selective data.

Table 3. NLT compartments and fire test results (February and March 2019).

Component / Result	Test NLT-1 (Feb 7)	Test NLT-2 (Feb 26)	Test NLT-3 (March 14)	Test NLT-4 (March 27)
NLT Walls A and C with interior lining	2x6 laminations with 2GB	2x6 laminations with 2GB	2x6 laminations with 2GB	2x6 laminations with 3GB
NLT Walls B and D with/without interior lining	2x6 laminations with 2GB	2x6 laminations with 2GB	2x8 laminations **exposed**	2x8 laminations **exposed**
NLT Ceiling without interior lining	2x8 laminations **exposed**	2x8 and 2x10 alternate laminations **exposed**	2x8 laminations **exposed**	2x8 laminations **exposed**
Glulam Beam (327 mm x 457 mm)	**exposed** (2.46 m^2)	**exposed** (2.46 m^2)	-	-
Glulam Column (457 mm x 457 mm)	**exposed** (4.81 m^2)	**exposed** (4.81 m^2)	-	-
Flashover (min)	3.7	3.9	3.2	3.3
Gypsum board performance	on Walls A,B,C,D	on Walls A,B,C,D	on Walls A,C	on Walls A,C
face layer 300°C@back (min)	16-23	17-23	18-24	NA
mid layer 300°C@back (min)	-	-	-	42-61
base layer 300°C@back (min)	40-53	40-56	41-52	89 - Nr
face layer falloff (min)	Nfo	Nfo	33	50 - Nfo
mid layer falloff (min)	-	-	-	Nfo
base layer falloff (min)	Nfo	Nfo	105	Nfo
Heat release rate at peak (MW)	4.1	4.2	4.4	4.6
Test duration (min)	251	241	120	255
Wall A NLT char (mm)	55-92	44-70	25-60	0-45
Wall B NLT char (mm)	64-85	50-61	102-126	61-79
Wall C NLT char (mm)	23-58	33-73	18-45	0-33
Wall D NLT char (mm)	57-58	53-80	81-104	44-89
Ceiling NLT char (mm)	94-124	69-107 †	97-119	44-64
Glulam char from each exposed side of beam (mm)	94-104 (side) 117-137(bottom)	84-94 (side) 94-135 (bottom)	-	-
Glulam char from each exposed side of column (mm)	94-108 (face Wall A/C) 98-114 (face Wall B/D)	86-96 (face Wall A/C) 88-114 (face Wall B/D)	-	-

2GB (3GB): two (three) layers of 12.7 mm (½") thick Type X gypsum board lining
NA: not available
Nr: not reached 300°C
Nfo: no fall-off
-: not used
† measured on the 2 x 8 laminations (38 mm x 184 mm lumber)

3.1 Test NLT-1

Test NLT-1 was conducted on February 7th, 2019 with a fully exposed NLT ceiling (2x8 laminations) and fully exposed Glulam beam and column. The Glulam beam was exposed from three sides with a total exposed surface area of 2.46 m^2; the Glulam column was exposed from four sides with a total exposed surface area of 4.81 m^2. The combined exposed surface area of the beam and column was equal to 19% of the perimeter walls. The NLT walls (2x6 laminations) were all lined with two layers of 12.7 mm (1/2 in.) thick Type X gypsum board. **Figure 14** is a photograph of the test compartment before Test NLT-1.

Figure 14. Fully exposed NLT ceiling, Glulam beam and column for Test NLT-1.

Figure 15 shows some photographs of the mass timber room during the fire test. Test NLT-1 started with ignition of the middle crib. The fire ignited the ceiling above at 3.0 min. Flame started to come out from the top of the doorway opening at 3.2 min, followed by large fire plume issuing from the doorway opening. Flashover occurred at 3.7 min. By 40 min, the fire plume from the opening reduced significantly and the interior of the room became visible. Char was observed to have formed on the NLT ceiling and Glulam beam and column. The flaming combustion of the exposed ceiling, beam and column continued to decline as time elapsed. However, there were constant flames coming from the gypsum-board protected walls through gypsum board cracks (indicating NLT charring behind the gypsum board) and along some gypsum board junctions.

The fire plume ceased to continuously issue from the opening at 120 min. There was no more flaming combustion on the ceiling afterwards but flaming continued on the Glulam column and along some gypsum-board junctions and cracks on the walls. These fire conditions had no obvious changes until the end of the test. Two layers of gypsum board still remained on the walls at the end of the test. At 251 min, water spay was applied to extinguish the remaining flames.

(a) at 30 min

(b) at 60 min

(c) at 90 min

(d) at 120 min

(e) at 150 min

(f) at 180 min

(g) at 210 min

(h) at 240 min

Figure 15. Fully exposed ceiling, beam and column in mass timber room during Test NLT-1.

3.1.1 Room temperatures

Figure 16 shows temperatures in the room during Test NLT-1, measured using thermocouple (TC) trees with thermocouples at 0.6 m, 1.2 m, 1.6 m, 2.0 m and 2.4 m heights. The room temperatures reached a peak of 1170 °C during the fully developed stage then started to decrease at 30 min. The room temperatures decreased to below 850 °C at 50 min. In the period of 50 min to 70 min, the room temperatures increased again because the protected NLT wall panels started to char behind the gypsum board, causing flaming to occur at cracks and some joints in the gypsum board which contributed heat to the room. In the period of 70 min to 180 min, the room temperatures resumed declining. Afterwards, with gradually increased flames from the gypsum board cracks and joints of the protected NLT walls, the room temperatures slowly increased again until the end of the test.

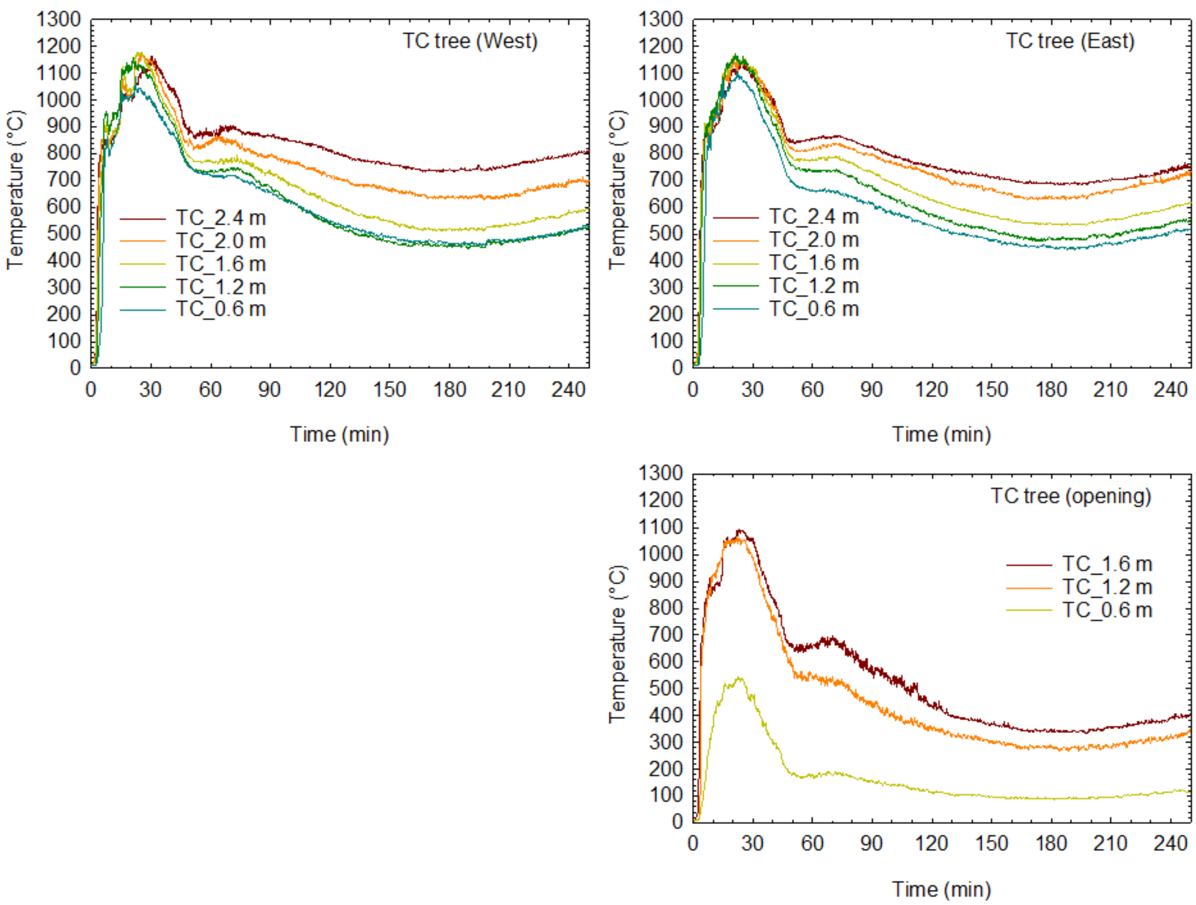


Figure 16. Room temperatures during Test NLT-1.

3.1.2 Temperatures at gypsum board interfaces and inside NLT panels

Figure 17 to **Figure 19** show the temperatures measured at the NLT surfaces, interfaces between gypsum board layers and inside NLT panels. **Table 4** shows the timing when the embedded thermocouples measured 300 °C in NLT assemblies, which is the typical temperature used as an indication that the wood has begun to char and therefore used as a criteria for determining the char front as it progresses through the wood.

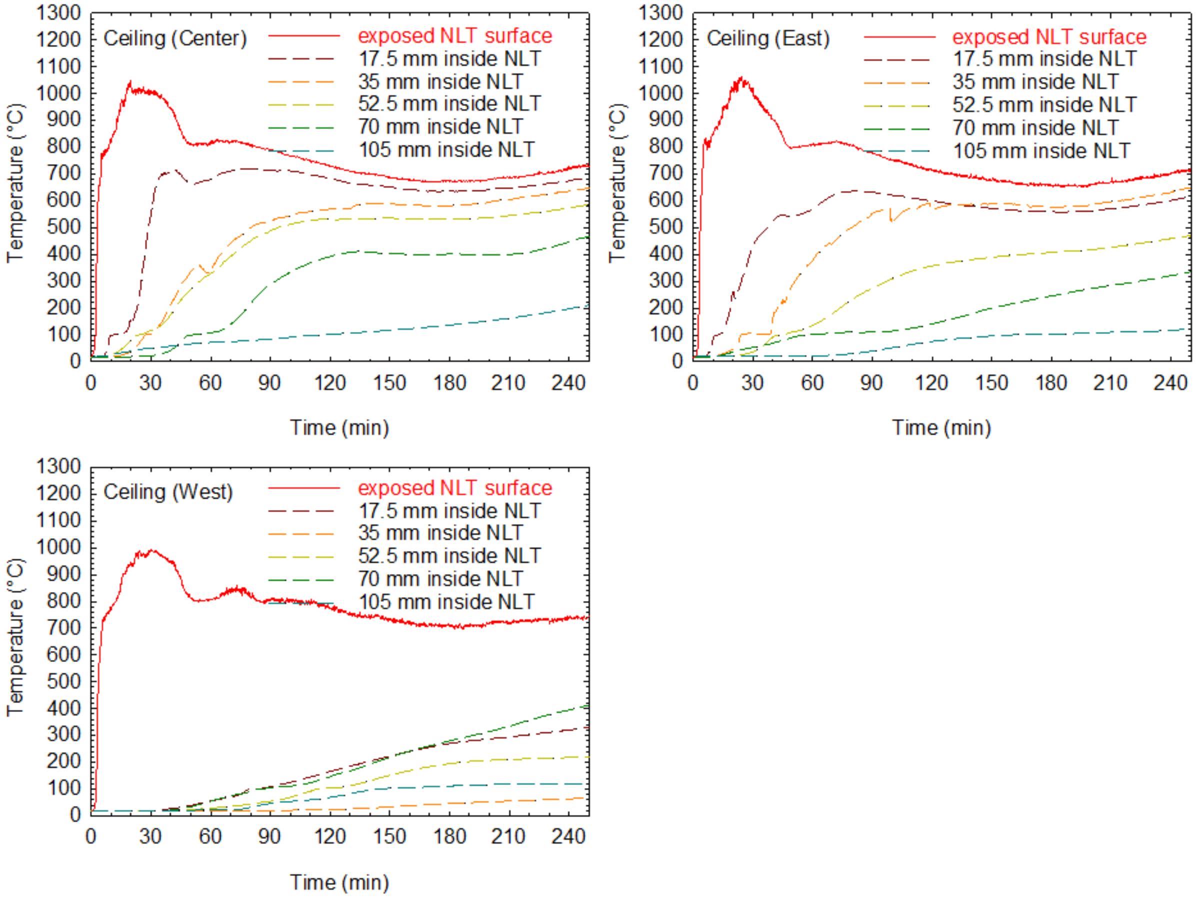


Figure 17. Temperatures in NLT ceiling panels in Test NLT-1.

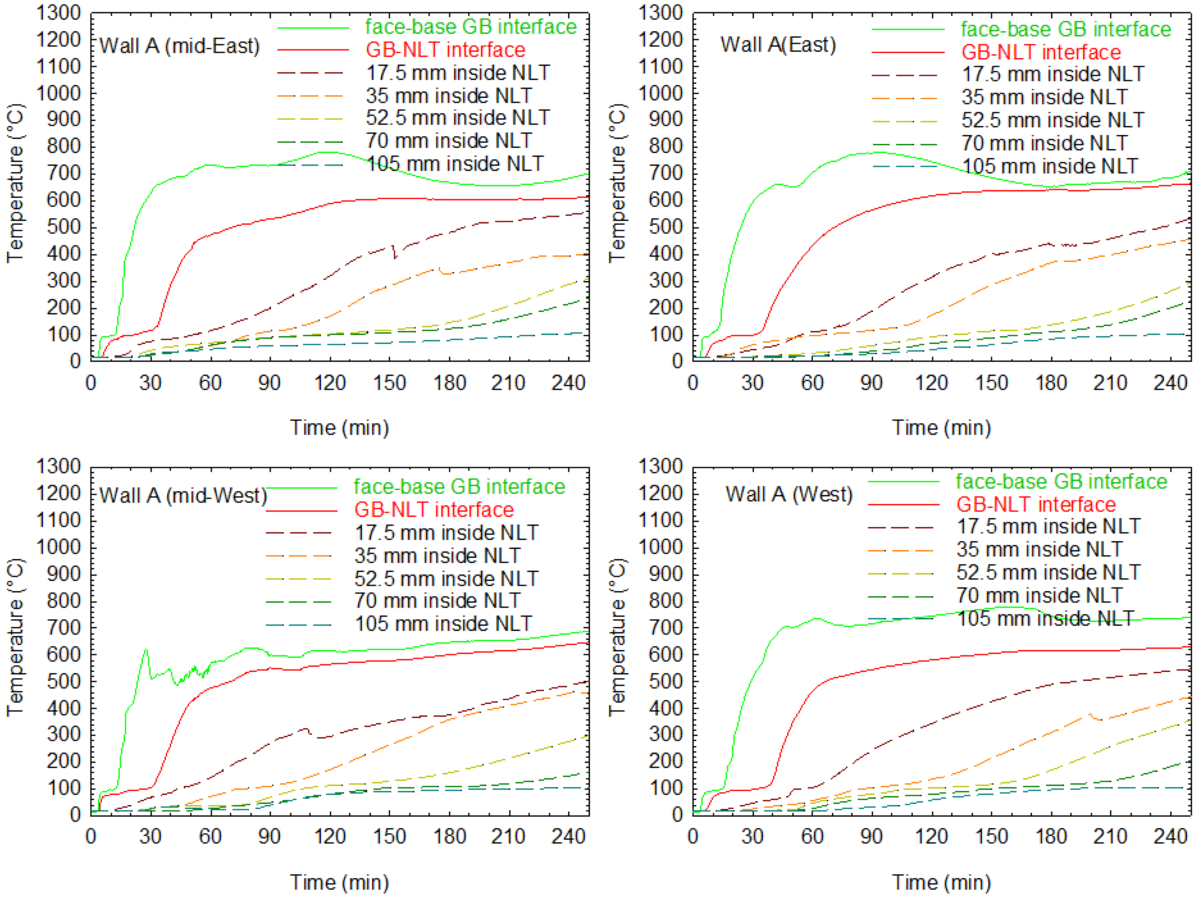


Figure 18. Temperatures in NLT and at gypsum board interfaces for Wall A in Test NLT-1.

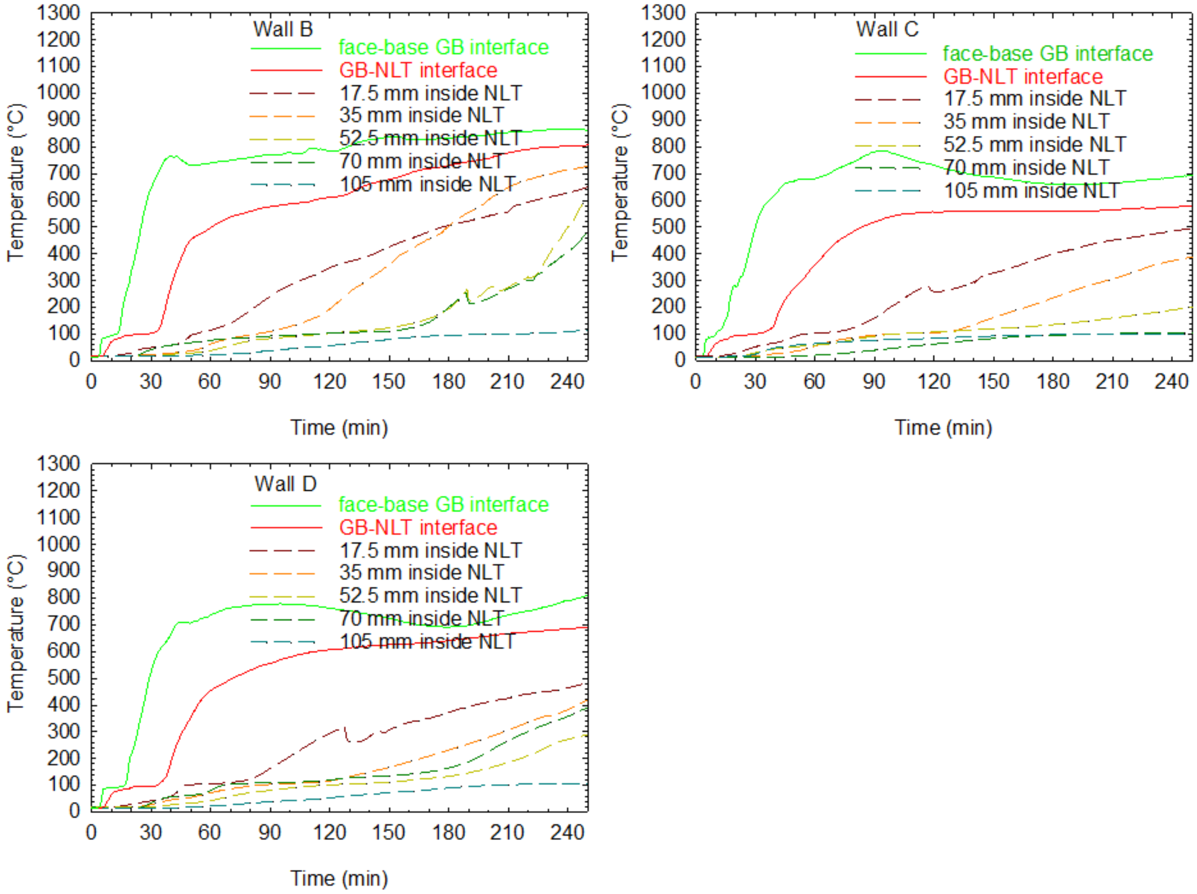


Figure 19. Temperatures in NLT and at gypsum board interfaces for Walls B, C and D in Test NLT-1.

Table 4. Time (min) to reach 300°C at gypsum board interfaces and inside NLT in Test NLT-1.

NLT panel	Gypsum board (GB) layer interface or NLT depth (mm)						
	GB face/base	0	17.5	35	52.5	70	105
Ceiling east	i.n.	3.00	24.17	51.00	97.25	223.58	-
Ceiling centre	i.n.	2.58	25.17	46.42	54.33	92.25	-
Ceiling west	i.n.	3.00	216.33*	-	-	191.83	-
Wall A east	16.42	46.58	115.58	154.58	251.50	-	-
Wall A mid-east	16.17	40.67	115.42	156.08	245.17	-	-
Wall A mid-west	16.83	41.50	99.33	162.08	250.25	-	-
Wall A west	20.75	47.25	104.92	176.33	225.83	-	-
Wall B	19.17	41.00	105.25	138.83	216.33	219.58	-
Wall C	21.58	53.08	141.06	207.00	-	-	-
Wall D	23.17	45.92	143.67	207.92	-	219.75	-

-: did not reach 300°C during the test.
i.n.: interface did not exist.
**: shielded right above the beam.*

Based on the timing when the embedded thermocouples in the NLT ceiling measured 300 °C, the char front reached 17.5 mm at 24-25 min, 35 mm at 46-51 min, 52.5 mm in 54-97 min and 70 mm in 92-223 min in the exposed area. At the end of the test, the temperatures at the 105 mm depth in the NLT panels were below 200 °C. The measurements from the embedded thermocouples in the ceiling indicated that the char front moved beyond 70 mm at the thermocouple locations.

All NLT wall assemblies were protected using gypsum board. The heat transfer through the gypsum board followed the typical three-stage pattern as indicated by the temperature profiles at the interfaces. The temperatures at the gypsum board base layer and NLT interface reached 300 °C at 40-53 min and increased to a maximum of 580-800 °C at the end of the test. This indicated that the NLT panels started charring behind the base layer gypsum board in the walls, causing flaming to occur at cracks and joints in the gypsum board and contributing heat to the room. This contributed to the temporary increase in the room temperatures around 50 min and relatively high room temperature afterwards, as shown in **Figure 16**.

3.1.3 Heat release rate

Figure 20 shows the heat release rate (HRR) during Test NLT-1, presenting the values of 1-min running averages. The HRR was 4.1 MW at the initial peak after the flashover (the peak value could have been slightly higher as a small portion of the smoke overflowed the collection hood at 20 min for a short while). As the fire decayed, the HRR reduced to 1.5 MW at 50 min. In the period of 60 min to 75 min, the HRR increased slightly due to the protected walls charring behind the gypsum board with flaming from the gypsum-board cracks and joints. Afterwards, the HRR resumed the declining trend. After two hours, the HRR reduced to below 1 MW until the end of the test. (Note: respectively at around 120 min and 200 min, the sampling pump was turned off briefly to change Drierite and remove clogging in the sampling line, which resulted in the artificial HRR variations around that times respectively.)

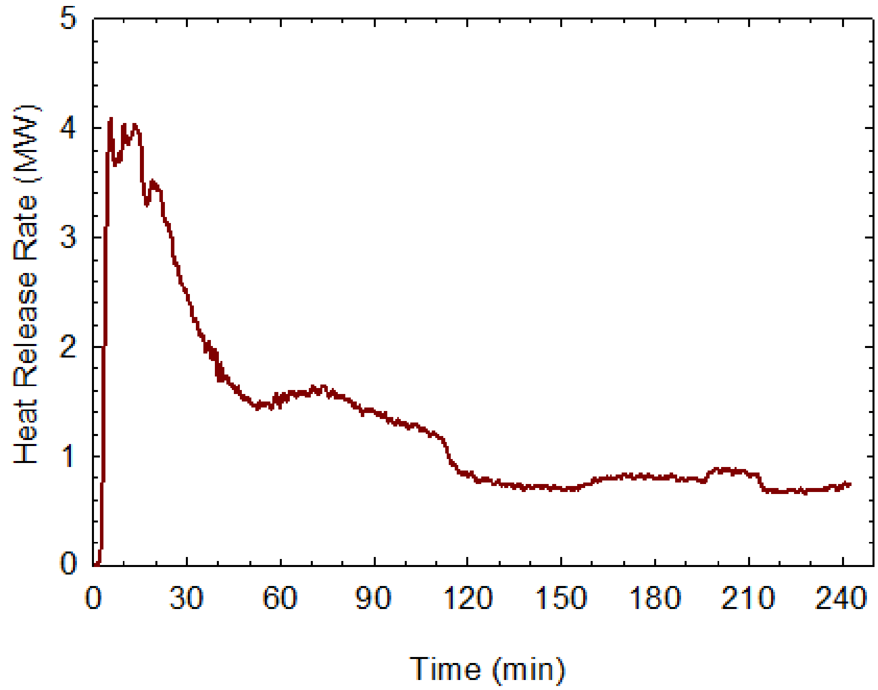


Figure 20. Heat release rate in Test NLT-1.

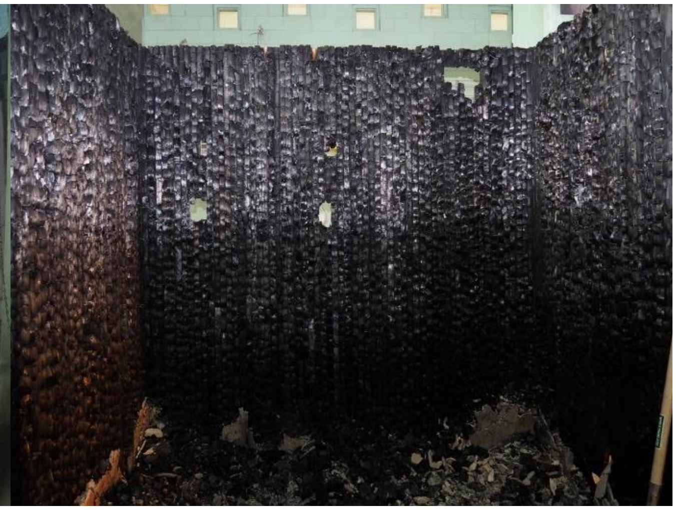
3.1.4 Char of Glulam beam and column as well as NLT panels

After Test NLT-1, the NLT panels and Glulam beam and column in the compartment were examined for char. **Figure 21** shows photographs of the NLT and Glulam elements after Test NLT-1.

The char depth was measured using the Resistograph drill as shown in **Figure 22**. A total of 66 sampling locations were drilled through for char depth measurements. The drilling resistance was recorded to determine the remaining thickness and, by subtracting the remaining thickness from the original dimension, the char depth was determined for each measurement.

Figure 23 shows the sampling locations and remaining depths of the Glulam beam and column after the fire test. Given the original cross section of 327 mm x 457 mm for the three-side exposed beam and 457 mm x 457 mm for the four-side exposed column, the char depth was in a range of 93 mm to 137 mm for each exposed side of the Glulam in 251 min, translating to a char rate of 0.37 to 0.55 mm/min.

(a) NLT exterior (gypsum board removed)

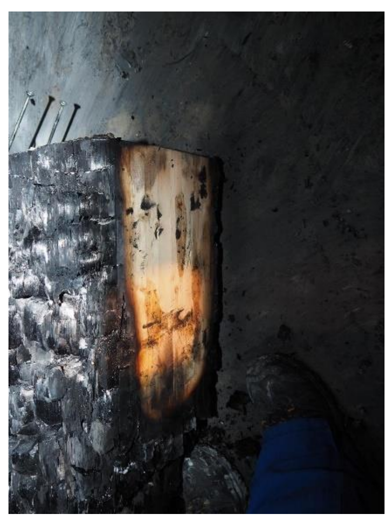


(b) NLT interior (gypsum board removed)

(c) Glulam beam and column

(d) bottom portion of Glulam column

(e) an end surface of Glulam beam



(f) another end surface of Glulam beam

Figure 21. Photograph of mass timber elements after Test NLT-1.

Figure 22. A Resistograph drill used to determine NLT char depth after the test.

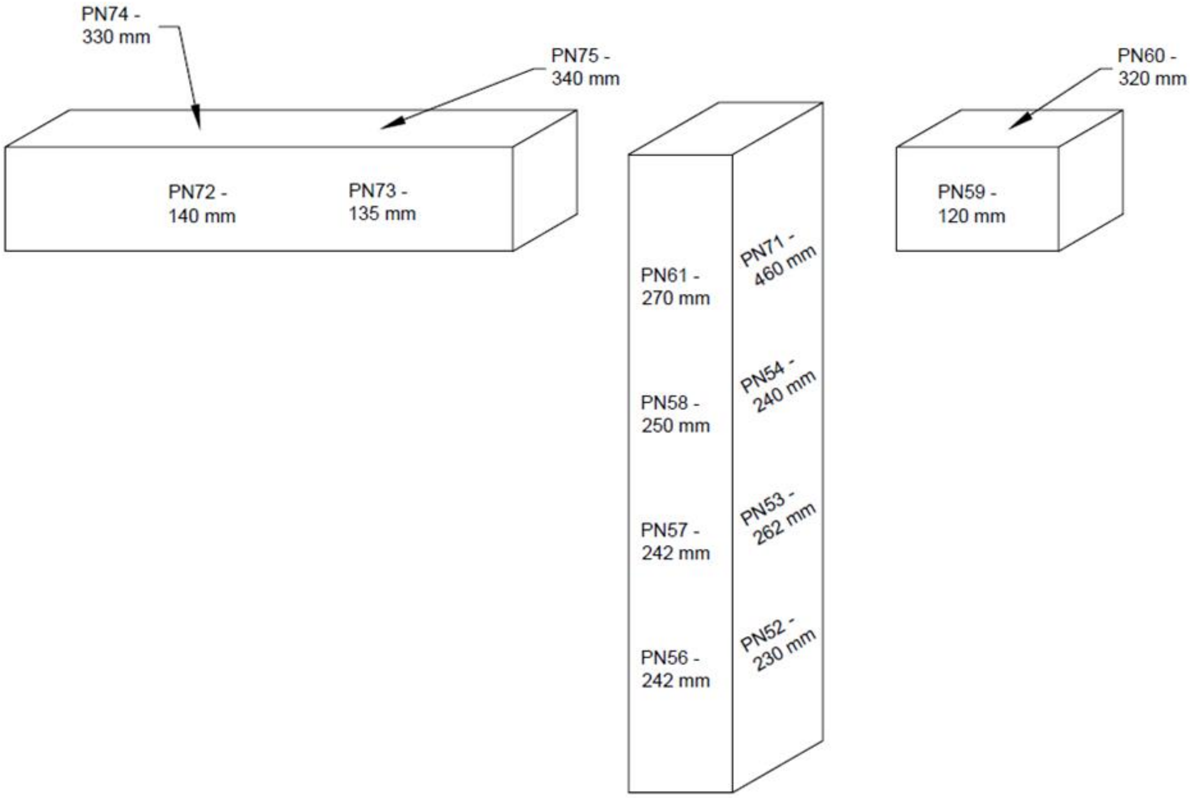


Figure 23. Sampling for remaining depth of Glulam beam and column after Test NLT-1.

Table 5 lists the total char depths measured for the NLT panels. Imagining the room as a cardboard box, Table 5 represents the unfolded cardboard box for an interior view of the charred NLT surfaces in the room. The positions of the char depth values in the table also illustrate the sampling locations for the char measurement on the walls and ceiling. The NLT ceiling panels had very little char in the NLT-Glulam contacting surface. In other area of the ceiling, the NLT panels charred 94-124 mm. The NLT wall panels had char of 55-92 mm on Walls A, B and D.

Table 5. Total char depth (mm) of NLT panels in Test NLT-1.

					Ceiling						
				9*	**121**	**109**	**109**				
				9*	**124**	**119**	**99**				
				9*	**119**	**114**	**94**				
				9*	**121**	**117**	**109**				
53	55			74	59	63	55			-	43
40	35	57	58	75	64	65	58	85	64	-	50
23	50	58	58	61	75	80	60	74	64	-	33
40	58			69	92	83	57			-	28
1/2 Wall C		Wall D			Wall A			Wall B		1/2 Wall C	

red numbers indicating unprotected NLT surfaces.
**: area shielded by the beam and column.*

Using data from **Table 4** (time to reach 300°C in NLT), the char front inside NLT is plotted versus time in **Figure 24**, assuming that NLT started to char at 300 °C. The plots show that the char rate generally slowed down with the increasing char depth, which acted as a thermal barrier against the advance of the char front. For the exposed ceiling, the NLT char rate was changed from 0.82 mm/min initially to 0.14 mm/min as the char front moved deeper. For the wall assemblies with the gypsum board protection, the char rate was approximately 0.26 mm/min.

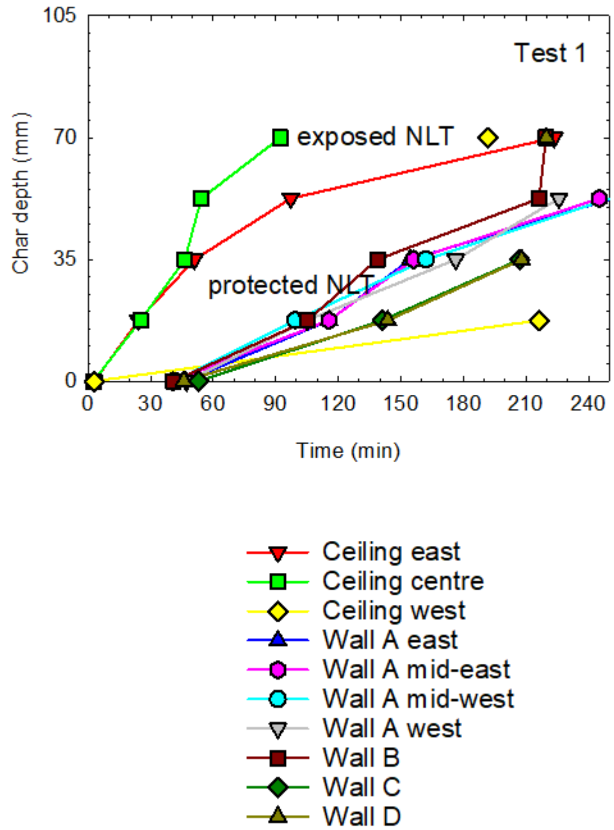


Figure 24. NLT char depth versus time in Test NLT-1.

3.1.5 Comparison of Test NLT-1 to Test CLT-4

Compared with the previous series of CLT room fire tests (with the second generation CLT panels) [4], Test NLT-1 had the same experimental configuration as Test CLT-4, except that NLT was used for the room structure in the current test series. It is important to note the lumber elements in the NLT panels were not as tightly fitted as the CLT panels, since the NLT had small gaps between laminations. These small gaps between the NLT laminations could provide passages for the flame and hot pyrolysis gas to travel.

Figure 25 and **Table 6** compare the results from the two tests. While the fire was completely self-extinguished in Test CLT-4, the NLT wall panels in Test NLT-1 continued to char behind the gypsum board with flames through gypsum board cracks and joints keeping the room hot. The char was much deeper in NLT panels than in CLT panels. During both tests, two layers of gypsum board remained on the walls; the times to reach 300°C at their interfaces were similar. The experimental results indicated that, in term of limiting mass timber contribution to the compartment fire, CLT performed better than NLT in this test arrangement primarily due to the tighter fitting lumber elements in the CLT compared to NLT lumber elements with small gaps.

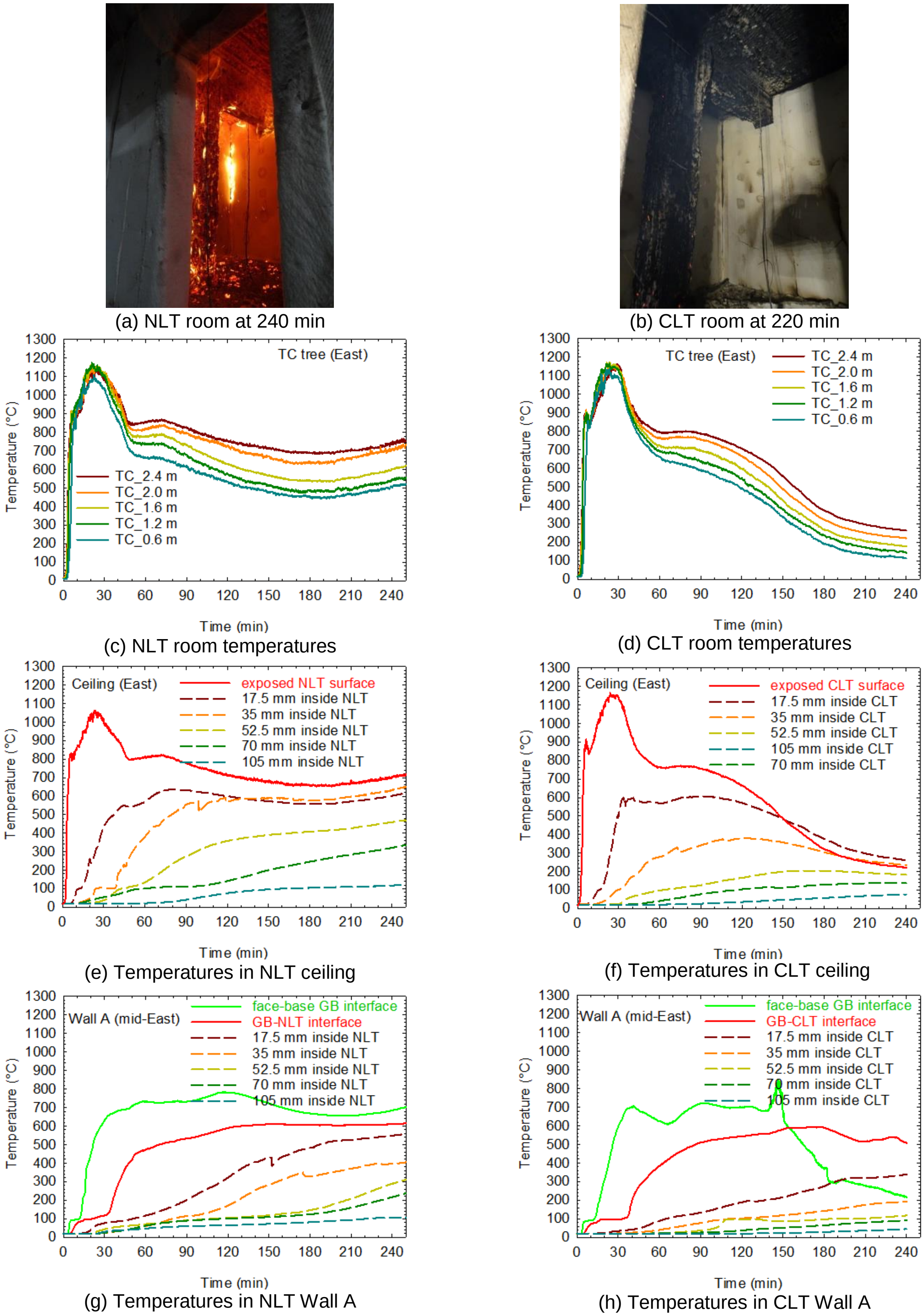


Figure 25. Comparison of Test NLT-1 and Test CLT-4.

Table 6. Comparison of Test NLT-1 to Test CLT-4.

Component / Result	Test NLT-1	Test CLT-4
Ceiling	**exposed** NLT	**exposed** CLT
Glulam Beam & Column	**exposed**	**exposed**
Gypsum board performance	2GB on walls	2GB on walls
face layer 300°C@back (min)	16-23	15-25
base layer 300°C@back (min)	40-53	44-66
face layer falloff (min)	Nfo	Nfo
base layer falloff (min)	Nfo	Nfo
Test duration (min)	251	240
Wall A char (mm)	55-92	17-45
Wall B char (mm)	64-85	25-35
Wall C char (mm)	23-58	34-40
Wall D char (mm)	57-58	24-38
Ceiling char (mm)	94-124	47-66
Glulam char from each exposed side of beam (mm)	94-137	63-82
Glulam char from each exposed side of column (mm)	94-114	62-94

2GB: two layers of 12.7 mm (½") thick Type X gypsum board lining
Nfo: no fall-off

3.2 Test NLT-2

Test NLT-2 was conducted on February 26th, 2019 with a fully exposed uneven NLT ceiling (alternate 2x8 and 2x10 laminations) and fully exposed Glulam beam and column. The Glulam beam was exposed from three sides with a total exposed surface area of 2.46 m^2; the Glulam column was exposed from four sides with a total exposed surface area of 4.81 m^2. The combined exposed surface area of the beam and column was equal to 19% of the perimeter walls. The NLT walls (2x6 laminations) were all lined with two layers of 12.7 mm (1/2 in.) thick Type X gypsum board. **Figure 26** is a photograph of the test compartment before Test NLT-2. Except for the uneven ceiling, Test NLT-2 was essentially the same as Test NLT-1 in the experimental configuration.

Figure 26. Fully exposed uneven NLT ceiling, Glulam beam and column for Test NLT-2.

Figure 27 shows some photographs of the mass timber room during the fire test. Test NLT-2 started with ignition of the middle crib. The fire ignited the ceiling at 2.5 min. Flame started to come out from the top of the doorway opening at 3.0 min, followed by large fire plume issuing from the doorway opening. Flashover occurred at 3.9 min. By 40 min, the fire plume from the opening reduced significantly and the interior of the room became visible. Char was observed to have formed on the NLT ceiling and Glulam beam and column with reduced burning as time elapsed; the flame on the NLT ceiling surface was less than on the Glulam beam and column. The fire plume ceased to issue from the opening at 120 min; the flame on the NLT ceiling were self-extinguished with flame remaining only along the edges of Glulam beam and column and some gypsum board joints and cracks. At 180 min and afterwards, only a few small flames remained on the Glulam surface and joint with gypsum board. The test was terminated at 240 min. At the end of the test, two layers of gypsum board were still on the walls although some cracks existed. At 241 min, water spay was applied to extinguish the remaining small flames.


(a) at 30 min


(b) at 60 min


(c) at 90 min


(d) at 120 min


(e) at 150 min


(f) at 180 min


(e) at 210 min


(f) at 240 min

Figure 27. Fully exposed ceiling, beam and column in mass timber room during Test NLT-2.

3.2.1 Room temperatures

Figure 28 shows temperatures in the room during Test NLT-4, measured using thermocouple (TC) trees with thermocouples at 0.6 m, 1.2 m, 1.6 m, 2.0 m and 2.4 m heights. The room temperatures reached a peak of 1170 °C during the fully developed stage then started to decrease at 30 min. The room temperatures decreased to below 800 °C at 50 min. In the period of 50 min to 80 min, the room temperatures increased again because the protected NLT wall panels started to char behind the gypsum board, causing flaming to occur at cracks and some joints in the gypsum board which contributed heat to the room. In the period of 80 min to 200 min, the room temperatures resumed declining. Afterwards, the room temperatures stayed at the same levels until the end of the test.

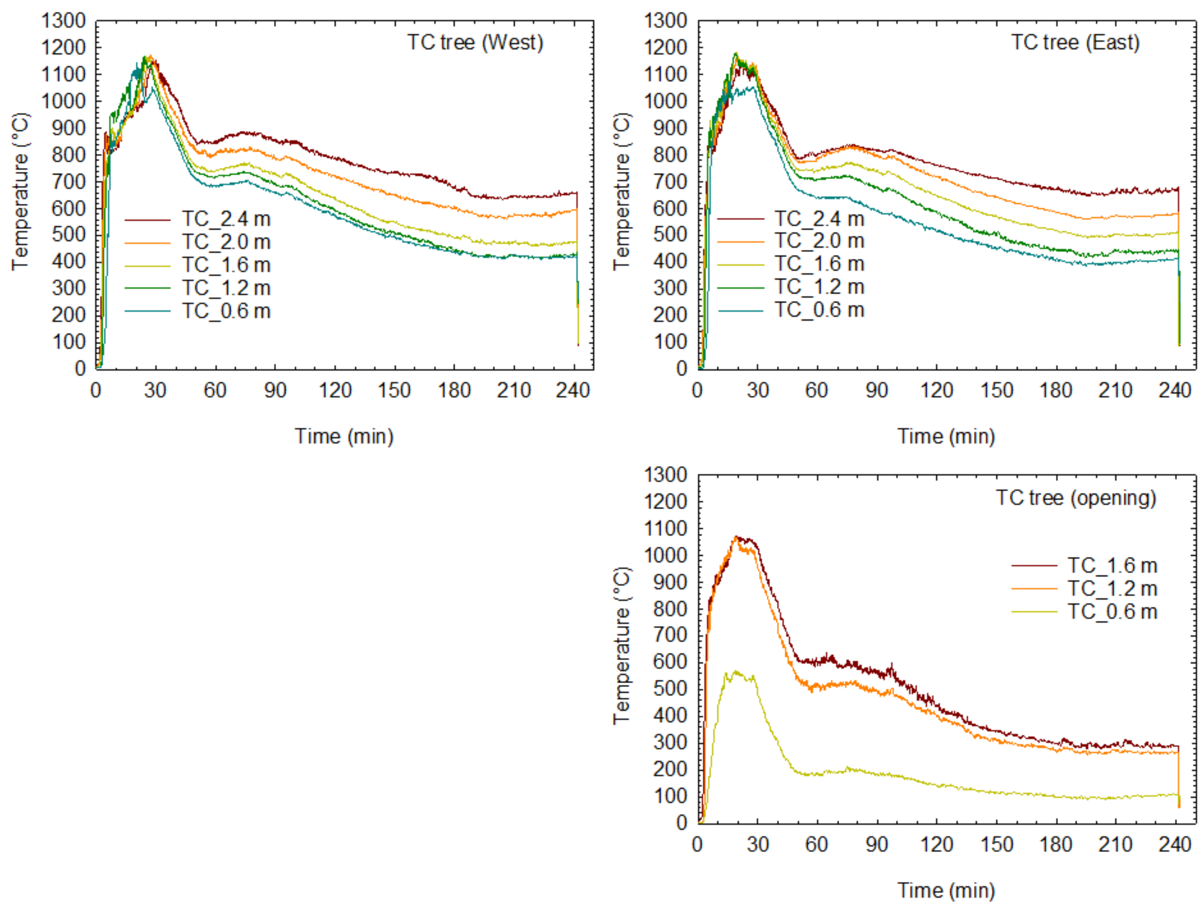


Figure 28. Room temperatures during Test NLT-2.

3.2.2 Temperatures at gypsum board interfaces and inside NLT panels

Figure 29 to **Figure 31** show the temperatures measured at the NLT surfaces, interfaces between gypsum board layers and inside NLT panels. **Table 7** shows the timing when the embedded thermocouples measured 300 °C in NLT assemblies, which is the typical temperature used as an indication that the wood has begun to char and therefore used as a criteria for determining the char front as it progresses through the wood.

Based on the timing when the embedded thermocouples in the NLT ceiling measured 300 °C, the char front reached 17.5 mm deep at 22-33 min and 35 mm deep at 76-116 min; the char front only reached 52.5 mm deep at two of the three measurement positions at 133-141 min.

All NLT wall assemblies were protected using gypsum board. The heat transfer through the gypsum board followed the typical three-stage pattern as indicated by the temperature profiles at the interfaces. The temperatures at the gypsum board base layer and NLT interface reached 300 °C at 40-56 min and increased to a maximum of 600 °C at the end of the test. This indicated that the NLT panels started charring behind the base layer gypsum board in the walls, causing flaming to occur at cracks and joints in the gypsum board. This contributed to the temporary increase in the room temperatures around 50 min and relatively high room temperature afterwards, as shown in **Figure 28**.

Table 7. Time (min) to reach 300°C at gypsum board interfaces and inside NLT in Test NLT-2.

NLT panel	Gypsum board (GB) layer interface or NLT depth (mm)						
	GB face/base	0	17.5	35	52.5	70	105
Ceiling east	i.n.	3.33	29.67	115.92	-	-	-
Ceiling centre	i.n.	2.75	22.42	88.83	132.92	-	-
Ceiling west	i.n.	2.83	32.92	75.92	140.83	-	-
Wall A east	17.83	42.42	118.58	185.25	-	-	-
Wall A mid-east	17.26	42.50	117.33	223.08	-	-	-
Wall A mid-west	17.50	56.50	157.92	229.25	-	-	-
Wall A west	23.33	50.50	119.42	202.92	-	-	-
Wall B	19.67	40.17	110.42	188.25	-		-
Wall C	19.08	51.08	123.67	-	-	-	-
Wall D	21.25	43.00	124.25	174.92	-	-	-

-: did not reach 300°C during the test.

i.n.: interface did not exist.

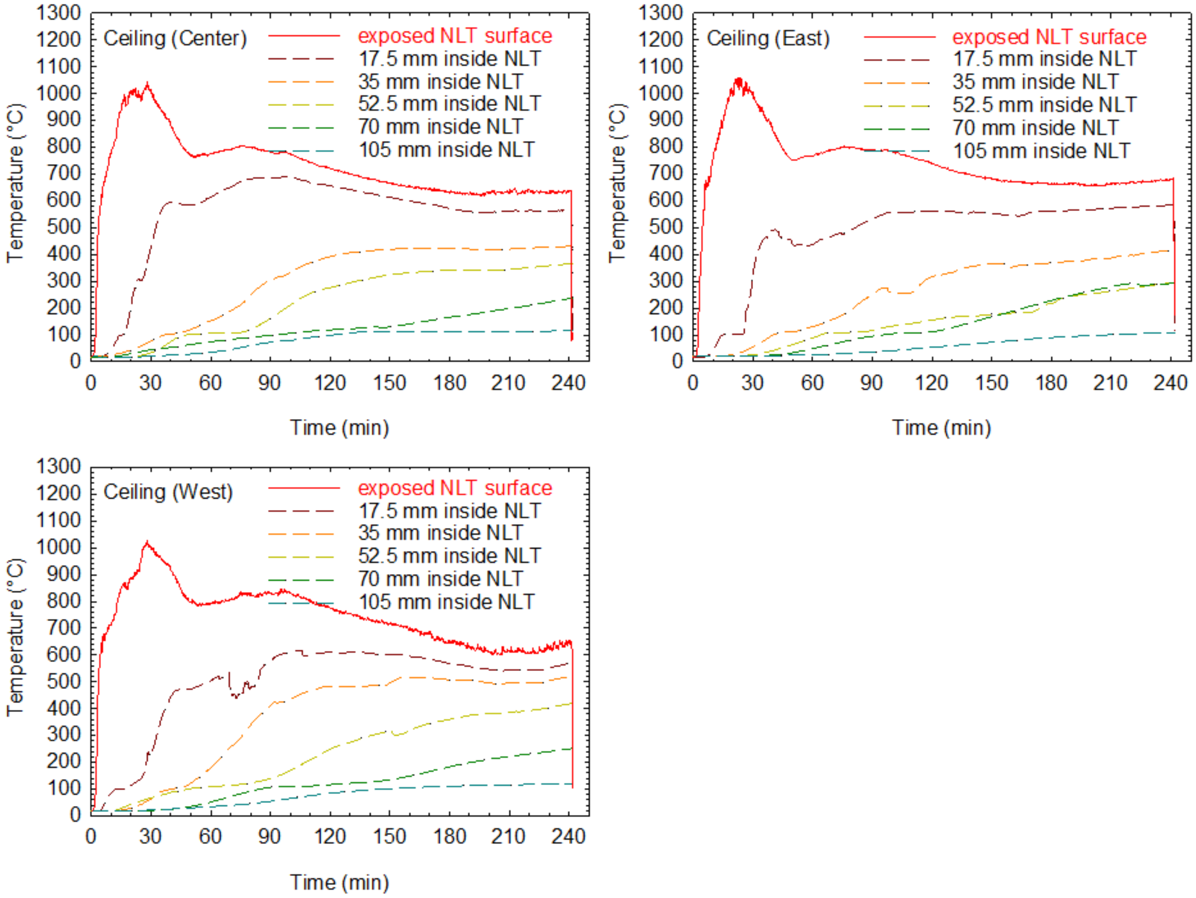


Figure 29. Temperatures in NLT ceiling panels in Test NLT-2.

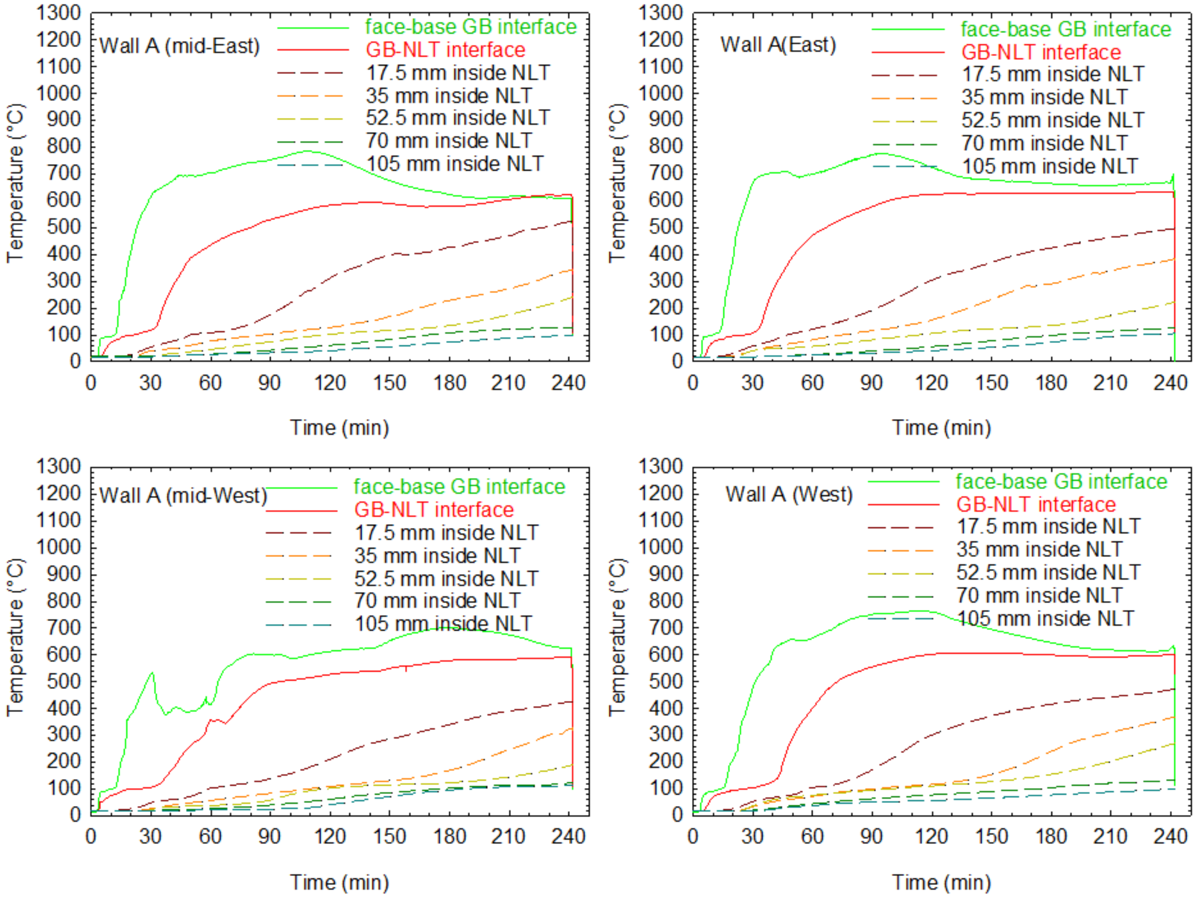


Figure 30. Temperatures in NLT and at gypsum board interfaces for Wall A in Test NLT-2.

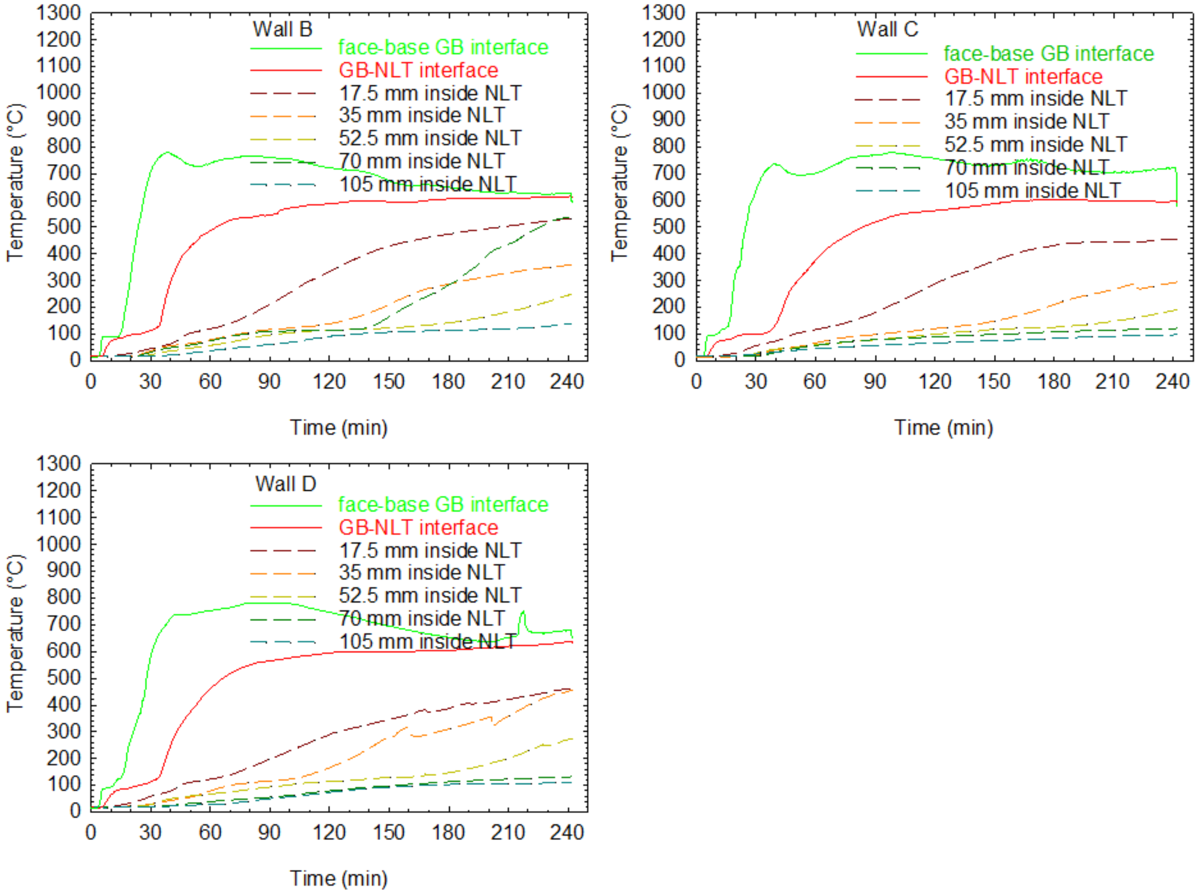


Figure 31. Temperatures in NLT and at gypsum board interfaces for Walls B, C and D in Test NLT-2.

3.2.3 Heat release rate

Figure 32 shows the heat release rate (HRR) during Test NLT-2, presenting the values of 1-min running averages. The HRR was 4.2 MW at the initial peak after the flashover (the peak value could have been slightly higher as a small portion of the smoke overflowed the collection hood at 20 min for a short while). As the fire decayed, the HRR reduced to 1.1 MW at 50 min. In the period of 60 min to 80 min, the HRR increased slightly to 1.2 MW due to the protected walls charring behind the gypsum board with flaming from the gypsum-board cracks and joints. Afterwards, the HRR resumed the declining trend. The HRR was below 0.5 MW at the end of the test.

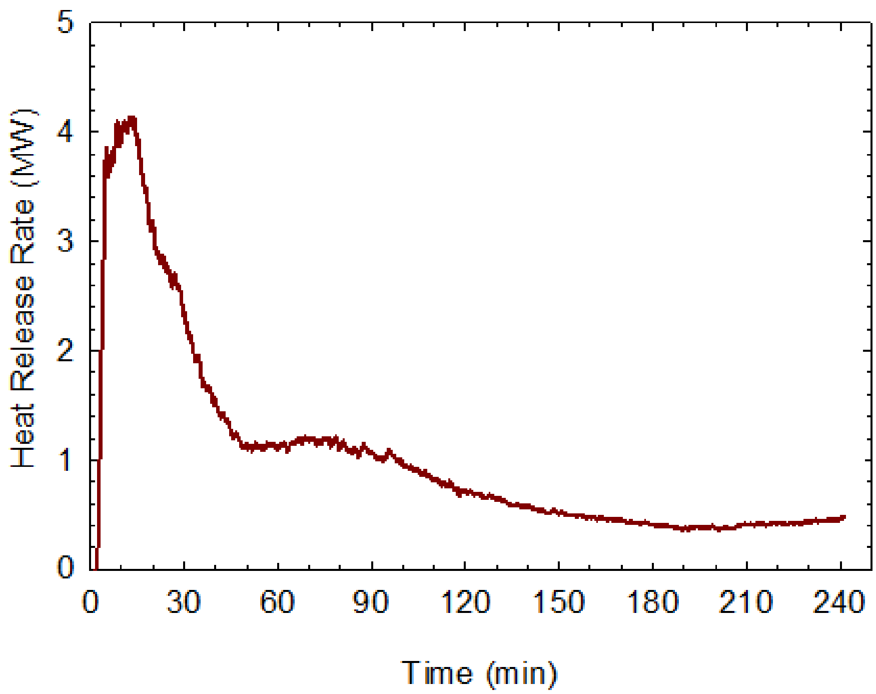


Figure 32. Heat release rate in Test NLT-2.

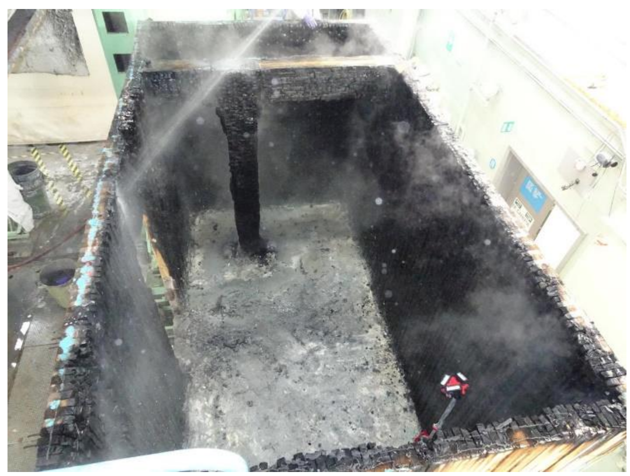
3.2.4 Char of Glulam beam and column as well as NLT panels

After Test NLT-2, the Glulam beam and column and NLT panels were examined for char. **Figure 33** shows photographs of the NLT and Glulam elements after Test NLT-2. A total of 70 sampling locations were drilled through for char depth measurements using the Resistograph.

(a) NLT ceiling part with area contacting Glulam

(b) top surface of Glulam beam and column

(c) NLT wall exterior (gypsum board removed)



(d) NLT wall interior (gypsum board removed)

Figure 33. Photograph of mass timber elements after Test NLT-2.

Figure 34 shows the sampling locations and remaining depths of the Glulam beam and column after the fire test. Given the original cross section of 327 mm x 457 mm for the three-side exposed beam and 457 mm x 457 mm for the four-side exposed column, the char depth was in a range of 84 mm to 135 mm for each exposed side of the Glulam in four hours, translating to a char rate of 0.35 to 0.56 mm/min.

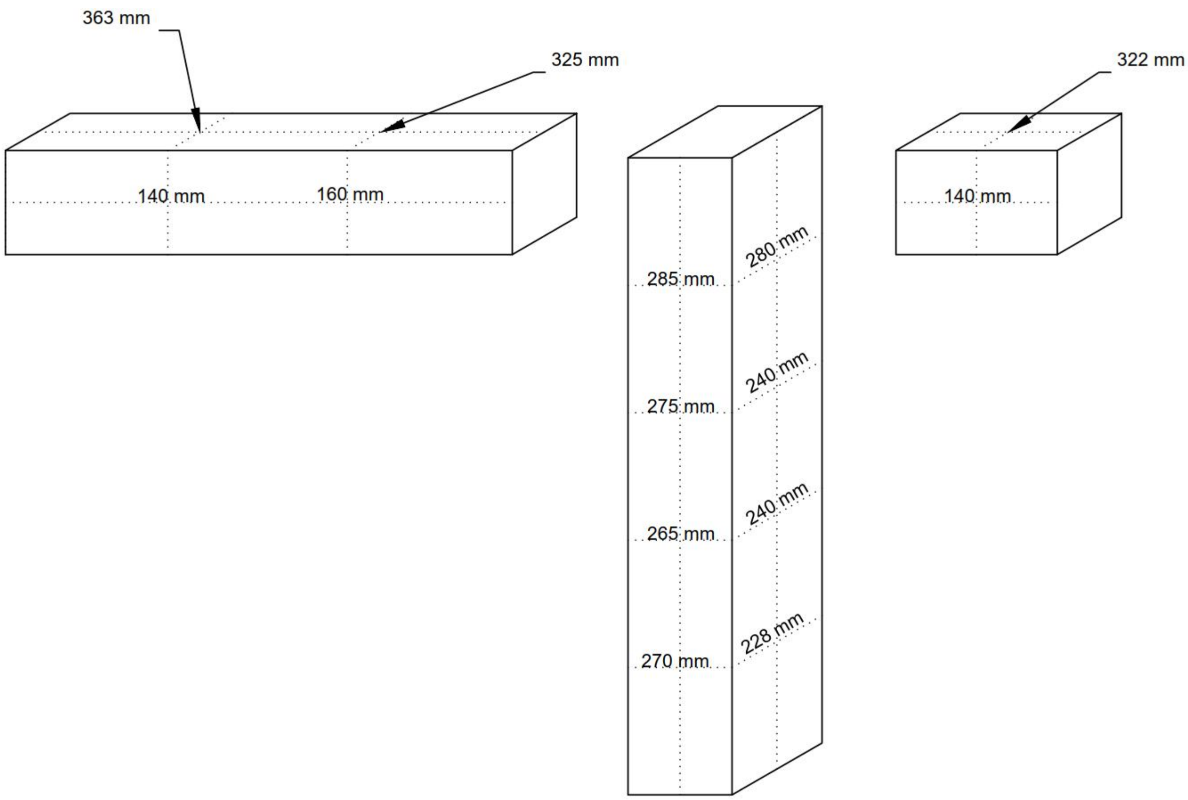


Figure 34. Sampling for remaining depth of Glulam beam and column after Test NLT-2.

Table 8 lists the total char depths measured for the NLT panels. Imagining the room as a cardboard box, **Table 8** represents the unfolded cardboard box for an interior view of the charred NLT surfaces in the room. The positions of the char depth values in the table also illustrate the sampling locations for the char measurement on the walls and ceiling.

As shown in **Figure 33**, the NLT ceiling panels had no char in the NLT-Glulam contacting surface. In other area of the ceiling, the NLT panels charred 69-107 mm in the 2x8 laminations and 120-138 mm in the 2x10 lamination, respectively. The NLT wall panels had char of 44-80 mm on Walls A, B and D. Using data from **Table 7** (time to reach 300°C in NLT), the char front inside NLT is plotted versus time in **Figure 35**, assuming that NLT started to char at 300 °C. The plots show that the char rate generally slowed down with the increasing char depth, which acted as a thermal barrier against the advance of the char front. For the exposed ceiling, the NLT char rate was changed from 0.8 mm/min initially to 0.3 mm/min as the char front moved deeper. For the wall assemblies with the gypsum board protection, the NLT char rate was approximately 0.24 mm/min.

Table 8. Total char depth (mm) of NLT panels in Test NLT-2.

Ceiling

94	107	133*	72
99	104	138*	69
89	87	125*	74
74	107	120*	94

1/2 Wall C		Wall D		Wall A				Wall B		1/2 Wall C	
53	53			50	55	59	44			47	35
73	55	80	54	70	47	50	60	61	55	33	53
63	50	65	53	55	50	44	48	60	50	45	35
34	55			63	50	44	54			45	35

red numbers indicating unprotected NLT surfaces.
** measured on the ceiling panel along 2x10 lumber (38 mm x 235 mm); others measured on the ceiling panel along 2x8 lumber (38 mm x 184 mm).*

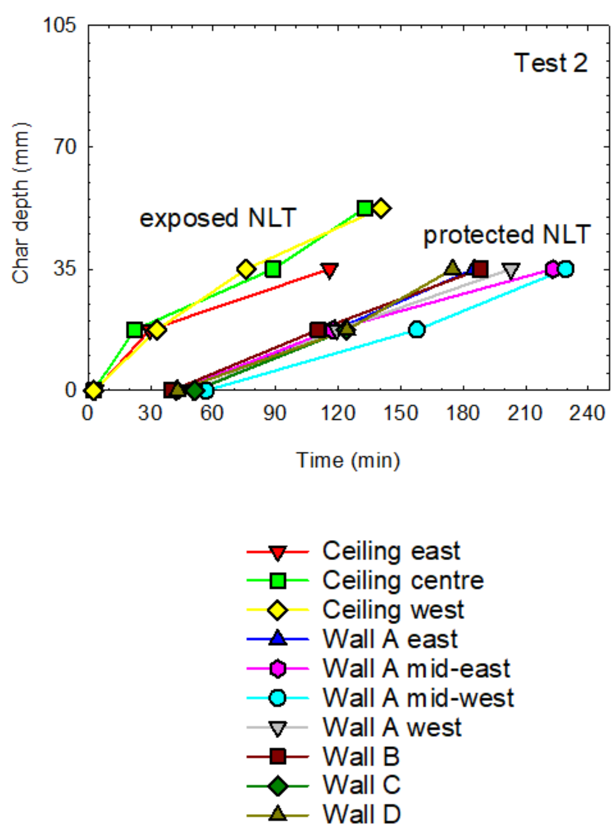


Figure 35. NLT char depth versus time in Test NLT-2.

3.2.5 Comparison of Test NLT-2 to Test NLT-1 and Test CLT-4

Table 9 and **Figure 36** compare the results from Test NLT-1, Test NLT-2 and Test CLT-4. These three tests had essentially the same configuration with the exposed ceiling, column and beam, and protected walls. During these three tests, two layers of gypsum board remained on the walls; the times to reach 300°C at their interfaces were similar. Test NLT-2 used the uneven NLT ceiling while Test NLT-1 had the even ceiling. In general, the two tests produced similar fire performance. However, the difference in the NLT ceiling construction did result in a slightly better performance in Test NLT-2 with a lower HRR, lower room and interface temperatures, less char depths and smaller remaining flames at the end of the testing than in Test NLT-1.

Compared with Test CLT-4 where the fire was completely self-extinguished, Test NLT-1 and Test NLT-2 had the protected NLT wall panels continuously charring behind the gypsum board with flames through some gypsum board cracks and joints. The char was much deeper in the NLT tests than in the CLT test. The test results also indicated that, in terms of reducing timber contribution to the fire, CLT performed better than NLT in this test configuration as the lumber elements in the NLT panels were not as tightly fitted as the lumber in the CLT panels. The NLT tests showed the issues of continued charring of the protected NLT walls behind the gypsum board, which prevented fire decaying to the full extent as in Test CLT-4. In this specific scenario with the full ceiling exposed, the two layers of gypsum board protection appeared to be insufficient to limit the contribution of the protected NLT walls to the fire.

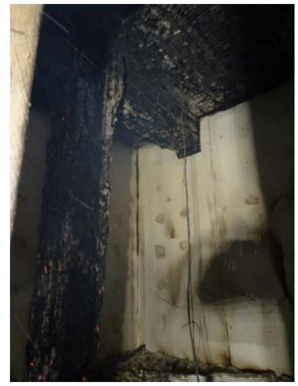
Table 9. Comparison of Test NLT-2 to Test NLT-1 and Test CLT-4.

Component / Result	Test NLT-1	Test NLT-2	Test CLT-4
Ceiling	**exposed** NLT	**exposed** uneven NLT	**exposed** CLT
Glulam Beam & Column	**exposed**	**exposed**	**exposed**
Gypsum board performance	2GB on walls	2GB on walls	2GB on walls
face layer 300°C@back (min)	16-23	17-23	15-25
base layer 300°C@back (min)	40-53	40-56	44-66
face layer falloff (min)	Nfo	Nfo	Nfo
base layer falloff (min)	Nfo	Nfo	Nfo
Test duration (min)	251	241	240
Wall A char (mm)	55-92	44-70	17-45
Wall B char (mm)	64-85	50-61	25-35
Wall C char (mm)	23-58	33-73	34-40
Wall D char (mm)	57-58	53-80	24-38
Ceiling char (mm)	94-124	69-107 †	47-66
Glulam char from each exposed side of beam (mm)	94-137	84-135	63-82
Glulam char from each exposed side of column (mm)	94-114	86-114	62-94

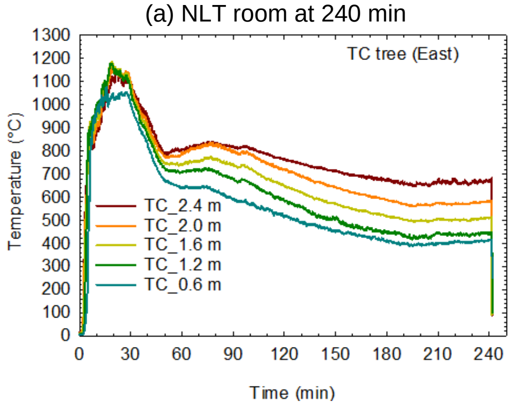
2GB: two layers of 12.7 mm (½") thick Type X gypsum board lining

Nfo: no fall-off *† measured on the 2 x 8 laminations (38 mm x 184 mm lumber)*

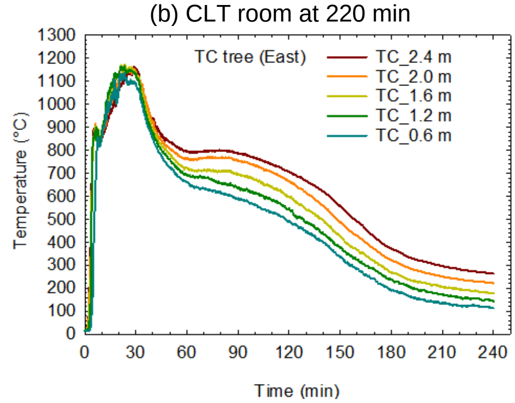
(a) NLT room at 240 min



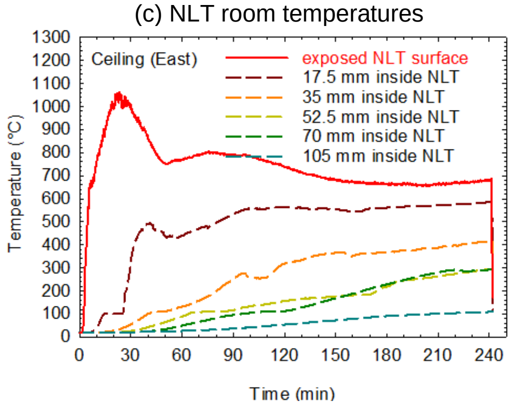
(b) CLT room at 220 min



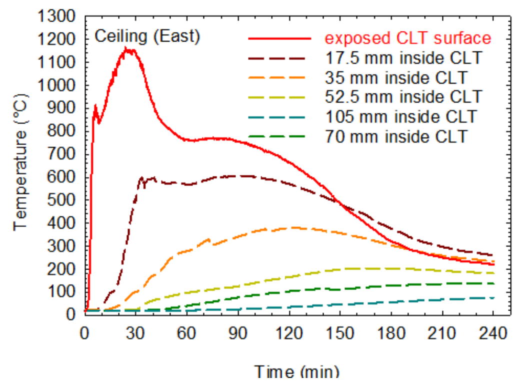
(c) NLT room temperatures



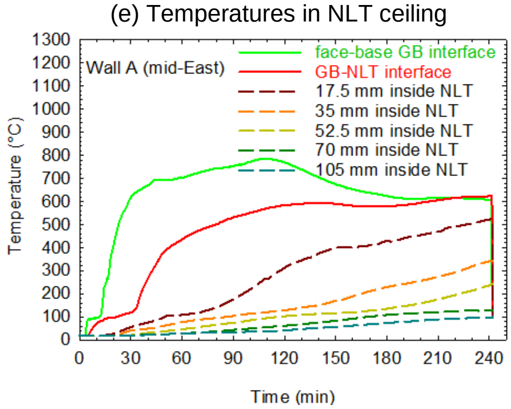
(d) CLT room temperatures



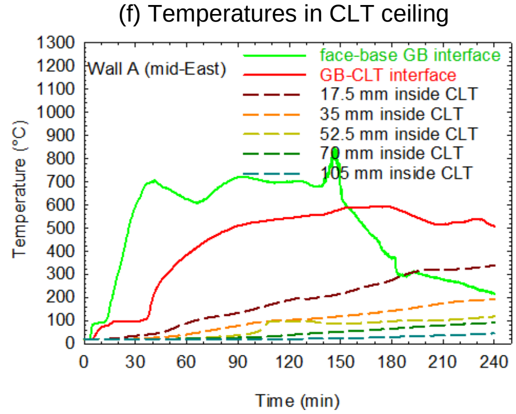
(e) Temperatures in NLT ceiling



(f) Temperatures in CLT ceiling



(g) Temperatures in NLT Wall A



(h) Temperatures in CLT Wall A

Figure 36. Comparison of Test NLT-2 and Test CLT-4.

3.3 Test NLT-3

Test NLT-3 was conducted on March 14th, 2019 with fully exposed ceiling, Wall B and Wall D (2x8 laminations). Wall A and Wall C (2x6 laminations) were lined with two layers of 12.7 mm (1/2 in.) thick Type X gypsum board. **Figure 37** shows photographs of the NLT compartment before Test NLT-3.

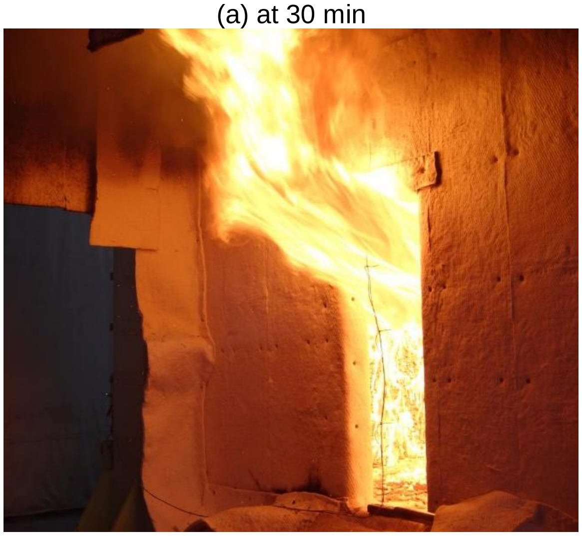
(a) view of exposed Wall B and ceiling (b) view of exposed Wall D and ceiling

Figure 37. Fully exposed NLT ceiling, Wall B and Wall D for Test NLT-3.

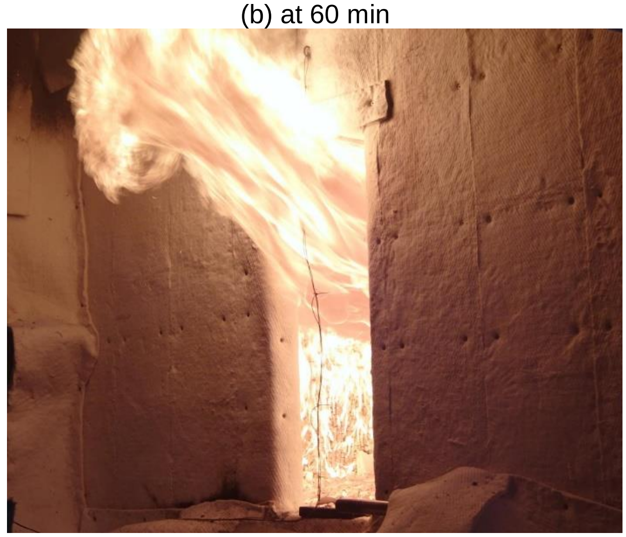
Figure 38 shows photographs of the NLT room during Test NLT-3. The test started with ignition of the middle crib, which ignited the ceiling at 2.5 min. Flame started to come out from the top of the doorway opening at 2.7 min, followed by large fire plume issuing from the doorway opening. Flashover occurred at 3.2 min. After 30 min, the wood cribs reduced to debris on the floor and the fire plume reduced by size, issuing only from the upper portion of the opening. The interior of the room became visible. The exposed ceiling, Wall B and Wall D was visibly burning vigorously. The face layer gypsum board on Wall A was observed to start falling off the west bottom section at 33.4 min. As time elapsed, more locations lost the face layer gypsum board, exposing the base layer gypsum board. The base layer gypsum board on Wall A was observed to crack at some spots with flames coming out through the cracks, indicating NLT burning behind the gypsum board. At 105 min, a large portion of the base layer gypsum board was observed to fall off, directly exposing the NLT panels on Wall A. More sections of the base layer gypsum board fell off soon after. Just like a relay race, as the exposed NLT panels weakening their contribution, the protected Wall A and Wall C increased their contribution to the fire. With the full involvement of Wall A and Wall C, the fire further intensified. It was decided to terminate the test by fire suppression after 120 min.

(a) at 30 min

(b) at 60 min



(c) at 90 min



(d) at 120 min

Figure 38. NLT room during Test NLT-3.

3.3.1 Room temperatures

Figure 39 shows temperatures in the room during Test NLT-3, measured using thermocouple (TC) trees with thermocouples at 0.6 m, 1.2 m, 1.6 m, 2.0 m and 2.4 m heights. The room temperatures reached a peak of 1200 °C during the fully developed stage then started to decrease slightly at 30 min. The average room temperature stayed above 1000 °C for the rest of the test duration. This is due to the fact that in addition to the exposed NLT surfaces, the NLT panels in the protected Wall A and Wall C charred behind the gypsum board and progressively contributed to the fire to the full extent after the fall-off of gypsum board.

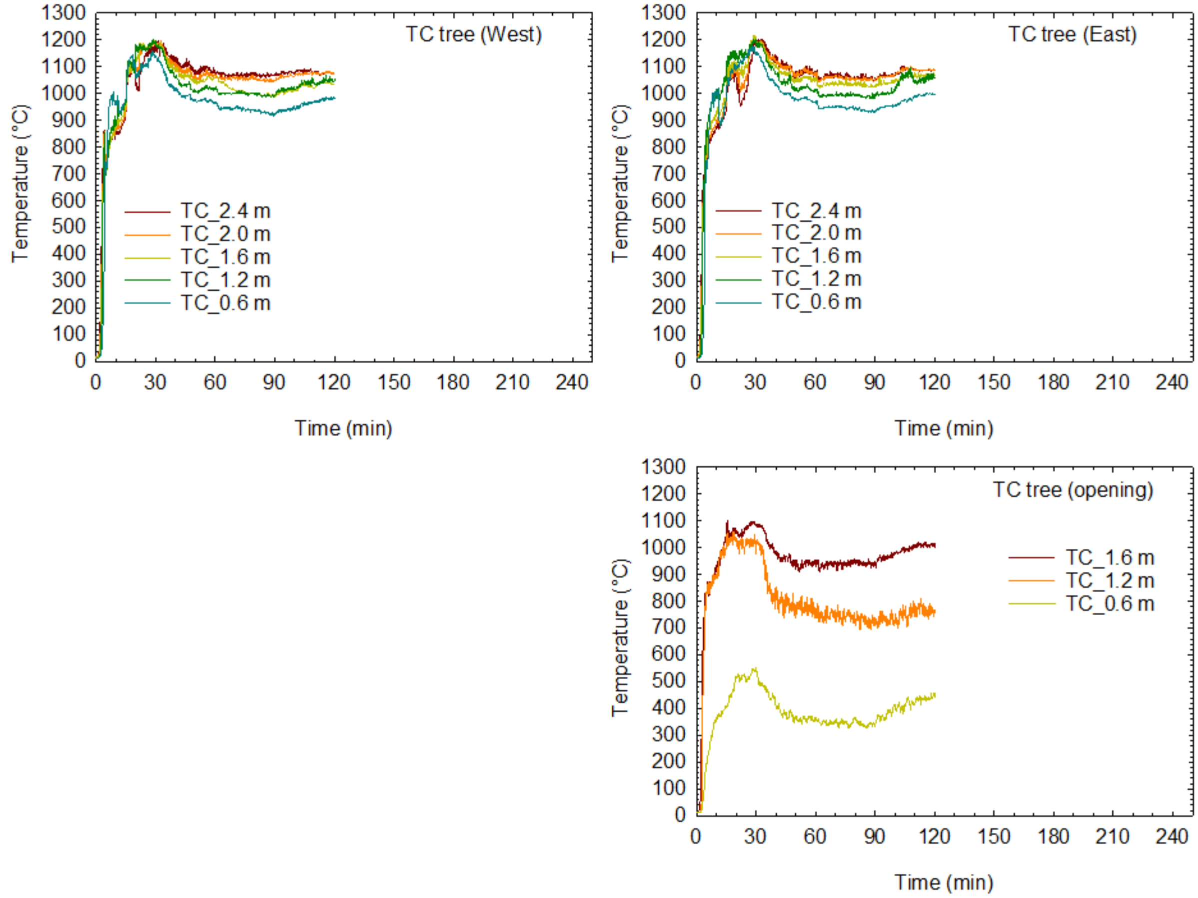


Figure 39. Room temperatures during Test NLT-3.

3.3.2 Temperatures at gypsum board interfaces and inside NLT panels

Figure 40 to **Figure 42** show the temperatures measured at the NLT surfaces, interfaces between gypsum board layers and inside NLT panels. **Table 10** shows the timing when the embedded thermocouples measured 300 °C in NLT assemblies, which is the typical temperature used as an indication that the wood has begun to char and therefore used as a criteria for determining the char front as it progresses through the wood.

Based on the timing when the embedded thermocouples in the exposed NLT assemblies measured 300 °C, the char front reached 17.5 mm at 21-24 min, 35 mm at 27-38 min, 52.5 mm at 58-69 min, and 70 mm at 69-106 min in the ceiling and Wall B and Wall D. The char front also reached 105 mm at 100-112 min in Wall B and Wall D.

Wall A and Wall C were protected using gypsum board. The heat transfer through the gypsum board followed the typical three-stage pattern as indicated by the temperature profiles at the interfaces. The temperatures at the gypsum board base layer and NLT interface reached 300 °C at 41-52 min. This indicated that the NLT panels started charring behind the base layer gypsum board in the walls. Inside the NLT panels, the temperatures reached 300 °C at the 17.5 mm depth at 92-108 min in Wall A and Wall C, and at the 35 mm depth after 108 min at one measurement location in Wall A. As shown in **Figure 41**, the temperatures at the gypsum board interfaces suddenly increased to above 1000 °C, indicating the fall-off of face layer gypsum board at 55-70 min and the fall-off of base layer gypsum board at 90-105 min on Wall A.

Table 10. Time (min) to reach 300°C at gypsum board interfaces and inside NLT in Test NLT-3.

NLT panel	Gypsum board (GB) layer interface or NLT depth (mm)						
	GB face/base	0	17.5	35	52.5	70	105
Ceiling east	i.n.	2.33	24.08	37.33	62.58	83.08	-
Ceiling centre	i.n.	2.33	21.92	27.33	64.08	69.00	-
Ceiling west	i.n.	2.25	22.58	38.33	62.75	78.00	-
Wall A east	23.92	44.92	92.67	108.83	-	-	-
Wall A mid-east	18.17	45.17	95.58	-	-	-	-
Wall A mid-west	19.58	52.42	103.08	-	-	-	-
Wall A west	19.58	49.00	108.33	-	-	-	-
Wall B	i.n.	2.67	24.33	36.42	69.25	95.58	100.67
Wall C	19.00	41.33	102.08	-	-	-	-
Wall D	i.n.	2.58	21.25	31.50	58.33	106.08	112.25

-: did not reach 300°C during the test.
i.n.: interface did not exist.

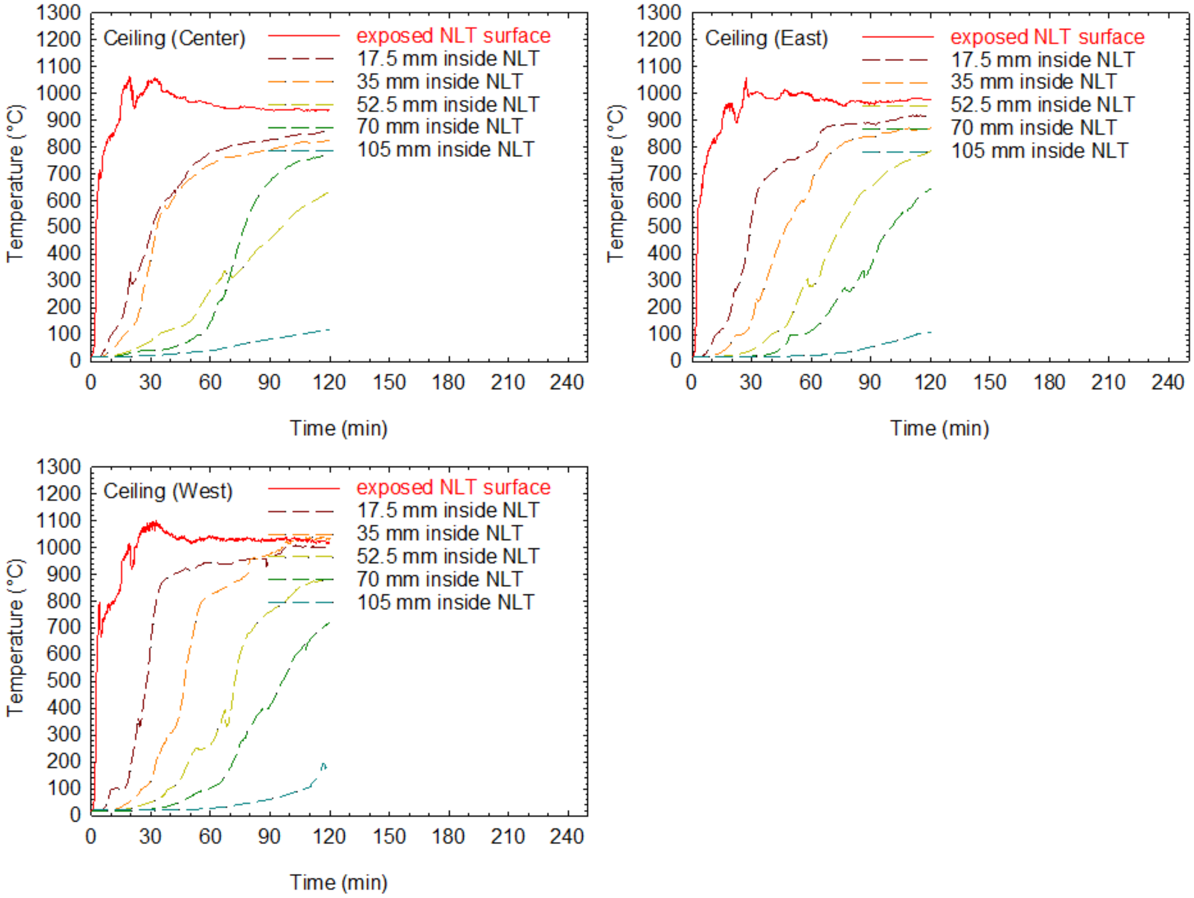


Figure 40. Temperatures in NLT ceiling panels in Test NLT-3.

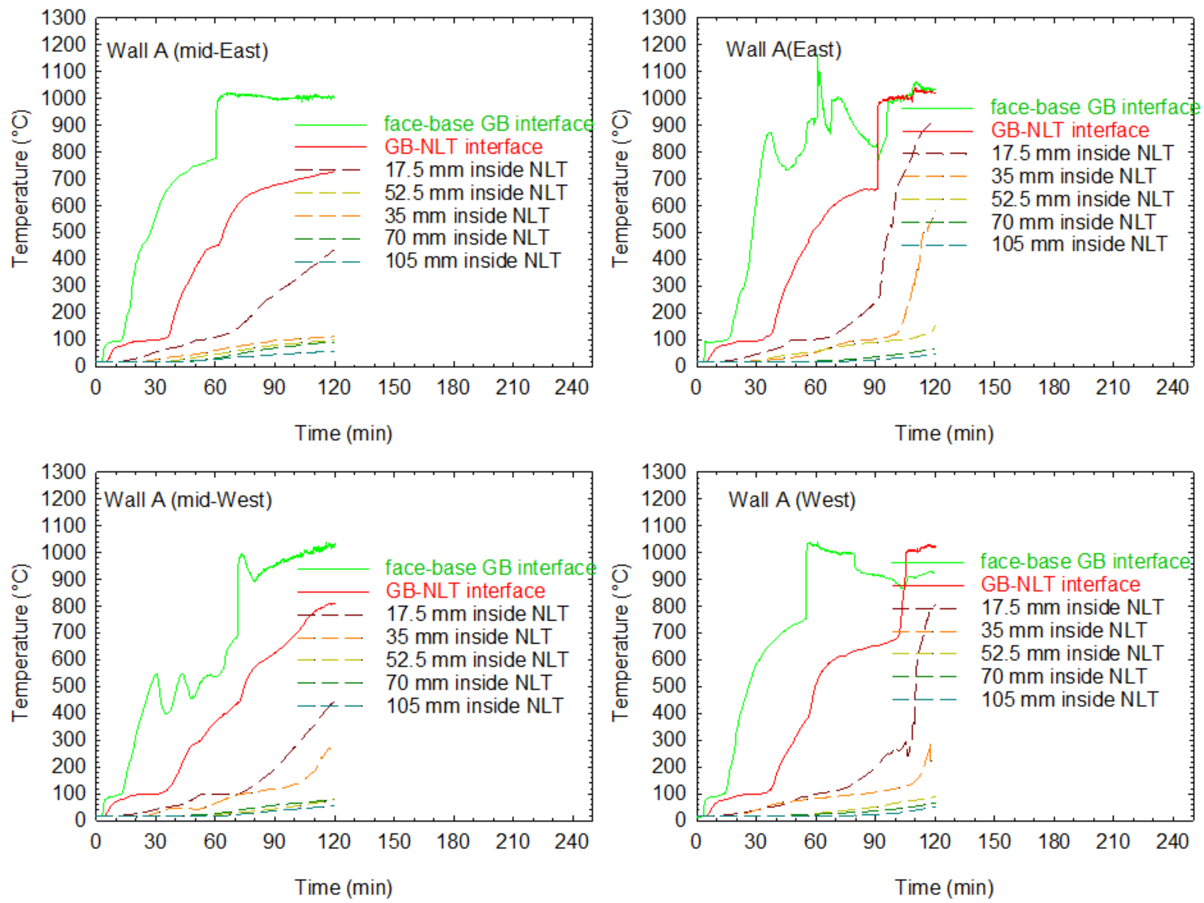


Figure 41. Temperatures in NLT and at gypsum board interfaces for Wall A in Test NLT-3.

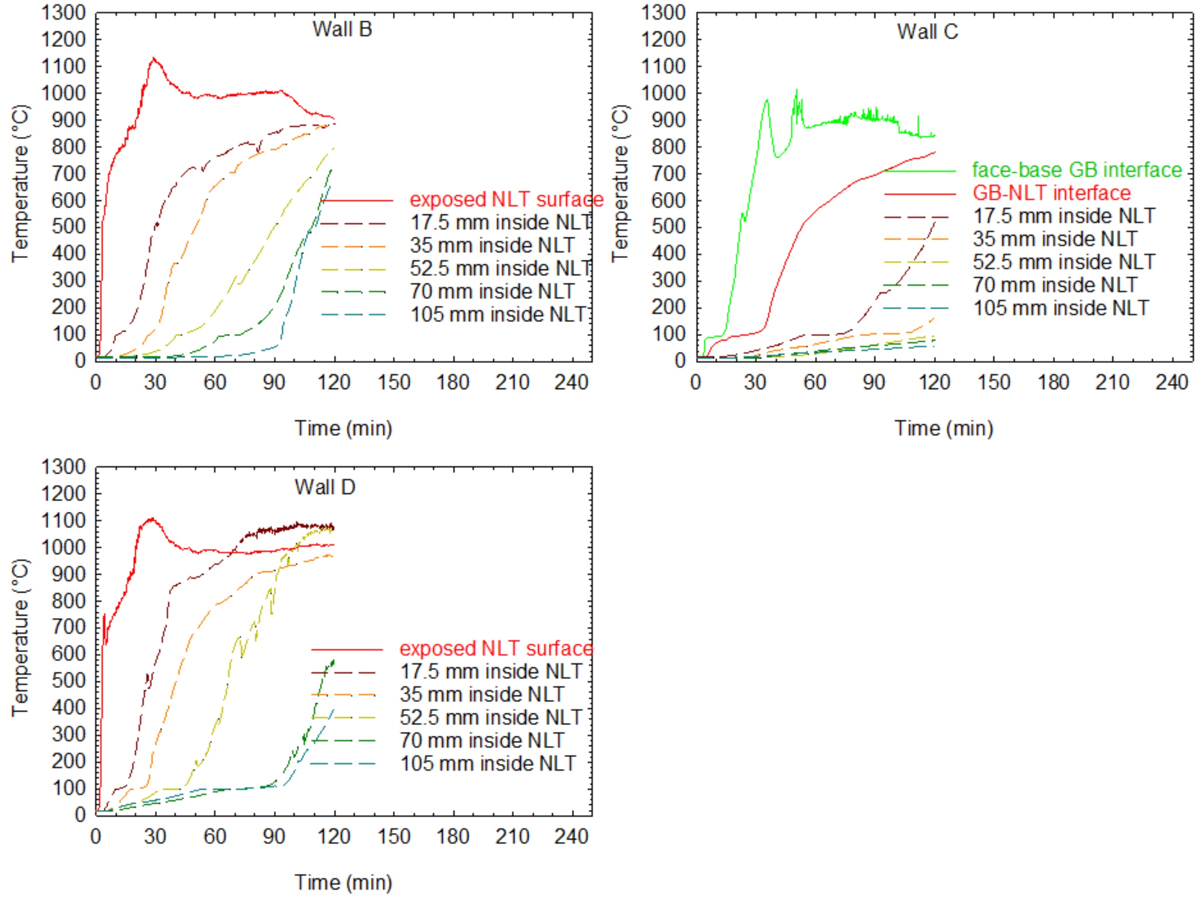


Figure 42. Temperatures in NLT and at gypsum board interfaces for Walls B, C and D in Test NLT-3.

3.3.3 Heat release rate

Figure 43 shows the heat release rate (HRR) during Test NLT-3, presenting the values of 1-min running averages. The HRR was 4.4 MW at the initial peak after the flashover (the peak value could have been slightly higher as a small portion of the smoke overflowed the collection hood at 20 min for a short while). The HRR reduced to 2.2 MW at 40 min and stayed at this level until 90 min. With the falling of the base layer gypsum board from the protected walls, the HRR increased again due to the full involvement of Wall A and Wall C in the fire. The test was terminated by fire suppression as the HRR grew to above 3 MW.

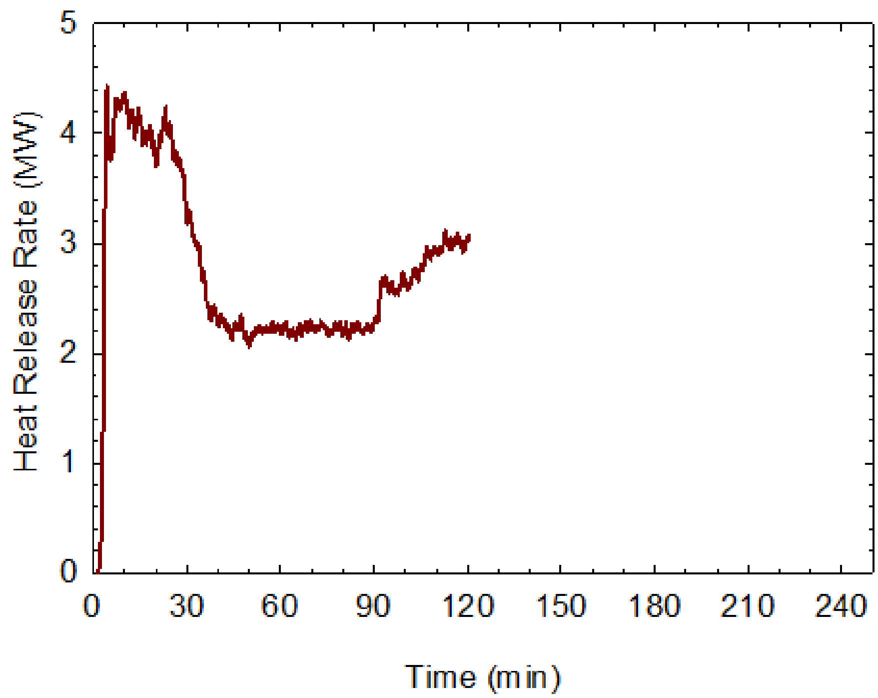


Figure 43. Heat release rate in Test NLT-3.

3.3.4 Char of NLT panels

Using data from **Table 10** (time to reach 300°C in NLT), the char front inside NLT is plotted versus time in **Figure 44**, assuming that NLT started to char at 300 °C. Comparing **Figure 44** to **Figure 24** and **Figure 35**, the NLT char rates in Test NLT-3 were initially similar to those in Test NLT-1 and Test NLT-2 but stayed that high during the test, largely due to the subsequent full participation of the protected walls in the fire. For the exposed NLT panels, the global average char rate in Test NLT-3 at least doubled those in Test NLT-1 and Test NLT-2, resulting in similar total char depth in Test NLT-3 with only half of the time compare to Test NLT-1 and Test NLT-2 (cf. **Table 3**).

After Test NLT-3, the NLT room was examined for char. A total of 56 sampling locations were drilled through for char depth measurements using the Resistograph. **Table 11** lists the total char depths measured for the NLT panels. Imagining the NLT room as a cardboard box, **Table 11** represents the unfolded cardboard box for an interior view of the charred NLT surfaces in the room. The positions of the char depth values in the table also illustrate the sampling locations for the char measurement on the walls and ceiling.

In the exposed ceiling, the NLT panels charred 97-119 mm. In the exposed Wall B and Wall D, the NLT panels charred 102-126 mm and 81-104 mm respectively, with Wall B charred more ceiling panels. In the gypsum board protected Wall A and Wall C, the char depths were 25-60 mm.

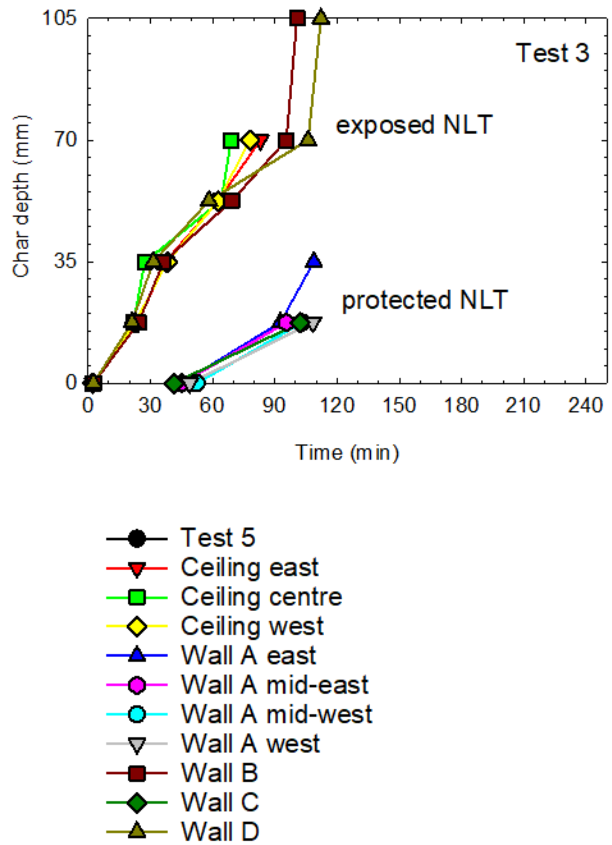


Figure 44. NLT char depth versus time in Test NLT-3.

Table 11. Total char depth (mm) of NLT panels in Test NLT-3.

Ceiling

104	**97**	**99**	**108**
114	**119**	**112**	**109**
107	**109**	**108**	**98**
104	**99**	**106**	**109**

Walls

1/2 Wall C		Wall D		Wall A				Wall B		1/2 Wall C	
23	40			42	45	30	60			35	45
25*	35	**89**	**104**	45	35	25	53	**109**	**102**	36	39*
38*	44	**88**	**81**	47	42	38	55	**126**	**108**	37	18*
25*	34			45	40	47	55			44	25*

red numbers indicating unprotected NLT surfaces.
*: around the rough doorway opening, there was more protection wrapped with two layers of gypsum board and 25 mm thick ceramic fiber insulation.

3.3.5 Comparison of Test NLT-3 to Test CLT-5

Figure 45 and **Table 12** compare the results from Test NLT-3 and previous Test CLT-5. These two tests had essentially the same experimental configuration with the exposed ceiling, two exposed short walls, and two long walls protected with two layers of gypsum board.

During these two tests, the times to reach 300°C at the gypsum board interfaces were essentially the same. However, the gypsum board started to fall off much earlier from the protected Wall A in Test NLT-3 than in Test CLT-5, particularly the face layer gypsum board.

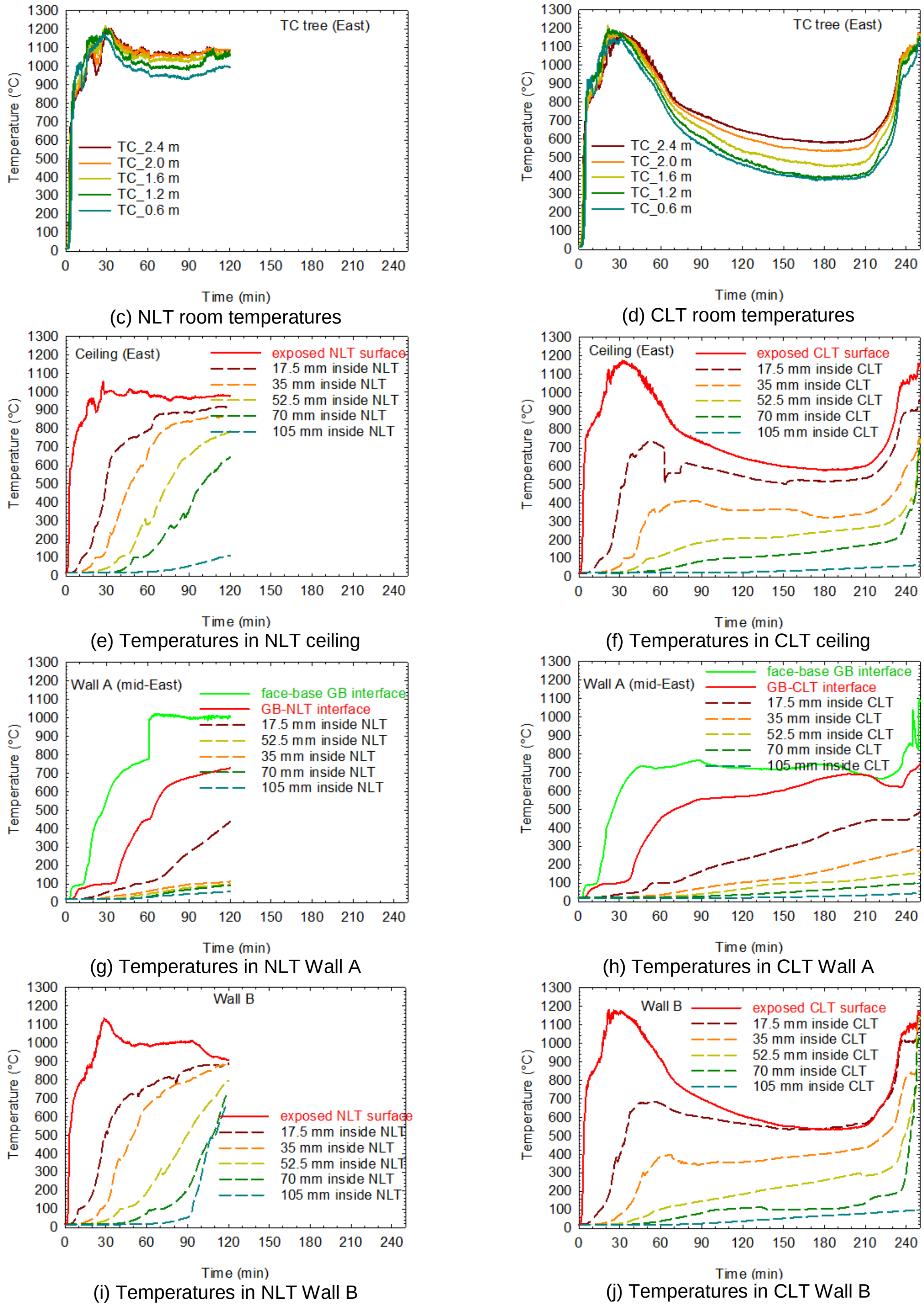
Test NLT-3 had no significant fire decay. Test CLT-5 had a long period of the fire decay stage starting at 30 min until 220 min, during which flaming combustion was ceased on the exposed CLT walls and ceiling at around 100 min but constant small flames came from the gypsum-board protected walls through some gypsum board cracks and junctions. With subsequent full involvement of the protected Wall A and Wall C that led to fire regrowth, Test NLT-3 had to be terminated by fire suppression at 120 min but Test CLT-5 was only terminated after 250 min.

Although Test NLT-3 only lasted half as long as Test CLT-5, the exposed NLT panels charred deeper than the exposed CLT panels in the ceiling, Wall B and Wall D. Again, the experimental results indicated that, in term of reducing mass timber contribution to the compartment fire, CLT performed better than NLT in this test arrangement as the lumber elements in the NLT panels were not as tightly fitted as the lumber in the CLT panels.

Observations made during Test NLT-3 and previous Test CLT-5 indicated that the protected timber walls charred continuously behind the gypsum board and eventually became exposed to become fully involved in the fire, which contributed to the fire. The two layers of gypsum board protection appeared to be insufficient to limit the contribution of the protected timber walls to the fire in this test configuration. An increased degree of encapsulation was worth investigation whether the same total area of exposed timber could be kept as in this configuration without excessive contributions to the fire.

(a) NLT room at 120 min

(b) CLT room at 120 min



(c) NLT room temperatures

(d) CLT room temperatures

(e) Temperatures in NLT ceiling

(f) Temperatures in CLT ceiling

(g) Temperatures in NLT Wall A

(h) Temperatures in CLT Wall A

(i) Temperatures in NLT Wall B

(j) Temperatures in CLT Wall B

Figure 45. Comparison of Test NLT-3 and Test CLT-5.

Table 12. Comparison of Test NLT-3 to Test CLT-5.

Component / Result	Test NLT-3	Test CLT-5
Ceiling	**exposed NLT**	**exposed CLT**
Walls B and D	**exposed NLT**	**exposed CLT**
Gypsum board performance	2GB on Walls A & C	2GB on Walls A & C
face layer 300°C@back (min)	18-24	18-23
base layer 300°C@back (min)	41-52	44-48
face layer falloff (min)	33	230
base layer falloff (min)	105	250
Test duration (min)	120	250
Wall A char (mm)	25-60	38-87
Wall B char (mm)	102-126	81-109
Wall C char (mm)	18-45	50-90
Wall D char (mm)	81-104	83-88
Ceiling char (mm)	97-119	70-90

2GB: two layers of 12.7 mm (½") thick Type X gypsum board lining

3.4 Test NLT-4

Test NLT-4 was conducted on March 27th, 2019 with fully exposed ceiling, Wall B and Wall D (2x8 laminations). Wall A and Wall C (2x6 laminations) were lined with three layers of 12.7 mm (1/2 in.) thick Type X gypsum board. Test NLT-4 was essentially the same as Test NLT-3 in the experimental configuration, except that three layers of gypsum board were installed on Wall A and Wall C. **Figure 46** shows photographs of the NLT compartment before Test NLT-4. Test NLT-4 aimed to investigate the feasibility of increasing the degree of encapsulation to limit the contributions of the protected walls to fire while still keeping the same total area of exposed surfaces as Test NLT-3.

(a) view of exposed Wall B and ceiling (b) view of exposed Wall D and ceiling

Figure 46. . Fully exposed NLT ceiling, Wall B and Wall D for Test NLT-4.

Figure 47 shows some photographs of the NLT room during Test NLT-4. The test started with ignition of the middle crib, which ignited the ceiling above at 2.5 min. Flame started to come out from the top of the doorway opening, followed by large fire plume issuing from the doorway opening. Flashover occurred at 3.3 min. At 50 min, the fire plume reduced significantly and the interior of the room became visible. The char on the exposed ceiling, Wall B and Wall D was visibly formed to slow down burning on the exposed NLT surfaces. At the same time, the face layer gypsum board on Wall A was observed to lose a 1.2 m wide section from the floor to 0.6 m height at the location near the middle wood crib. At 60 min, the fire plume ceased to issue from the opening. Flaming combustion on the ceiling, Wall B and Wall D was reduced as time elapsed and eventually ceased at around 90 min. The face layer gypsum board on Wall A fell off further to a 1.2 m wide x 1.2 m high section at the same location near the middle wood crib at 90 min. Since the face layer gypsum board was missing in this area, a vertical crack was observed on the mid layer gypsum board; small flames came out through the crack later at 150 min, indicating NLT burning behind the gypsum board (see also **Figure 47**(g)). At 167 min, the fall-off section of the face layer gypsum board doubled to a 2.4 m wide x 1.2 m high area on Wall A in its mid-length portion near the floor. Nevertheless, until the end of the test, three layers of gypsum board remained on approximately 70% of the surface area on Wall A with only small flame from the gypsum board crack near the mid-length, and no flames on the exposed surfaces. As four hours had passed without fire recurrent, the test was terminated at 255 min.

Test NLT-4 demonstrated that this test configuration of fully exposed ceiling, Wall B and Wall D along with increased encapsulation on Wall A and Wall C using three layers of the gypsum board successfully led to continuous fire decay with self-extinguishment on the exposed NLT surfaces and also limited the contributions of the protected NLT walls to the fire.

(a) fire plume at 30 min

(b) Wall D and ceiling at 60 min

(c) Wall A (partial), Wall B and ceiling at 90 min

(d) Wall A (partial), Wall D and ceiling at 120 min

(e) Wall A (partial), Wall D and ceiling at 150 min

(f) Wall A (partial), Wall D and ceiling at 210 min

(g) Wall A (central) and ceiling at 210 min

(h) Wall D and ceiling at 240 min

Figure 47. Photographs of the NLT room during Test NLT-4.

3.4.1 Room temperatures

Figure 48 shows temperatures in the room during Test NLT-4, measured using thermocouple (TC) trees with thermocouples at 0.6 m, 1.2 m, 1.6 m, 2.0 m and 2.4 m heights. The room temperatures reached a peak of 1190 °C during the fully developed stage then started to decrease at 30 min. After the flaming combustion ceased on the ceiling, Wall B and Wall D, the room temperatures decreased to below 300 °C by 130 min. After declining to below 250 °C at 180 min, with Wall A losing a portion of its face layer gypsum board and small flames coming out through the crack on the mid layer gypsum board, the room temperatures started to rise slightly but still stayed below 300 °C until the end of the test.

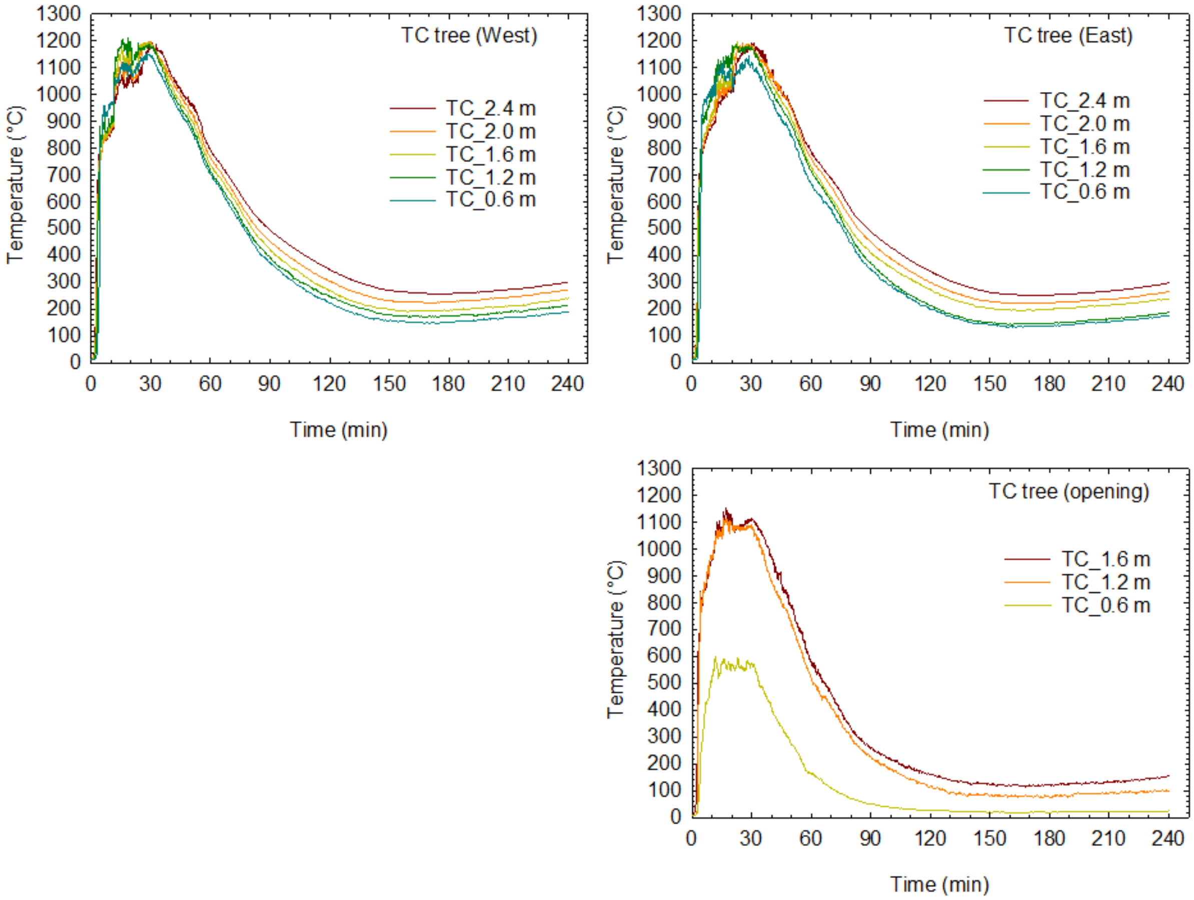


Figure 48. Room temperatures during Test NLT-4.

3.4.2 Temperatures at gypsum board interfaces and inside NLT panels

Figure 49 to **Figure 51** show the temperatures measured at the NLT surfaces, interfaces between gypsum board layers and inside NLT panels. **Table 13** shows the timing when the embedded thermocouples measured 300 °C in NLT assemblies, which is the typical temperature used as an indication that the wood has begun to char and therefore used as a criteria for determining the char front as it progresses through the wood.

Based on the timing when the embedded thermocouples in the exposed NLT assemblies measured 300 °C, the char front reached 17.5 mm at 17-32 min, 35 mm at 32-57 min, 52.5 mm at 43-68 min, and 70 mm at 219 min in the ceiling, Wall B or Wall D.

Wall A and Wall C were protected using three layers of gypsum board. The heat transfer through the gypsum board followed the typical three-stage pattern as indicated by the temperature profiles at the interfaces. The temperatures at the gypsum board base layer and NLT interface reached 300 °C at 89-98 min. This indicated that the NLT panels started charring behind the base layer gypsum board in the walls.

Table 13. Time (min) to reach 300°C at gypsum board interfaces and inside NLT in Test NLT-4.

NLT panel	Gypsum board (GB) layer interface or NLT depth (mm)						
	GB middle/base	0	17.5	35	52.5	70	105
Ceiling east	i.n.	2.58	29.17	-	-	-	-
Ceiling centre	i.n.	2.25	19.42	57.25	-	-	-
Ceiling west	i.n.	2.50	17.58	44.00	67.83	-	-
Wall A east	47.83	97.83	-	-	-	-	-
Wall A mid-east	48.17	-	-	-	-	-	-
Wall A mid-west	61.25	-	-	-	-	-	-
Wall A west	50.92	-	-	-	-	-	-
Wall B	i.n.	2.75	31.92	32.50	-	-	-
Wall C	42.33	88.92	-	-	-	-	-
Wall D	i.n.	2.58	24.67	49.83	43.08	219.08	-

-: did not reach 300°C during the test.

i.n.: interface did not exist.

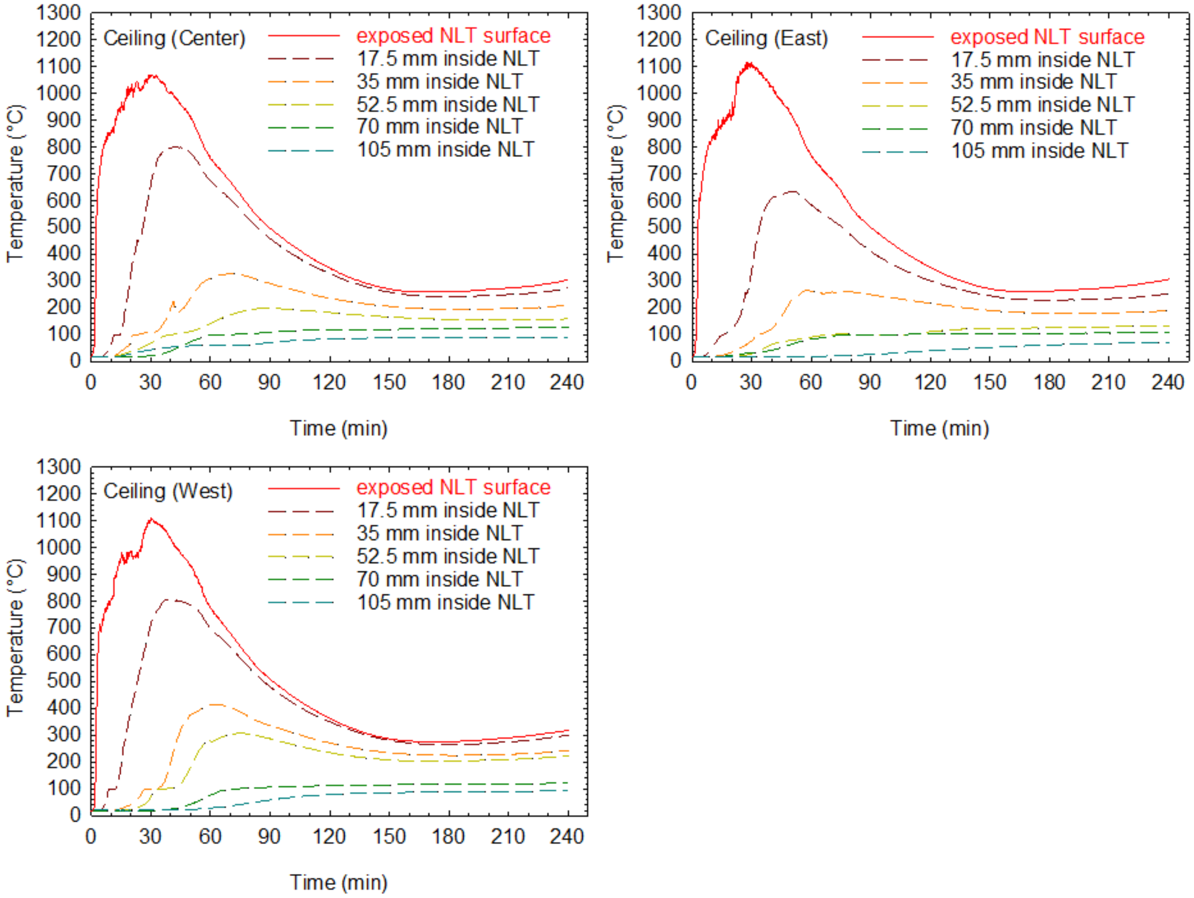


Figure 49. Temperatures in NLT ceiling panels in Test NLT-4.

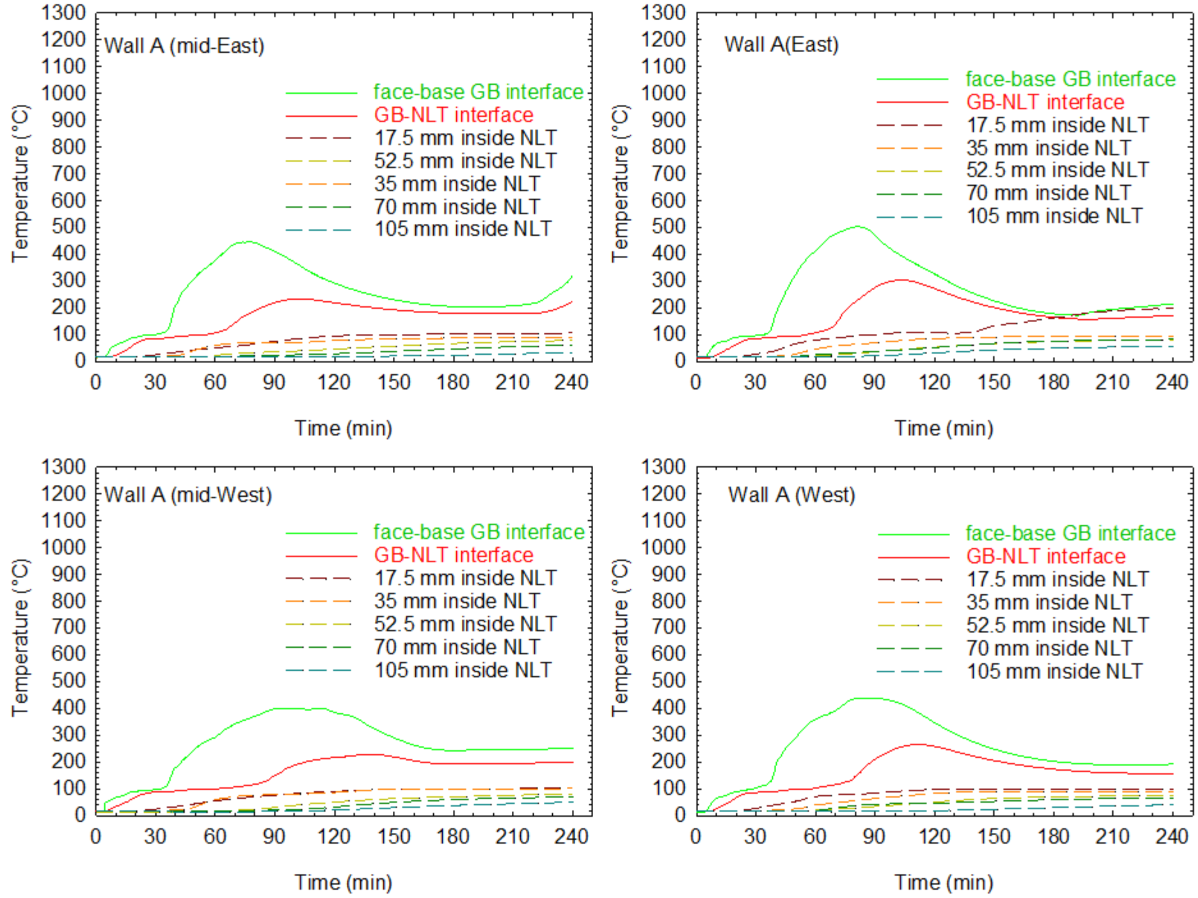


Figure 50. Temperatures in NLT and at gypsum board interfaces for Wall A in Test NLT-4.

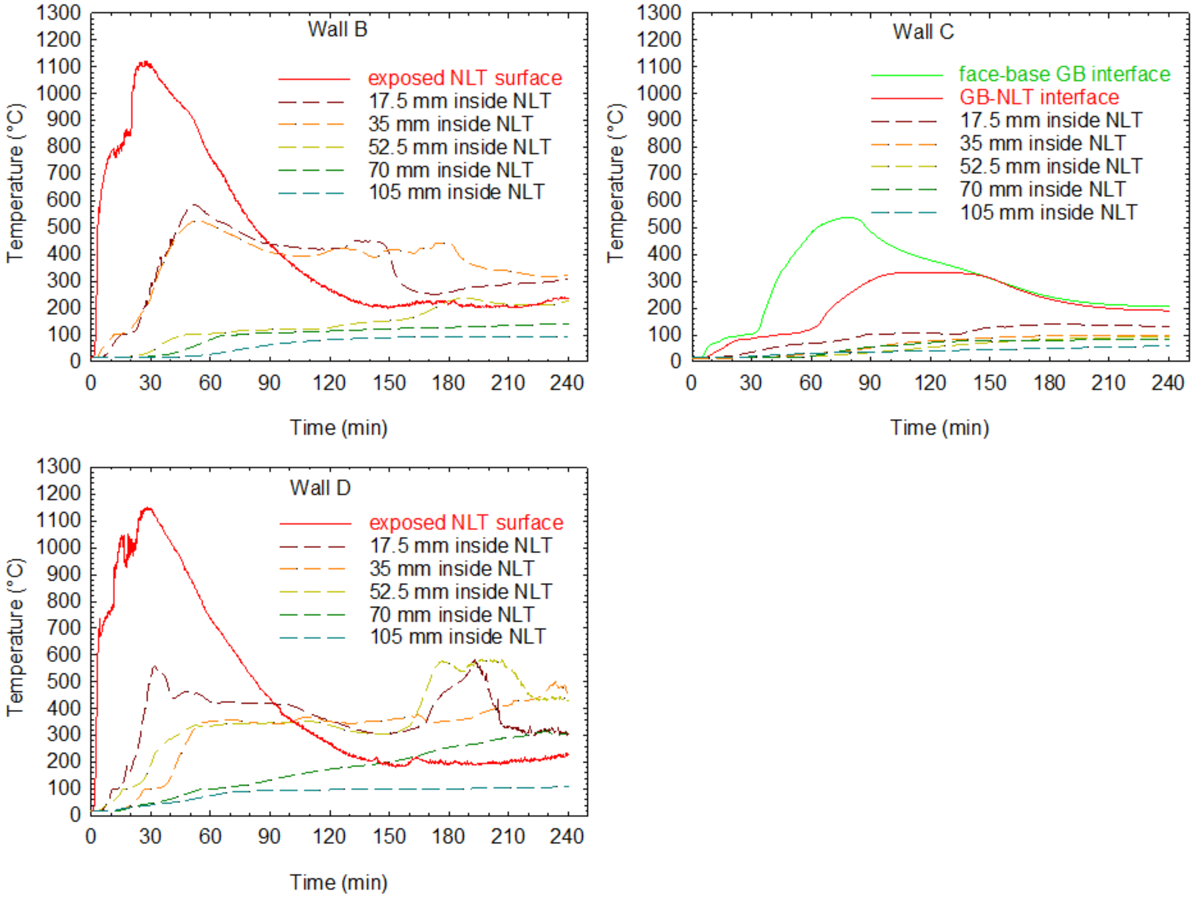


Figure 51. Temperatures in NLT and at gypsum board interfaces for Walls B, C and D in Test NLT-4.

3.4.3 Heat release rate

Figure 52 shows the heat release rate (HRR) during Test NLT-4, presenting the values of 1-min running averages. The HRR was 4.6 MW at the initial peak after the flashover (the peak value could have been slightly higher as a small portion of the smoke overflowed the collection hood at 20 min for a short while). As the fire decayed after 30 min, the HRR reduced to below 1 MW at 65 min. Afterwards the HRR reduced further to below 0.5 MW until the end of the test. (Note: at around 90 min, the sampling pump was turned off briefly to change Drierite and remove clogging in the sampling line, which resulted in the artificial HRR variations around that time.)

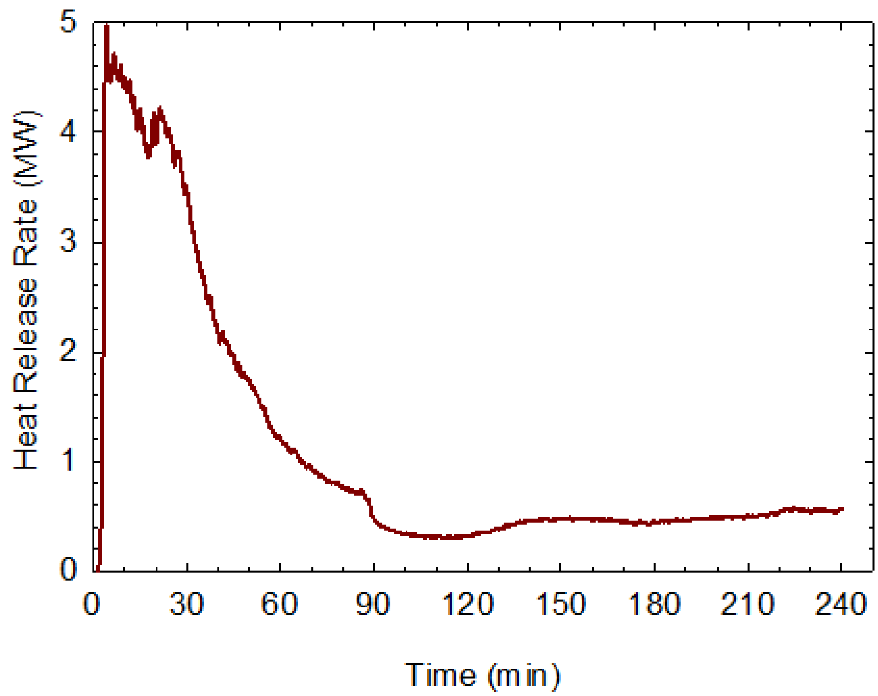


Figure 52. Heat release rate in Test NLT-4.

3.4.4 Char of NLT panels

After Test NLT-4, the NLT panels were examined for char. **Figure 53** are photographs of the NLT panels after Test NLT-4, showing the char on the NLT panels. As shown in **Figure 53**(c), the gypsum-board protected NLT panels only had limited surface char.

(a) NLT exterior (gypsum board removed)

(b) NLT ceiling (interior)

(c) Wall A (interior gypsum board removed)

(d) Wall B (interior)

Figure 53. Photograph of mass timber elements after Test NLT-4.

Using data from **Table 13** (time to reach 300°C in NLT), the char front inside NLT is plotted versus time in **Figure 54**, assuming that NLT started to char at 300 °C. As the large amount of the exposed NLT panels (fully exposed ceiling, Wall B and Wall D) produced more intensive combustion, the NLT char rate for the exposed NLT was initially up to 1 mm/min. For Wall A and Wall C with the gypsum board protection, the NLT only had mostly surface char.

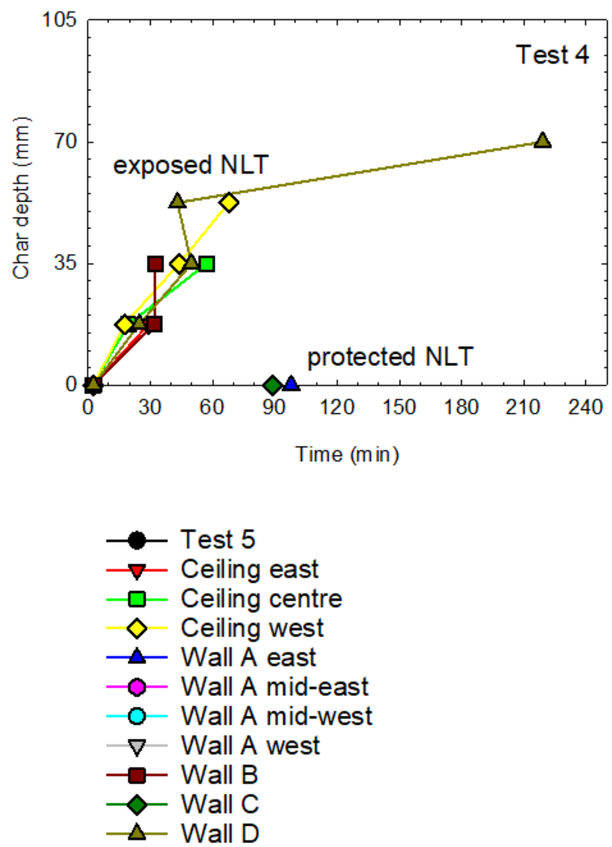


Figure 54. NLT char depth versus time in Test NLT-4.

The Resistograph was also used to measure char depths and a total of 56 sampling locations were drilled through. **Table 14** lists the total char depths measured for the NLT panels. Imagining the NLT room as a cardboard box, **Table 14** represents the unfolded cardboard box for an interior view of the charred NLT surfaces in the room. The positions of the char depth values in the table also illustrate the sampling locations for the char measurement on the walls and ceiling. In the exposed ceiling, the NLT panels charred 44-64 mm. In the exposed Wall B and Wall D, the NLT panels charred 44-89 mm. The char depth in the exposed wall panels was generally more than that in the exposed ceiling panels. The measurements also confirmed that the gypsum-board protected NLT walls had mostly surface char; except the place where the mid layer gypsum board cracked on Wall A and the char was up to 45 mm deep.

Table 14. Total char depth (mm) of NLT panels in Test NLT-4.

Ceiling

54	61	59	46
51	57	58	49
54	64	63	54
63	59	54	44

1/2 Wall C		Wall D		Wall A				Wall B		1/2 Wall C	
2	7			0	0	0	0			1	0
3	8	44	67	0	12	1	2	61	67	1	8
0	3	61	89	0	0	45	3	79	73	3	2
0	33			0	0	41	1			2	0

red numbers indicating unprotected NLT surfaces. (Ceiling values and Wall D and Wall B values are printed in red.)

3.4.5 Comparison of Test NLT-4 to Test NLT-3 and Test CLT-5

Table 15 and **Figure 55** compare the results from Test NLT-3, Test NLT-4 and Test CLT-5. The three tests had essentially the same test configuration with the exposed ceiling, two exposed short walls, and two protected long walls. Three layers of gypsum board were used to protect Wall A and Wall C in Test NLT-4 but two layers were used in Test NLT-3 and Test CLT-5.

In these three tests, the times to reach 300°C at the gypsum board interfaces were very similar for the respective layers. The three-layer encapsulation system in Test NLT-4 had only limited fall-off of the face layer gypsum board. The two-layer encapsulation systems, however, had almost full fall-off of both gypsum board layers in Test NLT-3 and Test CLT-5.

Test NLT-3 caused intense fire without significant decay and had to be terminated just after two hours. The previous Test CLT-5 (cf. **Figure 55**) had recurrent fire at 220 min after a long period of fire decay including flame self-extinguishing on the exposed CLT panels. This was largely due to the two layers of gypsum board being insufficient in this test configuration to protect Wall A and Wall C, which charred continuously behind the gypsum board and eventually became exposed to fully involve in the fire.

Test NLT-4, with the same amount of exposed NLT but enhanced encapsulation on Wall A and Wall C, led to continuous decay of the fire and much reduced contributions of the timber to the fire during the four-hour long test. The flames on exposed NLT panels eventually self-extinguished in Test NLT-4. As demonstrated by Test NLT-4, it is feasible to have this large amount of exposed timber surfaces without causing undue contribution to the fire with the enhanced encapsulation on the protected areas. Although Test NLT-4 lasted twice as long, the char depths were much less in Test NLT-4 than in Test NLT-3 for all NLT panels. The char depths were also significantly less in Test NLT-4 than in Test CLT-5 in all areas.

All other variables being equal, the second generation CLT generally performed better than NLT in the compartment fire tests to limit contributions of timber to the fire, because lumber elements in the NLT panels were not as tightly fitted as the lumber in the CLT panels, with gaps in the NLT allowing hot gases to travel. This can be demonstrated by comparing the results from this test series with the previous test series [4]: Test NLT-1 versus Test CLT-4; Test NLT-2 versus

Test CLT-4; and Test NLT-3 versus Test CLT-5. Therefore, it is reasonable to expect that, had the three-layer gypsum board protection been used on Wall A and Wall C, the recurrent fire at 220 min would not have occurred in Test CLT-5. The use of additional encapsulation, i.e. three layers of 12.7 mm thick Type X gypsum board, is necessary for the protected Wall A and Wall C in this partially encapsulated CLT room configuration (with fully exposed Wall B, Wall D and ceiling) to prevent the regrowth of the fire in Test CLT-5. It is also reasonable to expect that, with greater encapsulation, i.e. three-layer gypsum board protection, on Wall A and Wall C, the second generation CLT in this partial protection configuration would likely perform significantly better than Test NLT-4 to reach full decay of the fire.

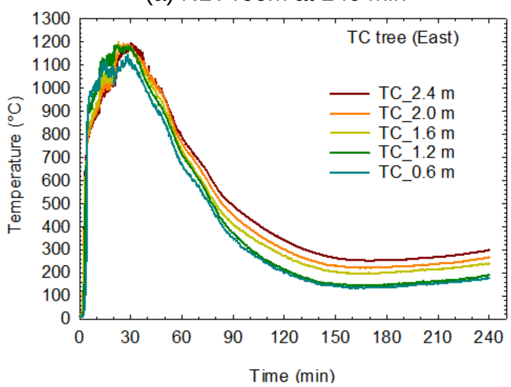
Table 15. Comparison of Test NLT-4 to Test NLT-3 and Test CLT-5.

Component / Result	Test NLT-3	Test NLT-4	Test CLT-5
Ceiling	**exposed NLT**	**exposed NLT**	**exposed CLT**
Walls B and D	**exposed NLT**	**exposed NLT**	**exposed CLT**
Gypsum board performance	2GB on Walls A & C	3GB on Walls A & C	2GB on Walls A & C
face layer 300°C@back (min)	18-24	NA	18-23
mid layer 300°C@back (min)	-	42-61	-
base layer 300°C@back (min)	41-52	89 - Nr	44-48
face layer falloff (min)	33	50 - Nfo	230
mid layer falloff (min)	-	Nfo	-
base layer falloff (min)	105	Nfo	250
Test duration (min)	120	255	250
Wall A char (mm)	25-60	0-45	38-87
Wall B char (mm)	102-126	61-79	81-109
Wall C char (mm)	18-45	0-33	50-90
Wall D char (mm)	81-104	44-89	83-88
Ceiling char (mm)	97-119	44-64	70-90

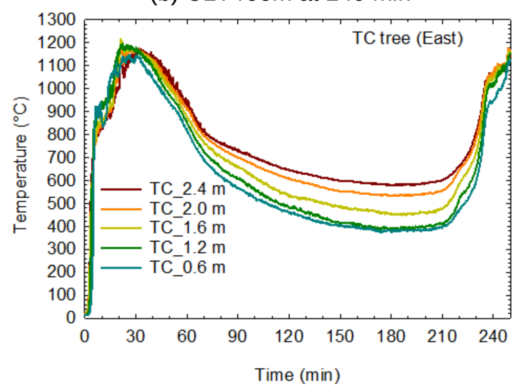
2GB (3GB): two (three) layers of 12.7 mm (½”) thick Type X gypsum board lining
NA: not available *Nr: not reached 300°C* *Nfo: no fall-off* *-: not used*


(a) NLT room at 240 min

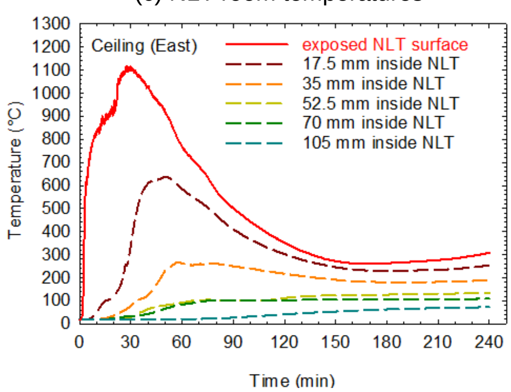

(b) CLT room at 240 min



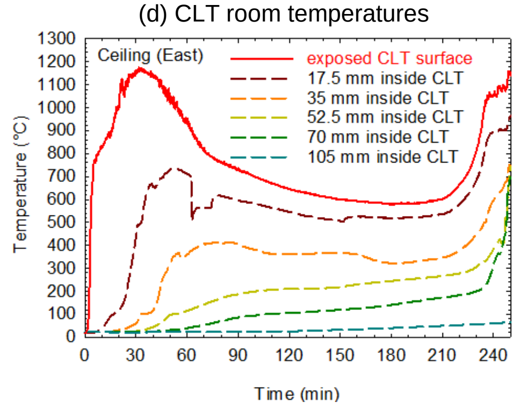
(c) NLT room temperatures



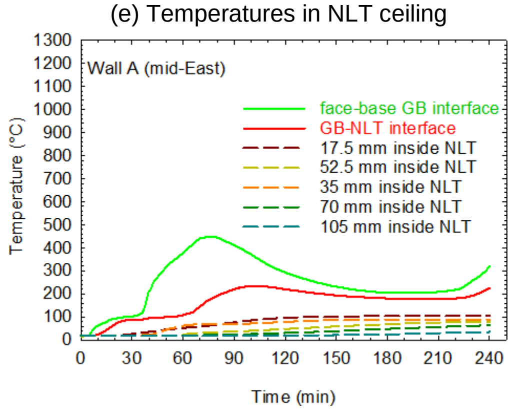
(d) CLT room temperatures



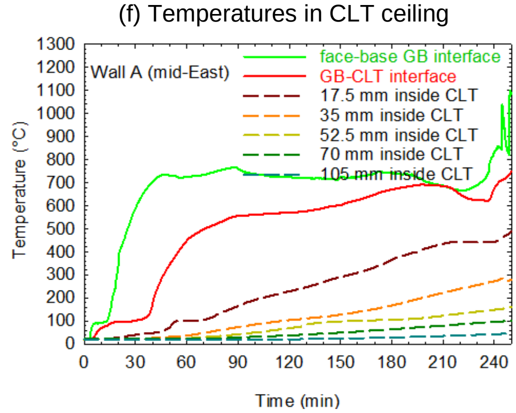
(e) Temperatures in NLT ceiling



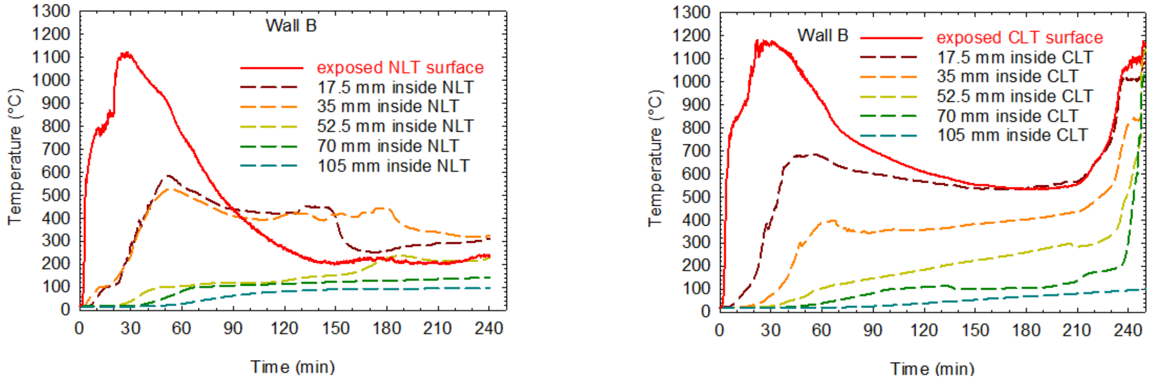
(f) Temperatures in CLT ceiling



(g) Temperatures in NLT Wall A



(h) Temperatures in CLT Wall A



(i) Temperatures in NLT Wall B

(j) Temperatures in CLT Wall B

Figure 55. Comparison of Test NLT-4 and Test CLT-5.

4. CONCLUSIONS

Four room fire tests were conducted, incorporating mass timber structural elements of Glulam beams, columns and NLT panels. The goal of this test series is to quantify the contribution of NLT mass timber elements to compartment fires and provide additional data for forming the technical basis for the amount of exposed mass timber elements to be allowed in EMTC buildings without significantly increasing the fire severity and duration. The fire tests were conducted without sprinklers in order to achieve this goal. This series of NLT compartment fire tests utilized two test configurations similar to the configurations used in the previous fire test series of the second-generation CLT compartments with a thermal resistant adhesive [4].

One test configuration was similar to the configuration used in Test CLT-4, including a fully exposed NLT ceiling (100% ceiling), a fully exposed Glulam beam and column (the combined exposed surface area of the Glulam beam and column was equal to 19% of the perimeter walls), and protected perimeter walls with two layers of 12.7 mm thick Type X gypsum board. The exposed mass timber surfaces used in this test configuration were much greater than the allowances proposed for exposed mass timber in EMTC buildings in the new fire safety provisions expected to be included in the National Building Code of Canada (NBCC) 2020. Proposed new NBCC (2020) provisions would permit exposed beams/columns/arches at 10% of total suite or fire compartment perimeter wall area, plus partially exposed ceilings at 10% or 25% of total suite ceiling area (provided that the ceiling flame spread rating is not greater than 150 or 75, respectively). And for the latter case of where 25% of the ceiling is permitted to be exposed, no exposed walls would be permitted.

Test NLT-1 and Test NLT-2 were conducted using the same configuration as Test CLT-4, except that Test NLT-1 used an even NLT ceiling while Test NLT-2 used an uneven NLT ceiling. Similarly in Test NLT-1, Test NLT-2 and Test CLT-4, two layers of gypsum board remained on the walls; the times to reach 300°C at their interfaces were similar to each other. Test NLT-1 and Test NLT-2 produced comparable fire performance, although Test NLT-2 with the uneven NLT ceiling had a slightly better fire performance (resulting in a lower HRR, lower temperatures in the room and inside the NLT assemblies, less char depths in the NLT panels, and smaller remaining flames at the end of the test). However, unlike Test CLT-4 where the fire fully burned-out and completely self-extinguished, Test NLT-1 and Test NLT-2 had the protected NLT wall panels continuously charring behind the gypsum board with flames through some gypsum board cracks and joints after the exposed NLT ceiling ceased flaming combustion. The continued charring of the protected NLT walls behind the gypsum board prevented fire decaying to the full extent as in Test CLT-4. The two layers of gypsum board protection appeared to be borderline in limiting the contribution of the protected NLT walls to the fire. The char was much deeper in the NLT tests than in the CLT test.

The other test configuration was similar to the configuration used in Test CLT-5, including a fully exposed NLT ceiling (100% ceiling), two exposed short walls facing each other (Wall B and Wall D, equal to 35% of perimeter wall area), and two long walls protected with two to three layers of 12.7 mm thick Type X gypsum board (Wall A and Wall C). The exposed mass timber surfaces used in this test configuration were much greater than the allowances proposed for exposed mass timber in encapsulated mass timber construction (EMTC) in the new fire safety provisions expected to be included in the National Building Code of Canada (NBCC) 2020. Proposed new NBCC (2020) provisions would permit exposed beams/columns/arches at 10% of total suite or fire compartment perimeter wall area, plus partially exposed ceilings at 10% or 25% of total suite ceiling area (provided that the ceiling flame-spread rating is not greater than 150 or 75, respectively). And for the latter case of where 25% of the ceiling is permitted to be exposed, no exposed walls would be permitted.

Test NLT-3 and Test NLT-4 were conducted using the same configuration as Test CLT-5, except that three layers of gypsum board were used in Test NLT-4 while two layers were used in Test NLT-3 and Test CLT-5 to protect the two long walls. Similarly, the times to reach 300°C at the gypsum board interfaces were very similar for the respective layers in these tests. However, Test NLT-3 caused intense fire without significant decay and had to be terminated just after two hours. Test CLT-5, after a long period of gradual fire decay including flame self-extinguishing on the exposed CLT panels, had recurrent fire at 220 min. In both Test NLT-3 and CLT-5, two layers of gypsum board were insufficient in this test configuration to protect Wall A and Wall C, which charred continuously behind the gypsum board and eventually became exposed to fully participate in the fire. On the other hand, Test NLT-4, with the same amount of exposed timber surface but enhanced encapsulation (three layers of gypsum board) on Wall A and Wall C, led to continuous decay of the fire and much reduced contributions of the timber to the fire during the four-hour long test. The flames on exposed NLT panels eventually self-extinguished in Test NLT-4. The char depths were much less in Test NLT-4 than in Test NLT-3 (although Test NLT-4 lasted twice as long as Test NLT-3) and Test CLT-5 in all areas.

The NLT panels typically have some small gaps between laminations. Efforts were made to minimize the gaps during the NLT panel fabrication and room construction for this NLT test series. However, small gaps still existed between NLT laminations. These small gaps provided passages for the flame and hot pyrolysis gas to travel in the NLT panels. Test NLT-3 and Test NLT-4 demonstrated that, in the absence of operationally effective sprinklers, to reach full decay of the fire three layers of 12.7 mm thick Type X gypsum board were necessary for NLT rooms with partially encapsulated walls and fully exposed ceilings to limit undue contributions of the protected NLT elements to the compartment fires, while still keeping the same total area of exposed surfaces as in the two test configurations. It is expected that with the scenarios in Test NLT-1 and Test NLT-2, a similar effect from using three layers of gypsum board would be seen and the fire would be expected to reach full decay.

It is important to note the lumber elements in the NLT panels were not as tightly fitted as the CLT panels, as the NLT had small gaps between laminations. All other variables being equal, the second generation CLT generally performed better than NLT in these compartment fire tests to limit contributions of timber to the fire. Therefore, it is reasonable to expect that, had the three-layer gypsum board protection been used on Wall A and Wall C in Test CLT-5, the recurrent fire at 220 min would not have occurred in that CLT test. The use of additional encapsulation, such as, three layers of 12.7 mm thick Type X gypsum board is necessary for the protected CLT elements in Wall A and Wall C in this partially encapsulated CLT room configuration to prevent the regrowth of the fire. It is also reasonable to expect that, with greater encapsulation, e.g. three-layer gypsum board protection, on Wall A and Wall C, the second generation CLT in this partial protection configuration would likely perform significantly better than Test NLT-4 to reach full decay of the fire.

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