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# EVALUATING FIRE PERFORMANCE OF NAIL-LAMINATED TIMBER

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**March 10, 2019**

Client: Forestry Innovation Investment Ltd.

EVALUATING FIRE PERFORMANCE OF NAIL LAMINATED TIMBER
PROJECT NO. 301013024

ACKNOWLEDGEMENTS
FPInnovations would like to thank Forestry Innovation Investment Ltd. for funding this project and supporting our research. FPInnovations would also like to thank its industry members and Natural Resources Canada (the Canadian Forest Service) for their continued guidance and financial support.

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# 1. INTRODUCTION

Nail-laminated timber (NLT) is a mass timber element that has traditionally been used for floors in old industrial facilities and is now gaining popularity again for use in new mass timber constructions. Although not commonly used for walls, it can be used in the construction of vertical shafts, such as for elevators. NLT has many potential applications for use in larger and taller wood buildings. It is simple to construct, uses a large volume of low-grade readily-available lumber, and is as cost competitive as other prefabricated mass timber elements. The recent publication of Canadian and American editions of the NLT design guide [1] [2], provide guidance on how to design and construct with NLT. Due to the limited knowledge available at that time, these documents provide only high-level generic guidance in regards to the fire performance of NLT.

NLT is recognized as “solid wood” construction in the National Building Code of Canada (NBCC) [3]; however, significant knowledge gaps exist related to its fire performance. The basis for the assigned fire resistance ratings for solid wood assemblies in the NBCC is unknown; a review of existing research yielded no direct data to support these ratings. The current method to determine the fire resistance rating for an NLT assembly includes either taking a rating from Table D-2.4.1. in the NBCC based on assembly thickness (a summarized excerpt from this table is given in Table 1), using engineering judgment to calculate the fire resistance rating (assuming a charring rate), or conducting fire resistance testing. The NBCC permits Fire-Resistance Ratings (FRR) of solid timber assemblies to be increased by 15 min if 12.7 mm (½”) gypsum board is applied on the fire exposed side (D-2.4.2.).

Table 1. Minimum Thickness of Solid Wood Walls and Floors (mm) (Table D-2.4.1. NBCC [3])

| Assembly | Details | Fire Resistance Rating | | | |
|---|---|---|---|---|---|
| | | 30 min | 45 min | 1 h | 1.5 h |
| **Wall** | Loadbearing vertical plank [1] | 89 | 114 | 140 | 184 |
| **Floor** | Building paper and finished flooring on top [1] | 89 | 114 | 165 | 235 |
| **Floor** | Splined or tongued and grooved floor with building paper and finish flooring on top[2] | 64 | 76 | - | - |

[1] 38 mm thick members on edge fastened with 101 mm common wire nails. Spaced not more than 400 mm, staggered
[2] Floor of 64 x 184 mm planks, tongued and grooved or splined. Fastened with 88 mm nails spaced not more than 400 mm.

There is a need to provide technical and scientific data to support the fire safe design of these mass timber assemblies. Performance data and technical information need to be generated so that designers have the tools to get designs approved, which will facilitate faster and more widespread market acceptance of mass timber construction.

# 2. OBJECTIVE

The objective of this work is to generate fire resistance data for NLT assemblies to address significant gaps in technical knowledge. This research will support designers and builders in the use of mass timber assemblies in larger and taller buildings, as well as provide scientific justification for Authorities Having Jurisdiction (AHJ) to review and accept this construction method. The intent is to demonstrate that NLT construction can meet or exceed NBCC fire safety requirements for use in buildings of mass timber construction.

The data could be used towards the inclusion of an NLT fire resistance calculation methodology into Annex B of CSA O86 – Engineering Design for Wood [4], which currently addresses only glue-laminated timber (GLT), structural composite lumber (SCL) and cross-laminated timber (CLT).

# 3. TECHNICAL TEAM

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# 4. PROCEDURE

Full-scale tests were carried out to assess the fire resistance of NLT assemblies in accordance with CAN/ULC-S101 [5]. Testing was completed at the National Research Council Fire Research Laboratory in Ottawa, ON.

Three assemblies were evaluated:

1. 2x6 NLT wall, 1 layer 12.7 mm (½”)  plywood on unexposed side
2. 2x8 NLT wall, 2 layers 12.7 mm (½”) Type C gypsum board on both sides
3. 2x6 NLT floor, 1 layer 12.7 mm (½”) plywood on unexposed side

All of the assemblies were constructed using nominal SPF No. 2 lumber (38 mm thick) and fastened with 75 mm (3”) common nails, spaced 450 mm o.c. staggered in the direction of the grain, as recommended in the Canadian NLT Design Guide [1]. The guide recommends using 75 mm (3”) nails for practicality and ease of construction, as opposed to the 101 mm stipulated by CSA O86.

## 4.1 Wall Tests

Both walls were constructed with two panels measuring 1825 mm (6’) wide x 3048 mm (10’) high, for total dimensions of 3658 mm (12’) x 3048 mm (10’). The overall layout of the assembly is shown in Figure 1. The panels were fastened together side-by-side with ASSY self-tapping screws 3.0 Φ 8 x 160 mm spaced 305 mm

(12") o.c., 150 mm (6") from either end. The screws were installed in an X pattern at a 45° angle. The joint detail is shown in Figure 6.

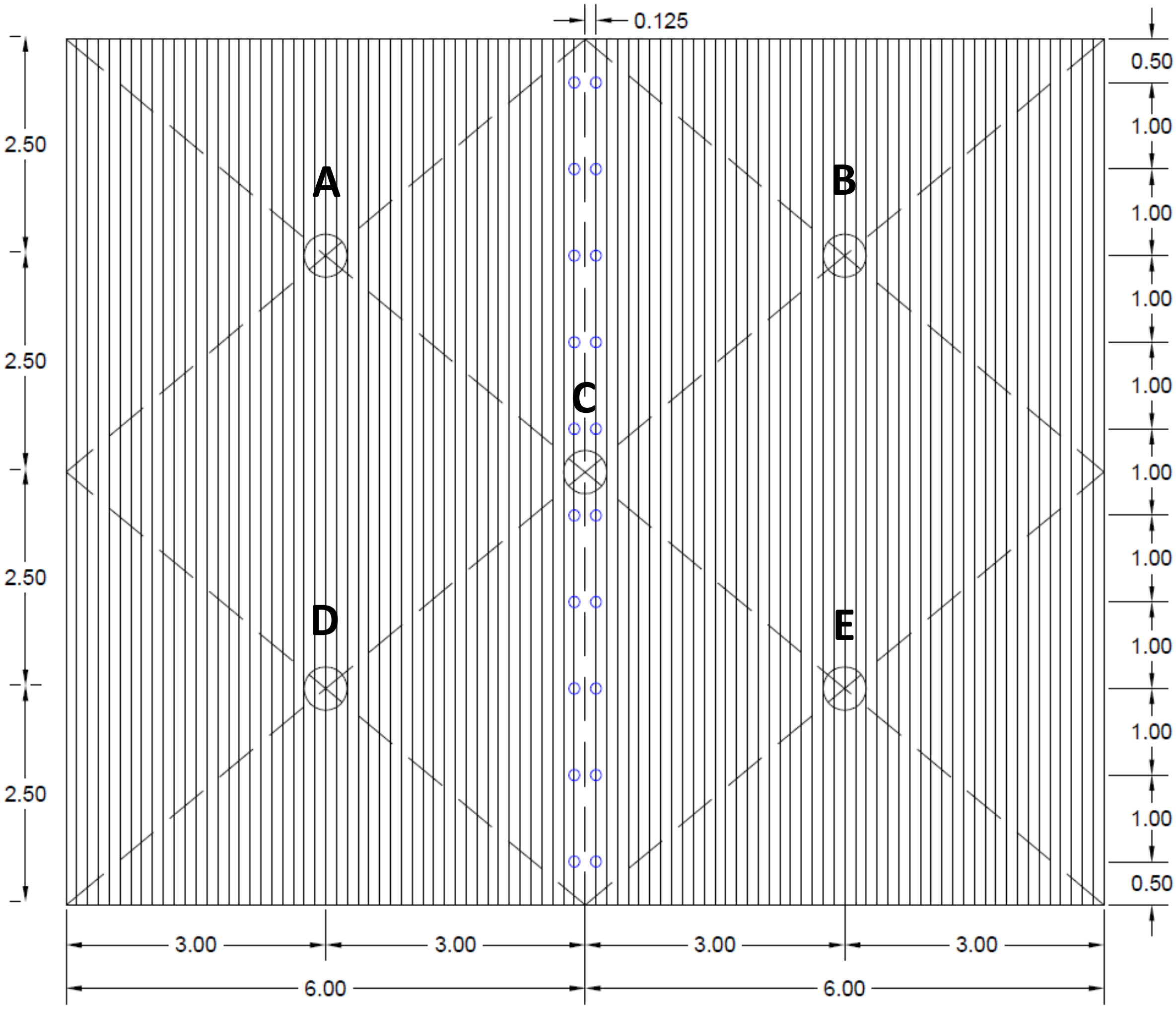



Figure 1. Wall dimensions and thermocouple locations, from exposed side (dimensions in ft.).

### 4.1.1 2x6 NLT Wall

The 2x6 wall, with a thickness of 140 mm, was protected on the unexposed side by one layer of 12.7 mm (½") plywood, no protection was provided on the exposed side. The butt-end plywood was installed with 2.5" wood screws spaced 150 mm (6") around the perimeter and 305 mm (12") in the field. The plywood schematic layout details for the 2x6 wall can be found in Appendix I. The average lumber moisture content of the exposed face before the test was 8.6% using a hand-held moisture meter.

Figure 2 shows the unexposed side of the wall prior to the installation of plywood. Figure 3 shows the exposed side of the assembly before the test. Figure 4 shows the plywood layout and locations of the unexposed surface thermocouples.

Figure 2. 2x6 NLT Unexposed side before plywood installation.

Figure 3. 2x6 NLT Exposed side of assembly.

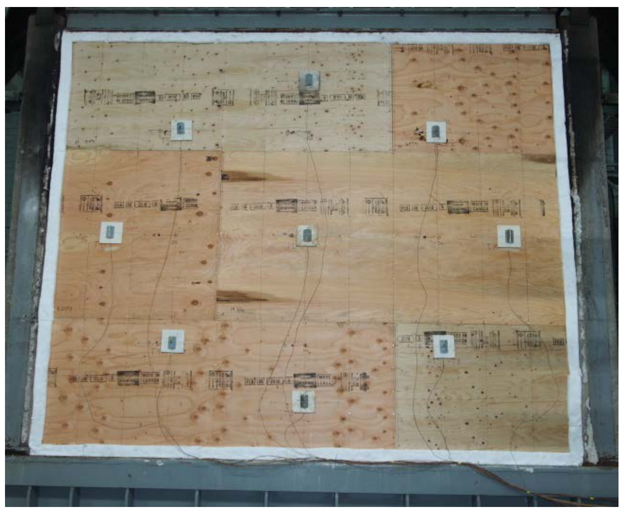


Figure 4. 2x6 NLT unexposed side before test.

#### 4.1.1.1 Instrumentation

The assemblies were instrumented with Type K thermocouples embedded within the assemblies as well as on the unexposed side to assess charring and failure. Nine thermocouples were placed across the unexposed surface, as per the CAN/ULC-S101 standard. Embedded thermocouples were located at the centre of the assembly and at the centre of each quadrant, as shown for the walls in Figure 1 (labelled A through E).

Thermocouples were installed at five depths in the 2x6 wall assembly, at 15, 25, 50, and 75 mm from the exposed side, as well as between the NLT and the 12.7 mm (½”) plywood on the unexposed side, as shown in Figure 5.

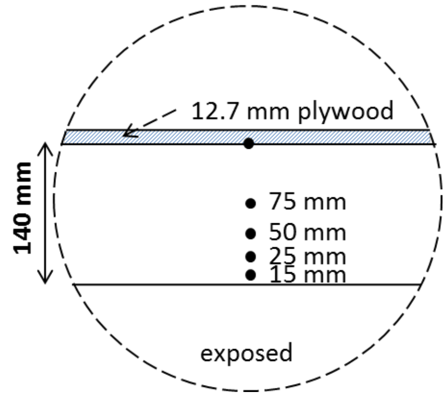



Figure 5. Embedded thermocouple depths, 2x6 wall.

For both the 2x6 and 2x8 wall tests two thermocouples were installed in the joint at depths of 15 and 75 mm from the exposed side. These were installed in the joint, 760 mm (2.5') from the top of the assembly.

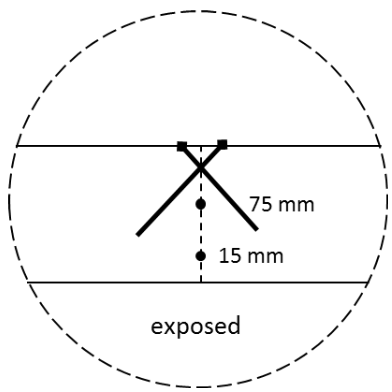



Figure 6. Joint detail with thermocouples for the 2x6 and 2x8 walls.

### 4.1.2 2x8 NLT Wall

The 2x8 wall, with a thickness of 184 mm, was protected with two layers of 12.7 mm (½") Type C gypsum board on both sides of the assembly. The gypsum board was fastened with (2 ¼") Type S screws spaced 305 mm (12") o.c. and 38 mm (1 ½") from the edges. Both sides of the NLT surface before the application of gypsum board are shown in Figure 7 and Figure 8. The installation of the gypsum board is shown in Figure 9 to Figure 12. Figure 10 shows how gypsum joints were placed so as not to line up with spaces between NLT boards, when possible.

The NLT surface was not perfectly level due to natural variability of the boards and manufacturing methods. This meant that in some cases that gypsum board joints did not meet straight on, where one protruded out further than the adjacent board, as shown in Figure 11. This created a disparity at the joint and an air gap behind the gypsum board in some locations. The final exposed surface of the 2x8 NLT wall assembly is shown in Figure 12.

The gypsum board schematic layout details for the 2x8 wall can be found in Appendix II. The average lumber moisture content of the exposed face before the test was 8.9% using a hand-held moisture meter.

Figure 7. 2x8 NLT wall exposed side before gypsum application.

Figure 8. 2x8 NLT wall unexposed side before gypsum application.

Figure 9. 2x8 NLT wall gypsum installation.

Figure 10. 2x8 NLT wall gypsum joint alignment.

Figure 11. 2x8 NLT Gypsum board disparity.

Figure 12. 2x8 NLT exposed side before test.

4.1.2.1 Instrumentation

Thermocouples were installed at the same five depths in the 2x8 wall assembly, at 15, 25, 50, and 75 mm from the exposed side, as well as at the interface between the NLT and gypsum board on the exposed and unexposed sides, as shown in Figure 13. Two thermocouples were also installed in the joint in the same location as for the 2x6 wall test (see Figure 6).

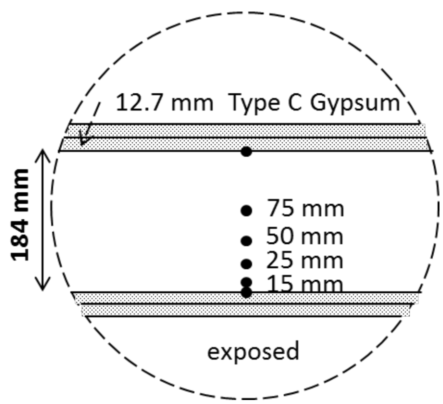



Figure 13. Embedded thermocouple depths, 2x8 wall.

### 4.1.3 Floor Test

The NLT floor consisted of three panels each measuring 1500 mm (59") x 3937 mm (155") long. The total dimensions of the assembly were 4495 mm (177") x 3937 mm (155") long. The overall layout of the assembly is shown in Figure 14. The panels were fastened side-by-side together with ASSY self-tapping screws 3.0 Φ 8 x 160 mm spaced 305 mm (12") o.c., 150 mm (6") from either end. The screws were installed in an 'X' pattern at a 45$^{o}$ angle. The joint detail is the same as the wall assemblies, as is shown in Figure 6.

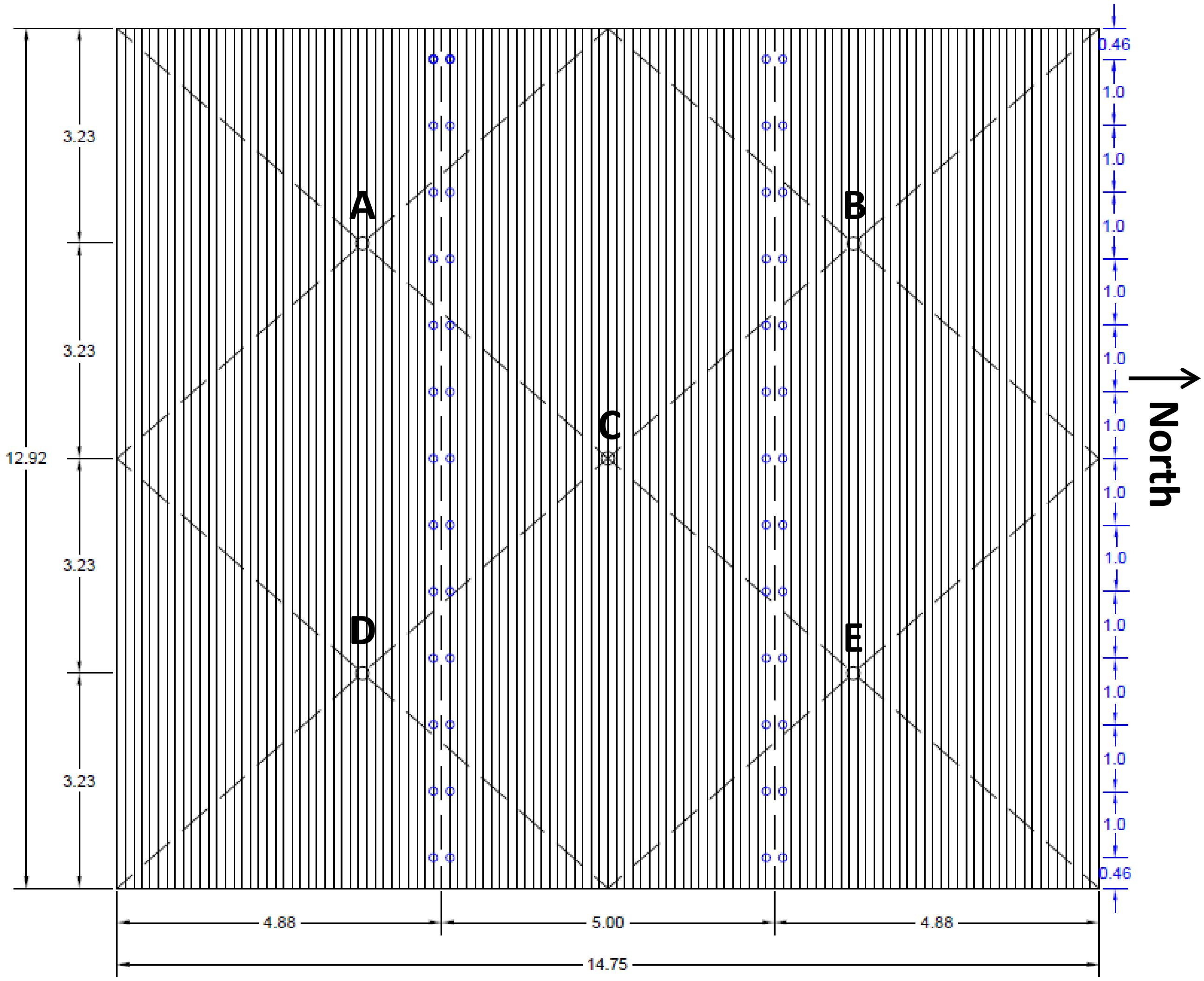



Figure 14. Embedded thermocouple locations in NLT floor, from unexposed side (dimensions in ft.).

The 2x6 floor was protected on the unexposed side by one layer of 12.7 mm (½") plywood, no protection was provided on the exposed side. The exposed NLT surface is shown in Figure 15. The butt-end plywood was installed with 2.5" wood screws spaced 150 mm (6") around the perimeter and 305 mm (12") in the field. The installation of the plywood is shown in Figure 16. The plywood schematic layout details for the 2x6 floor can be found in Appendix III. The average moisture content of the exposed face before the test was 9.9% using a hand-held moisture meter.

Figure 15. 2x6 NLT floor, exposed surface.

Figure 16. 2x6 NLT floor, installation of plywood.

#### 4.1.3.1 Instrumentation

Embedded thermocouples were located at the centre of the assembly and at the centre of each quadrant, as shown in Figure 14 (labelled A through E).

Thermocouples were installed at five depths in the 2x6 floor assembly, at 15, 25, 50, and 75 mm from the exposed side, as well as between the NLT and the 12.7 mm (½") plywood on the unexposed side, as shown in Figure 17.

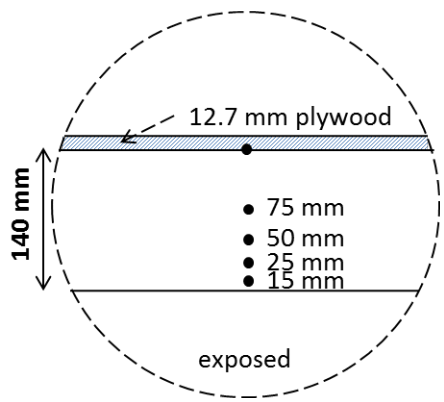



Figure 17. Embedded thermocouple depths, 2x6 floor.

Two thermocouples were installed in the joint at depths of 15 and 75 mm from the exposed side. These were installed a distance of 985 mm (3.23') from the end of the assembly in the north joint.

# 5. RESULTS

## 5.1 2x6 Wall

The 2x6 wall was tested on October 18, 2018. A 335 kN/m vertical load was applied. During preloading the initial maximum deflection at mid-height was 4 mm. The ambient temperature on the unexposed side at the beginning of the test was 18°C.

For the first minute of the test, smoke was leaking through the plywood joints in the top right corner (from the unexposed side); little smoke leakage was observed for the remainder of the test.

After 33 minutes from the start of the test, integrity failure occurred at a plywood joint; ignition of a cotton pad was used to confirm the failure, as shown in Figure 18. Once burn-through was detected a piece of plywood was used to cover the spot, which allowed the test to continue. Additional burn through spots occurred at 50 min, 52 min, and 63 min, each of which was also covered with a piece of plywood to continue the test to structural failure. These secondary spots were all through the plywood layer and not at a plywood joint. Figure 19 shows a plywood cover over the primary integrity failure and a secondary failure close by. The test ran until structural failure occurred at 71 min. Figure 20 shows the exposed side of 2x6 wall at the end of the test, and Figure 21 shows the condition of the exposed side after the wall had cooled. There appeared to be a depression in the wall at the location of the first burn-though, where more charring had occurred. This is consistent with the location of the negative pressure drawing more air in at the bottom of the furnace. Figure 22 shows the structural failure of the wall, deflecting out of the furnace.

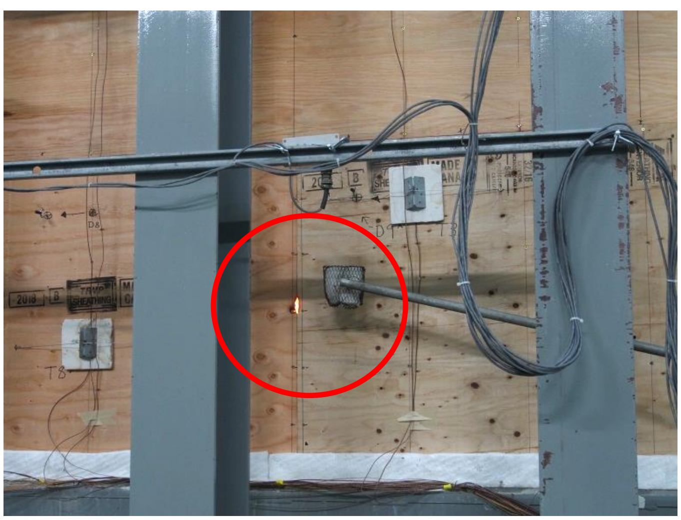


Figure 18. 2x6 NLT wall insulation failure.

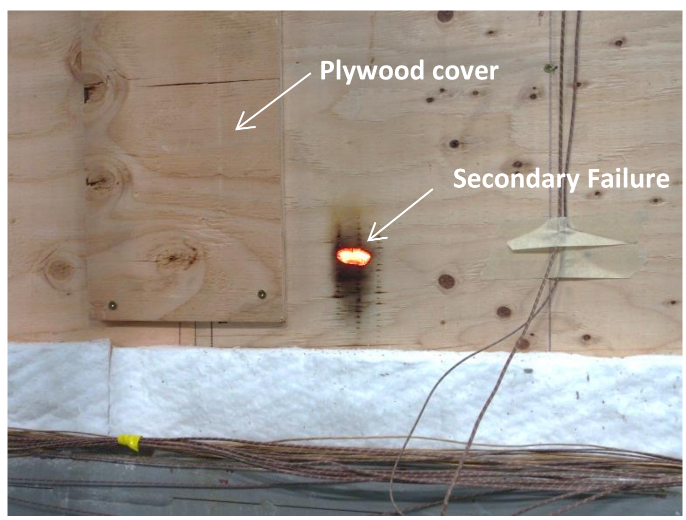



Figure 19. 2x6 NLT wall plywood cover and secondary insulation failure.

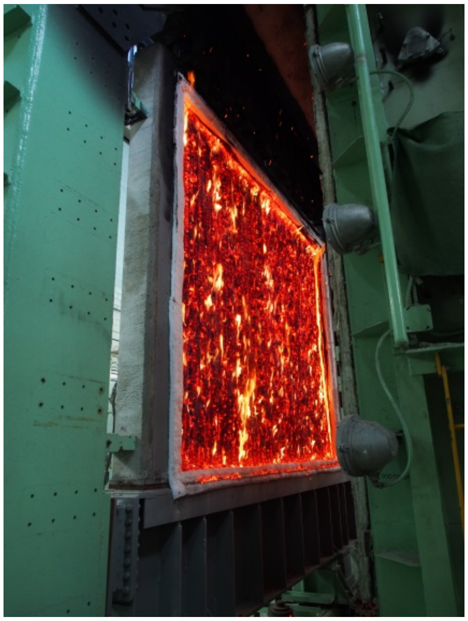


Figure 20. 2x6 NLT wall at end of test.

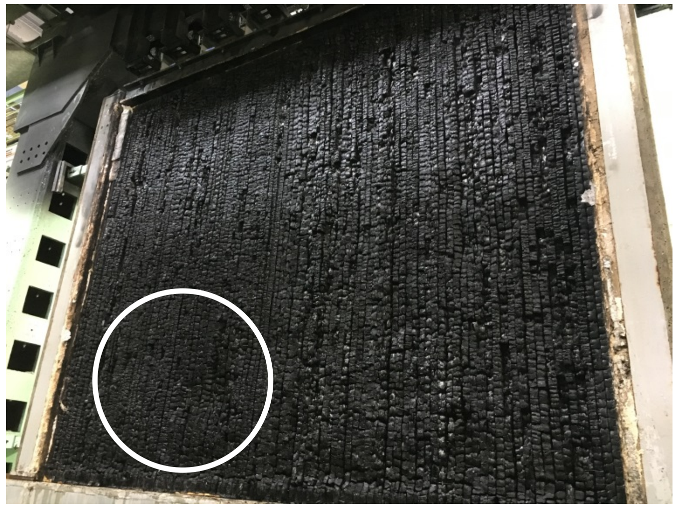


Figure 21. 2x6 NLT wall surface after test, depression.

Figure 22. 2x6 NLT wall structural failure, deflection.

The average furnace temperature during the test is shown in Figure 23. Average embedded thermocouple temperatures (for depths of 15 mm, 25 mm, 50 mm, and 75 mm) are shown in Figure 24; in this figure thermocouple measurements in the joint are depicted by a dashed line. The thermocouple 15 mm deep at location B (2-B-15) malfunctioned between 41 to 46 min and the thermocouple 25 mm deep at location B (2-C-25) also malfunctioned; this data was not included in the plot.

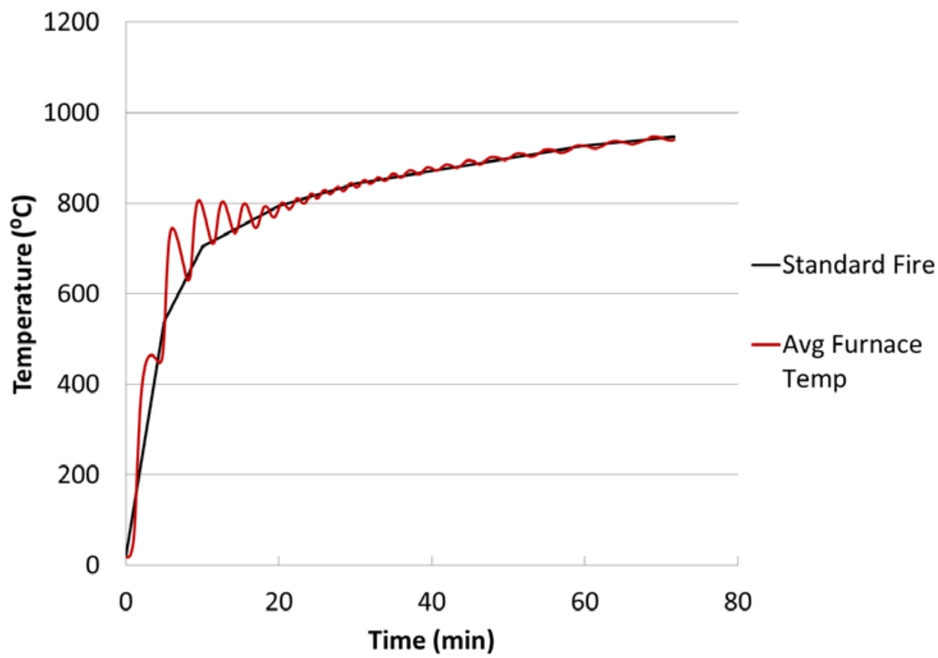



Figure 23. 2x6 NLT wall furnace temperature.

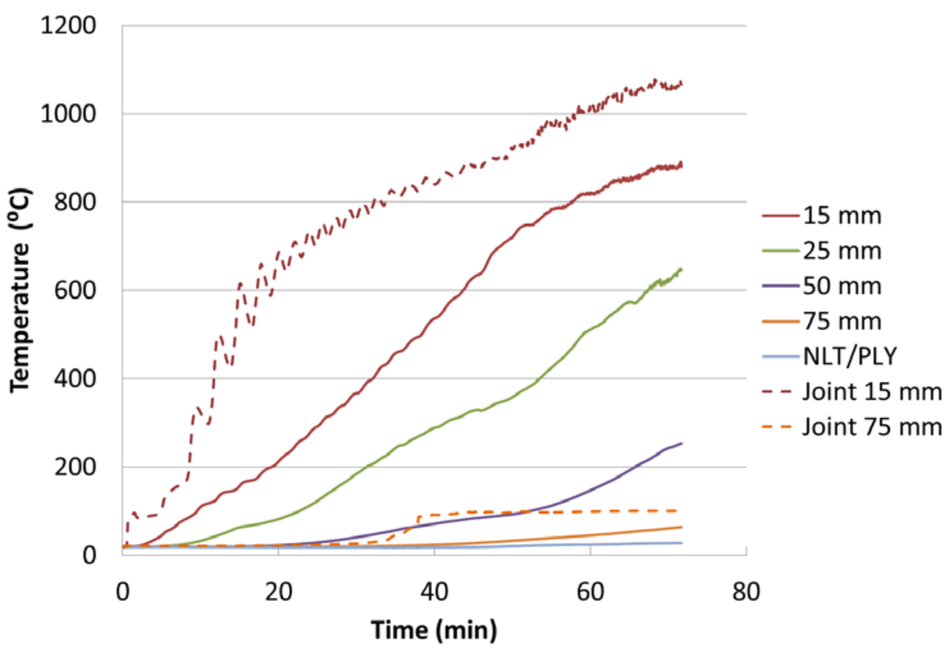



Figure 24. 2x6 NLT wall average temperatures at embedded thermocouple locations.

Despite several locations of integrity failure, the maximum measured temperature increase from thermocouples on the unexposed side was 41°C. This is within the limit according to CAN/ULC-S101, where temperatures on the unexposed side cannot rise more than an average of 140°C or more than 180°C at any individual point.

At failure, the maximum deflection was 67 mm at mid-height (not including initial preload deflection). Maximum deflection throughout the test is shown in Figure 25.

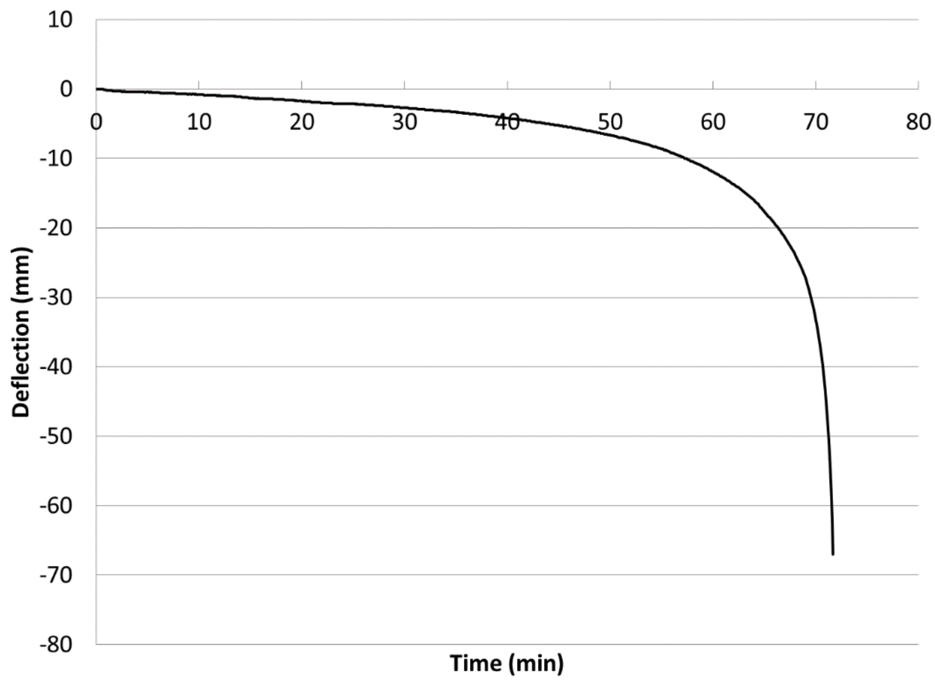



Figure 25. 2x6 NLT wall maximum deflection.

Figure 26 shows the unexposed wall surface after it has been removed from the furnace, with various locations of plywood installed to cover locations of burn-through.

After the test, the plywood on the unexposed side of the assembly was removed to assess the condition of the NLT itself. Figure 27 shows the wall assembly with some of the plywood panels removed, revealing the extent of burn-through at different locations. A section was cut to evaluate the depth of charring around the location of the first burn-through where there appeared to be the most significant depth of charring. The cut section is shown in Figure 28. Figure 29 shows the typical depth of char at a location where no burn-through occurred. The residual depth was determined to be between 75 to 85 mm based on physical measurements and a resistograph.

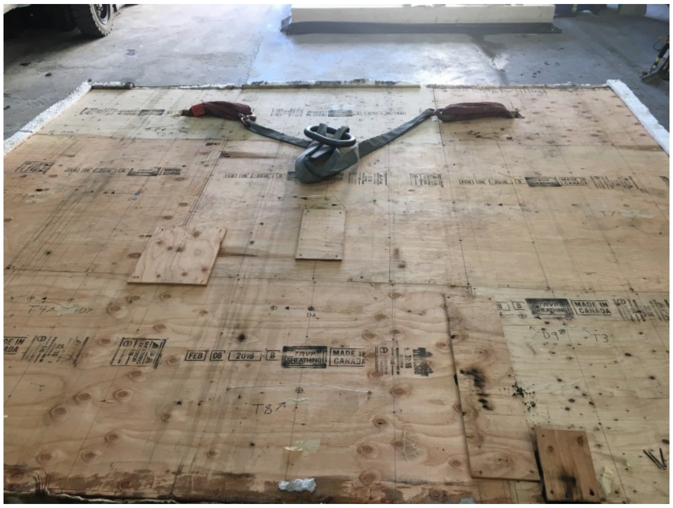


Figure 26. 2x6 NLT wall layout of added plywood pieces.

Figure 27. 2x6 NLT wall unexposed surface after plywood removal.

Figure 28. 2x6 NLT wall section taken at primary failure.

Figure 29. 2x6 NLT wall typical depth of char.

## 5.2 2x8 Wall

The 2x8 wall was tested on October 26, 2018. A vertical load of 450 kN/m was applied. During preloading the initial maximum mid-height deflection was 3 mm. The ambient temperature on the unexposed side at the beginning of the test was 18°C. The first layer of gypsum was observed to begin falling off after 90 min. The second layer began falling off after 2 h. The test ran until structural failure at 3 h 37 min. Figure 30 shows the exposed side of the assembly after the test. Structural failure is shown in Figure 31 and the condition of the exposed side of the assembly after cooling is shown in Figure 32. A similar depression, as was noted in the 2x6 wall test, was also observed in the 2x8 wall test, indicating increased charring where furnace pressure was negative and thus drawing more air.

Figure 30. 2x8 NLT wall after test.

Figure 31. 2x8 NLT wall structural failure.

Figure 32. 2x8 NLT wall exposed surface after test, depression.

The average furnace temperature during the test is shown in Figure 33. Average embedded thermocouple temperatures (for depths of 15 mm, 25 mm, 50 mm, and 75 mm) are shown in Figure 34; in the figure thermocouple measurements in the joint are depicted by a dashed line. The thermocouple embedded 15 mm at location A (TC 1-A-15) was not included in the average plot because it malfunctioned.

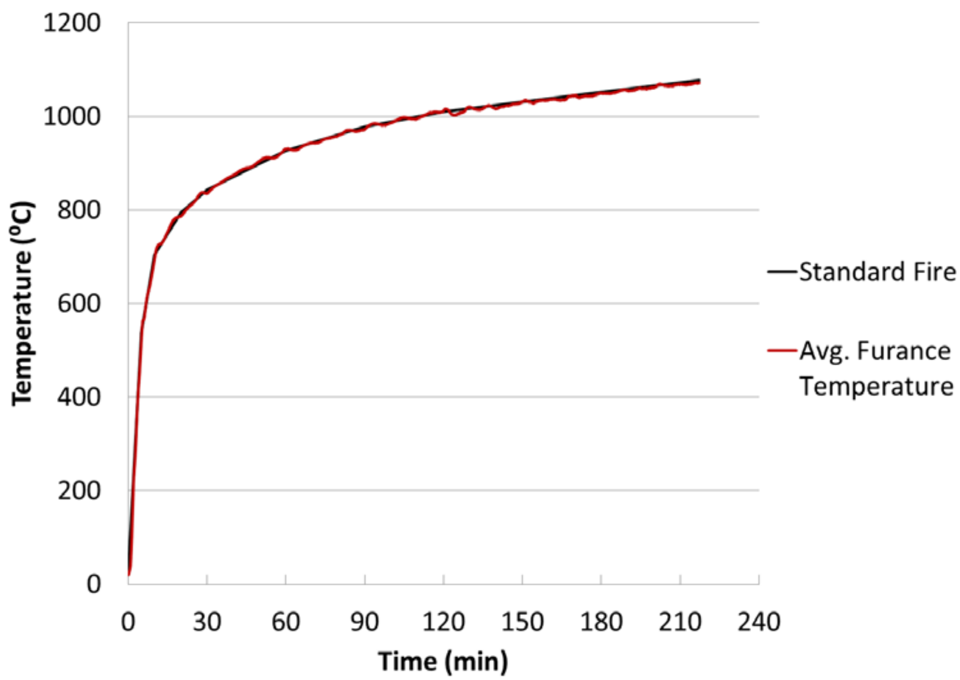



Figure 33. 2x8 NLT wall furnace temperature.

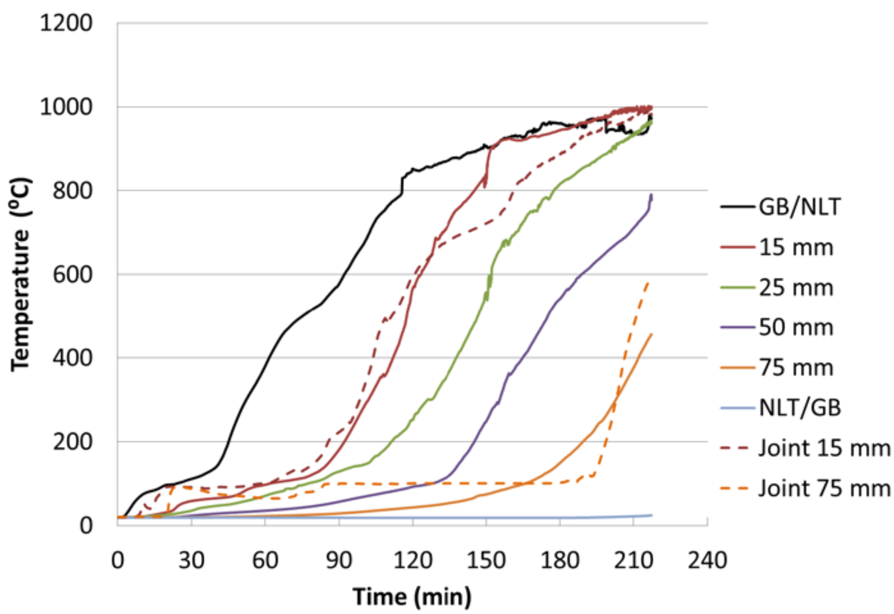



Figure 34. 2x8 NLT wall average temperatures at embedded thermocouple locations.

Temperatures on the unexposed did not increase; they actually decreased on average by about 1$^{o}$C from the initial ambient temperature. This decrease can be attributed to the opening of a loading door to provide ventilation to the lab during the test.

At failure, the maximum deflection was 120 mm at mid-height (not including the initial preload deflection). Maximum deflection throughout the test is shown in Figure 25.

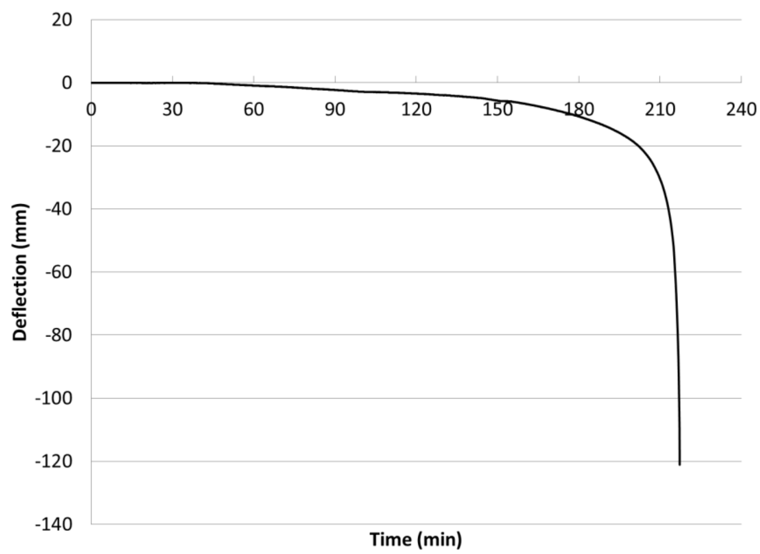



Figure 35. 2x8 NLT wall maximum deflection.

Following the test the gypsum board was removed from the unexposed side of the assembly to inspect the condition of the NLT. Figure 36 indicates three locations of burn-through that were observed. The largest spot, in the centre of the figure, is associated with the location of increased char depth noted on the exposed side, and coincided with where the wall cracked during structural failure. A section was cut from the wall to assess the depth of char. The wall was also pulled apart to investigate how charring varied along the height of the wall, as shown in Figure 37. The residual depth was determined to be between 90 to 95 mm based on physical measurements and a resistograph.

Figure 36. 2x8 NLT wall unexposed surface after test, gypsum removed.

Figure 37. 2x8 NLT wall depth of charring along length of board.

## 5.3 2x6 Floor

The 2x6 floor was tested on October 11, 2018. A 4.8 kPa vertical load was applied. During preloading the initial maximum deflection was 8 mm at centre span. The ambient temperature on the unexposed side at the beginning of the test was 20$^{o}$C.

At the beginning and periodically during the test, light smoke leakage came through at some of the plywood joints, as shown in Figure 39. The test was stopped 101 min into the test because the temperature in the exhaust exceeded a safety threshold. This is thought to be a result of increasing deflection which may have exposed uncharred wood between the boards, i.e., opened up gaps between the boards. Figure 38 shows temperature measurements at the nine locations inside the furnace, as well as the average and the standard fire curve. Around 90 min, three readings began to increase beyond the standard fire temperature, while the others began to decrease. With this overall average decrease in temperature, it is thought that the automated system tried to compensate by adding more propane to the furnace. This ultimately led to a fuel rich environment and a lack of oxygen which limited the ability for burning to occur inside the furnace. As the gases were exhausted it mixed with oxygen and was then able to burn, thus burning occurred in the exhaust pipe and raised the temperature within the exhaust beyond safe levels. At this point the furnace was turned off.

Upon inspection of the assembly after the test, it was evident that structural failure would likely have occurred soon had the test not been stopped. Figure 40 shows the removal of the floor from the furnace. Figure 41 shows the charred surface of the floor after it had cooled and Figure 42 shows a location of burn-through (that occurred after the furnace was turned off). Once the furnace was turned off, the dynamics inside the furnace change, which could partially explain why burn-through occurred shortly later. It takes a few minutes from the end of the test until the assembly can be removed from the furnace and any remaining flames extinguished, which is an opportunity for the assembly to continue to burn. At these post-test burn-through locations, increased charring must have been occurring during the test for burn-through to occur so quickly after the test.

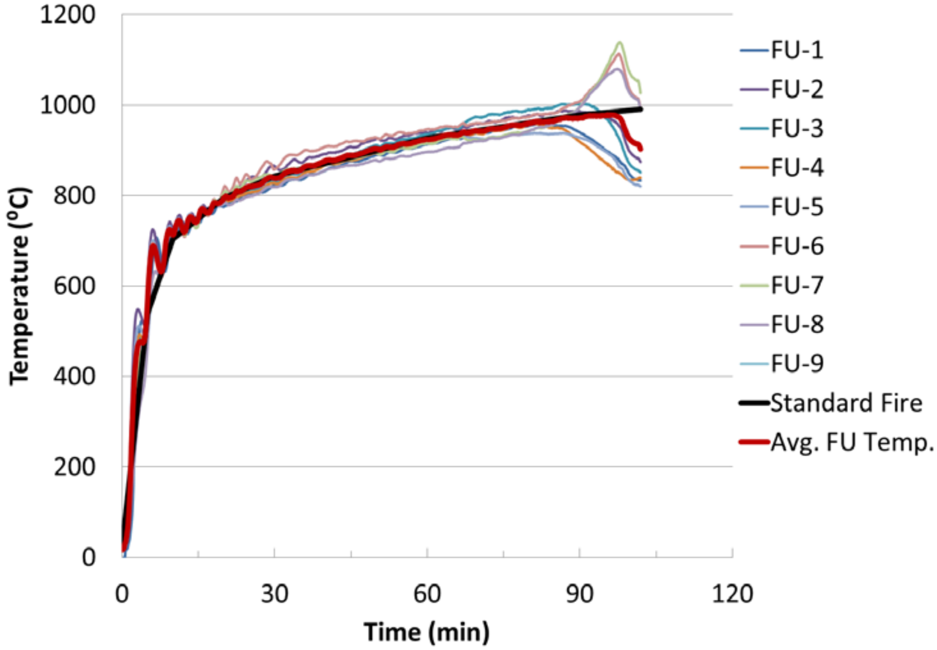



Figure 38. 2x6 NLT floor furnace temperatures.

Figure 39. 2x6 NLT floor intermittent light smoke leakage during test.

Figure 40. 2x6 NLT floor removal from furnace.

Figure 41. 2x6 NLT floor condition of exposed surface after test.

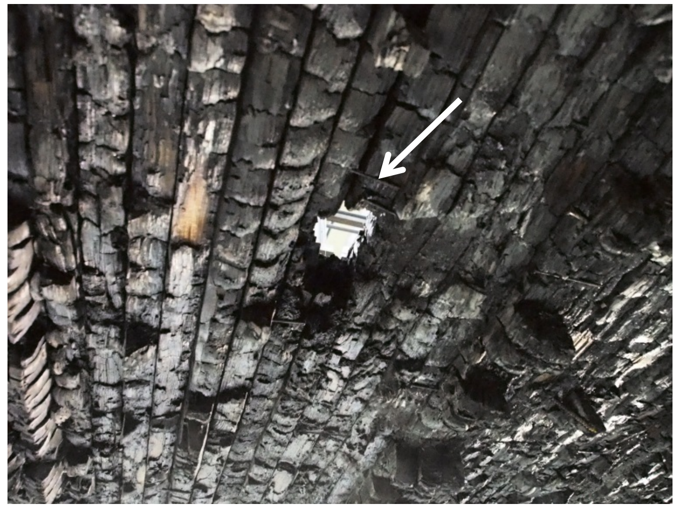


Figure 42. 2x6 NLT floor burn-through after test.

Average embedded thermocouple temperatures (for depths of 15 mm, 25 mm, 50 mm, and 75 mm) are shown in Figure 43; in the figure thermocouple measurements in the joint are depicted by a dashed line. Embedded thermocouples up to 25 mm experienced a similar peak and decrease in temperature as was noted for several furnace temperatures. The thermocouple at 75 mm at location A (5-A-75) appeared to malfunction after 95 min, this data is not included in the average plot.

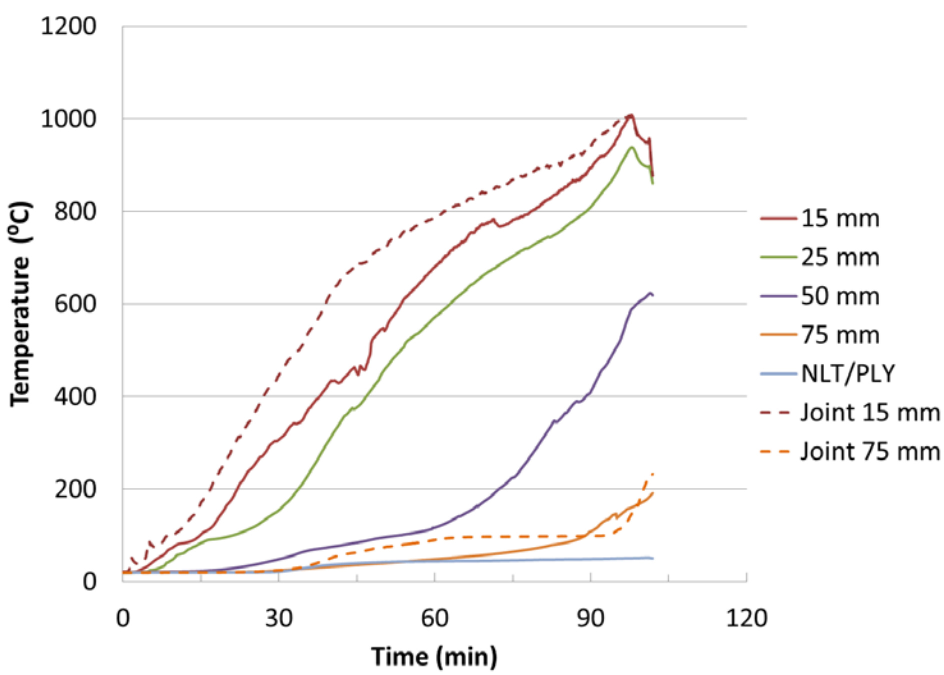



Figure 43. 2x6 NLT floor average temperatures at embedded thermocouple locations.

The maximum measured temperature increase from thermocouples on the unexposed side was 24°C. At failure, the maximum deflection was 87 mm, measured at mid-length (not including initial pre-load deflection). Maximum deflection throughout the test is shown in Figure 44.

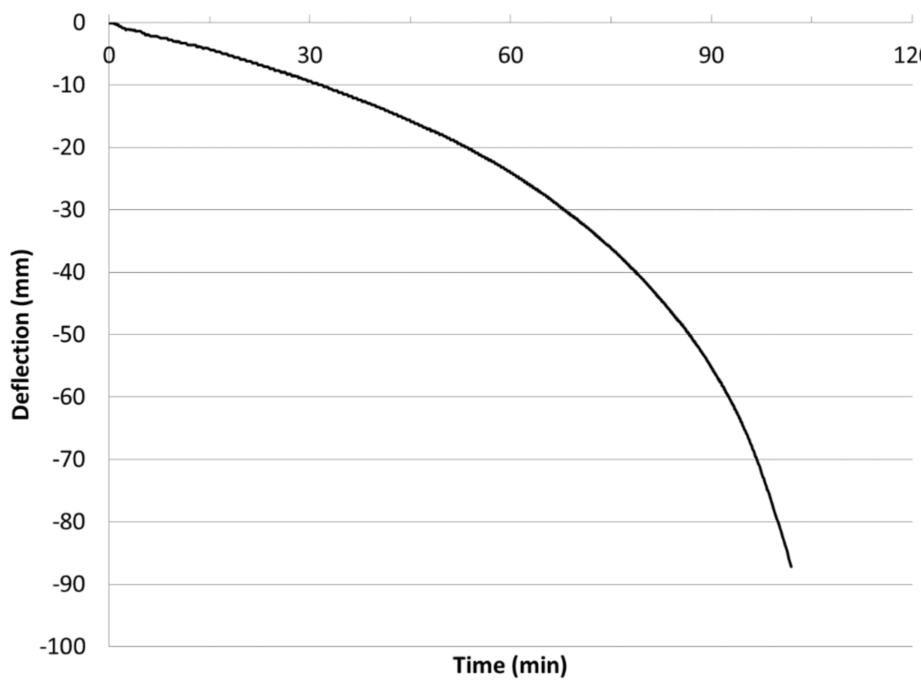



Figure 44. 2x6 NLT floor maximum deflection.

Following the test, the condition of the assembly was assessed. The unexposed side of the assembly after the test is shown in Figure 45. There was discolouration at some plywood joints where smoke leakage had occurred. Five locations of charring through the assembly and plywood were noted, which occurred after the test had ended. Figure 46 shows a close-up view of one spot from the unexposed side. The plywood was removed to assess the overall condition of the NLT, as shown in Figure 47. For the majority of the assembly there was no evidence of charring behind the plywood. A sample was cut to evaluate the typical depth of char, as shown in Figure 48. The residual depth was determined to be between 65 to 75 mm based on physical measurements and a resistograph.

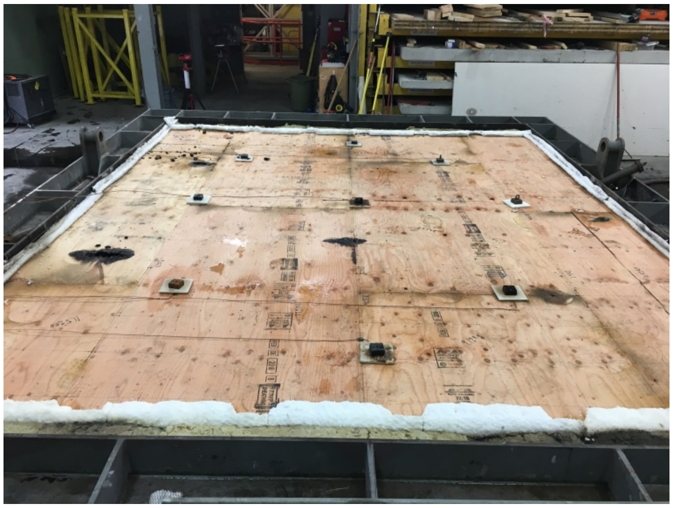


Figure 45. 2x6 NLT floor unexposed surface after test. Charring through plywood after end of test.

Figure 46. 2x6 NLT floor location of burn-through.

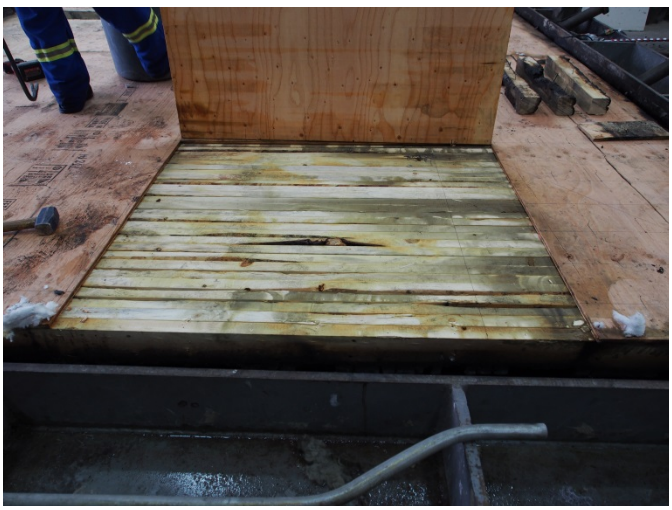


Figure 47. 2x6 NLT floor condition of NLT unexposed surface, plywood removed.

Figure 48. 2x6 NLT floor depth of char in cut sample.

# 6. DISCUSSION

## 6.1 Charring

Based on the average temperature readings at each of the thermocouple depths, an average charring rate was calculated assuming charring occurred once 300°C was reached. The average time that each thermocouple depth reached 300°C and the associated calculated average charring rates are presented in Table 2. Any malfunctioning thermocouples were not included in these calculations.

Neither the 2x6 wall nor the 2x6 floor reached 300°C at the 75 mm depth, except for one thermocouple in the floor. For the 2x8 wall, the initial onset of charring was taken as the encapsulation time of 47.7 min, which is discussed in the following section (6.1.1 Encapsulation).

Table 2. Charring rates for NLT assemblies

| | Thermocouple Depth | 15 mm | 25 mm | 50 mm | 75 mm |
|---|---|---|---|---|---|
| 2x6 Wall | Time to 300°C (min) | 26.6 | 45.4 | 64.8[1] | _ |
| | Charring rate (mm/min) | 0.56 | 0.55 | 0.77 | _ |
| 2x8 Wall[2] | Time to 300°C (min) | 30.0 | 78.2 | 109.7 | 152[3] |
| | Charring rate (mm/min) | 0.42 | 0.30 | 0.43 | 0.49 |
| 2x6 Floor | Time to 300°C (min) | 32.1 | 41.5 | 83.9 | _[4] |
| | Charring rate (mm/min) | 0.47 | 0.60 | 0.60 | _ |

[1] Only 2 thermocouples exceeded 300°C

[2] Protected with two layers of 12.7 mm (½”) Type C gypsum

[3] Only 4 thermocouples exceeded 300°C

[4] Only 1 thermocouple exceeded 300°C

A one-dimensional char rate of 0.65 mm/min is commonly used for softwoods, and can also be used for other mass timber products such as glulam and SCL [6]. The measured charring rates of the NLT were generally less than this value except as calculated for the 50 mm depth in the 2x6 wall. At this location only two thermocouples were used to calculate the charring rate, as the others did not exceed 300°C, so charring was likely slower at the other locations.

The 2x8 wall exhibited consistently slower charring rates than the other two assemblies. This can be attributed to gypsum board which stayed in place well beyond the encapsulation time. The first layer fell off around 90 min and the second layer after 2 h. The inclusion of direct applied gypsum board to mass timber not only delays the onset of charring and involvement in the fire, but also continues to insulate the wood while it stays in place, thus reducing the charring rate of the wood. This effect can be observed in Table 2 where the charring rates for the 2x8 wall up to 120 min are less than 0.45 mm/min (when gypsum boards were still in place) and increased to 0.49 mm/min after 152 min (gypsum board no longer in place).

The charring rates presented are intended to represent the typical observed behaviour and do not account for localized spots of increased charring. Because of the repetitive nature of NLT construction, a few local spots of increased charring do not seem to have a significant impact on the overall residual structural capacity of the assembly after fire exposure.

The depth of the remaining cross-section was evaluated after the tests using a resistograph and by visual measurements, the determined values are given in Table 3. Resistograph measurements were taken close to where embedded thermocouples were placed. Samples were cut from locations with the apparent greatest depth of charring; visual measurements of the residual cross-section were taken on these samples. The overall charring rate was calculated from these measurements and the length of the test. The assemblies were able to continue charring for a few minutes following the end of the tests before the fire was extinguished, so the exposure time was slightly longer than the reported end of test, which would increase the calculated charring rate. Generally these charring rates are higher than where determined from thermocouple measurements. This could be in part due to the precision of the resistograph or interpretation of the results. The visual measurements were taken at locations of apparent greater charring and are not necessarily representative of the entire specimen.

Table 3. Measured char depth of NLT assemblies

| | Initial Depth (mm) | Residual Section | | Estimated Char Depth (mm) | Length of Test | Charring Rate (mm/min) |
|---|---|---|---|---|---|---|
| | | Visual (mm) | Resistograph (mm) | | | |
| 2x6 Wall | 140 | 75 | 85 | 65 | 1 h 11 min | 0.92 |
| 2x8 Wall | 184 | 90 | 92 | 94 | 3 h 37 min | 0.55[1] |
| 2x6 Floor | 140 | 65 | 63 | 77 | 1 h 41 min | 0.76 |

[1] Accounting for 47.7 min encapsulation time

### 6.1.1 Encapsulation

Encapsulation time was determined as the time that the average of the thermocouples between the gypsum board and the NLT on the exposed side increased 250$^o$C or any one point increased 270$^o$C, whichever is less, as is currently being considered for acceptance into the NBCC for encapsulated mass timber construction [7] as per the new standard test method CAN/ULC S146 [8] (under-development/review). The encapsulation time for two layers of ½" Type C gypsum board directly attached to NLT was determined to be 47.7 min based on a single point. The average time to reach 250$^o$C was 51.3 min. The times 250$^o$C and 270$^o$C temperature increases were reached at each of the thermocouple location is given in Table 4.

Table 4. Encapsulation time for 2x8 NLT wall

| Thermocouple Location | A | B | C | D | E |
|---|---|---|---|---|---|
| Time to 250$^o$C (min) | 51.3 | 48.9 | 46.0 | 51.7 | 49.8 |
| Time to 270$^o$C (min) | 52.8 | 50.7 | 47.7 | 53.8 | 51.3 |

For other mass timber products with more uniform surfaces, such as CLT, using two layers of 12.7 mm (½") Type X gypsum can be used to increase fire resistance by 60 min [4]. The delay in the onset of charring in these tests was less than 60 min for these NLT assemblies, however these were loaded tests and would be considered more severe than a standard encapsulation test. The NLT wood surface was not perfectly smooth which could have generated stresses in the boards during gypsum installation and reduced their effectiveness. Installation of gypsum board on to NLT assemblies and how it affects fire resistance warrants further investigation.

## 6.2 Preventing Insulation and Integrity Failure

The FRR of an assembly determined in accordance with CAN/ULC-S101 is based on three failure criteria:

1. Structural failure: inability to sustain the applied load.
2. Integrity failure: passage of flame or hot gases through the assembly, enough to ignite a cotton pad.
3. Insulation failure: thermocouples on the unexposed surface measure an average temperature increase of 140°C, or a single point increase of 180°C.

For both the 2x6 wall and 2x6 floor tests, localized increased charring was an issue. Both of these assemblies only had 12.7 mm (½") plywood on the unexposed side, as compared to the 2x8 wall with two layers of gypsum on both sides. The integrity failure in the 2x6 wall test reduced the assigned FRR of the assembly. For the 2x6 floor, although structural failure was not reached, several locations that could have led to integrity failures became apparent at the end of the test. It is likely that the inclusion of additional protection on the unexposed side (for example gypsum board for the wall, or a concrete topping on the floor) would aid in delaying or preventing integrity failures. A 15.9-mm Type X gypsum board can provide 30 minutes of additional fire resistance to CLT assemblies when used on the exposed side [6]; if this were to be used on the unexposed side of an NLT wall assembly above a layer of plywood, it is expected that it would provide additional protection time due to the reduced localized fire exposure on the unexposed side.

Because of the nature of NLT as a product, using multiple lumber boards laminated together, the natural imperfections in the lumber can impact the quality of the assembly. There are various defects that are typical in lumber such as twisting, cupping, bowing, wane, etc. These can result in two boards not pressed in full contact with each other, which can create gaps or pockets between the boards which can lead to localized increased charring rates. Figure 49 to Figure 51 show examples of gaps that formed during construction of these assemblies. Care should be taken in the selection of boards for use in NLT to limit the creation of these kinds of gaps. It may be prudent to press boards together during nailing, to increase contact between boards to improve quality and fire resistance. Moisture content of boards should be monitored to avoid unnecessary creation of gaps due to wood shrinkage once assemblies are in service. These measures will help to minimize and limit the size and number of gaps between boards, which should reduce the possibility of integrity failures. Additional layers of protection on the unexposed side which create an air barrier may also limit charring at these gaps if it prevents airflow through the system. A cross-section of NLT is shown in Figure 52, indicating that the surface is not perfectly smooth. This can affect the application of direct applied gypsum board, but creating local air gaps behind the board. More research is warranted to investigate methods to address local integrity failure in NLT assemblies.

Figure 49. Gap between NLT boards.

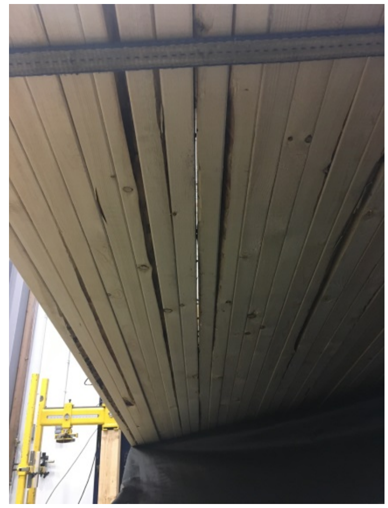


Figure 50. Light able to pass through assembly.

Figure 51. Gap due to wane.

Figure 52. Cross-section of NLT.

## 6.3 Fire Resistance Ratings

The assigned FRRs for each of the assemblies are given in Table 5. As mentioned previously, the 2x6 wall assembly could have achieved a greater FRR had additional protection been provided on the unexposed side to delay integrity failure.

Table 5. Assigned fire resistance ratings for NLT assemblies.

| Assembly | Thickness | Protection | Load | FRR | Type of failure |
|---|---|---|---|---|---|
| **2x6 Wall** | 140 mm | 12.7 mm plywood on unexposed | 335 kN/m | 30 min[1] | Integrity |
| **2x8 Wall** | 184 mm | 2 layers 12.7 mm Type C gypsum board, both sides | 450 kN/m | 3 h | Structural |
| **2x6 Floor** | 140 mm | 12.7 mm plywood on unexposed | 4.8 kPa | 1.5 h | [2] |

[1] Structural failure happened after 1 hour

[2] Test stopped before failure reached

The NBCC prescribes FRRs for solid timber based on minimum thicknesses up to a maximum of 1.5 h, presented in Table 1. The NBCC would assign a FRR of 1 h to a 140-mm NLT wall, without any protection on the unexposed side. The 2x6 wall test demonstrated that, a solid wood wall alone (or with plywood on the unexposed side) cannot achieve this rating due to increased charring if gaps are present. Design guidelines for NLT should reflect this behaviour, and provisions should be included to address prevention of premature flame-through. The NBCC does indicate that the inclusion of protection methods on the exposed side of a solid wood assembly can increase the FRR by 15 min (D-2.4.2.). Provisions should also be provided to account for other methods of encapsulation that can significantly prolong the FRRs. Further research is warranted to better understand the fire resistance of NLT and how different methods of protection affect fire resistance of walls and floors.

The results of the 2x6 floor test demonstrated that a 140 mm floor with a plywood subfloor can achieve a 1.5 h rating. The plywood likely delayed integrity failure the same as would finish flooring, as is prescribed by the NBCC; a 140-mm floor has a 45 min prescribed FRR. Protection on the unexposed side is important to slow air flow through the assembly at gaps and to slow the potential of increased charring.

The NBCC also prescribes the use of 101 mm (4”) common nails to construct these assemblies. In these test 75 mm (3”) nails were used which were sufficient for the floor assembly to achieve better ratings than are prescribed in the NBCC.

# 7. CONCLUSION

FPInnovations conducted three full-scale fire resistance tests at the NRC Fire Research Laboratory in Ottawa, ON in October 2018. The details of the assemblies and the results of the tests are summarized in Table 6.

Table 6. Assigned fire resistance ratings for NLT assemblies.

| Assembly | Thickness | Protection | Load | Failure | Fire Resistance | Type of failure |
|---|---|---|---|---|---|---|
| **2x6 Wall** | 140 mm | 12.7 mm plywood on unexposed | 335 kN/m | 33 min | 30 min [1] | Integrity |
| **2x8 Wall** | 184 mm | 2 x 12.7 mm Type C gypsum board, both sides | 450 kN/m | 3 h 37 min | 3 h | Structural |
| **2x6 Floor** | 140 mm | 12.7 mm plywood on unexposed | 4.8 kPa | [2] | 1.5 h | [2] |

[1] Structural failure happened after 1 hour (failure at 1 h 11 min)

[2] Test stopped at 1 h 41 min before failure reached

This research demonstrates that NLT can be designed to safely meet various FRR requirements. It is important that protection be provided on the unexposed side of assemblies to limit air flow to address the potential of integrity failures due to gaps that can form between NLT boards. Care should be taken during construction to limit the creation of gaps, such as by pressing boards during nailing or quality control checks to remove any boards with excess bends, twists, wane, etc. Moisture content should also be controlled to inhibit the creation of gaps due to wood shrinkage during service conditions.

This data can be used to support future building code changes related to solid timber or the inclusion of a fire resistance calculation methodology for NLT assemblies in Annex B of CSA-O86.

# REFERENCES

[1] "Nail-Laminated Timber. Canadian Design & Construction Guide v1.0," Binational Softwood Lumber Council & Forestry Innovation Investment Ltd, 2018.

[2] "Nail-Laminated Timber. U.S. Design & Construction Guide v1.0," Binational Softwood Lumber Council, 2017.

[3] "National Building Code of Canada," Canadian Commission on Building and Fire Codes. National Research Council Canada, Ottawa, ON, 2015.

[4] CSA, "CSA-O86-14: Engineering Design in Wood," CSA Standards, Mississauga, ON, 2014.

[5] *CAN/ULC-S101-14. Fire Endurance Tests of Building Construction and Materials,* Toronto, ON: Underwriters Laboratory of Canada (ULC), 2014.

[6] C. Dagenais, "Fire performance of cross-laminated timber assemblies (revised)," in *CLT Handbook*, Quebec, QC, FPInnovations, 2014.

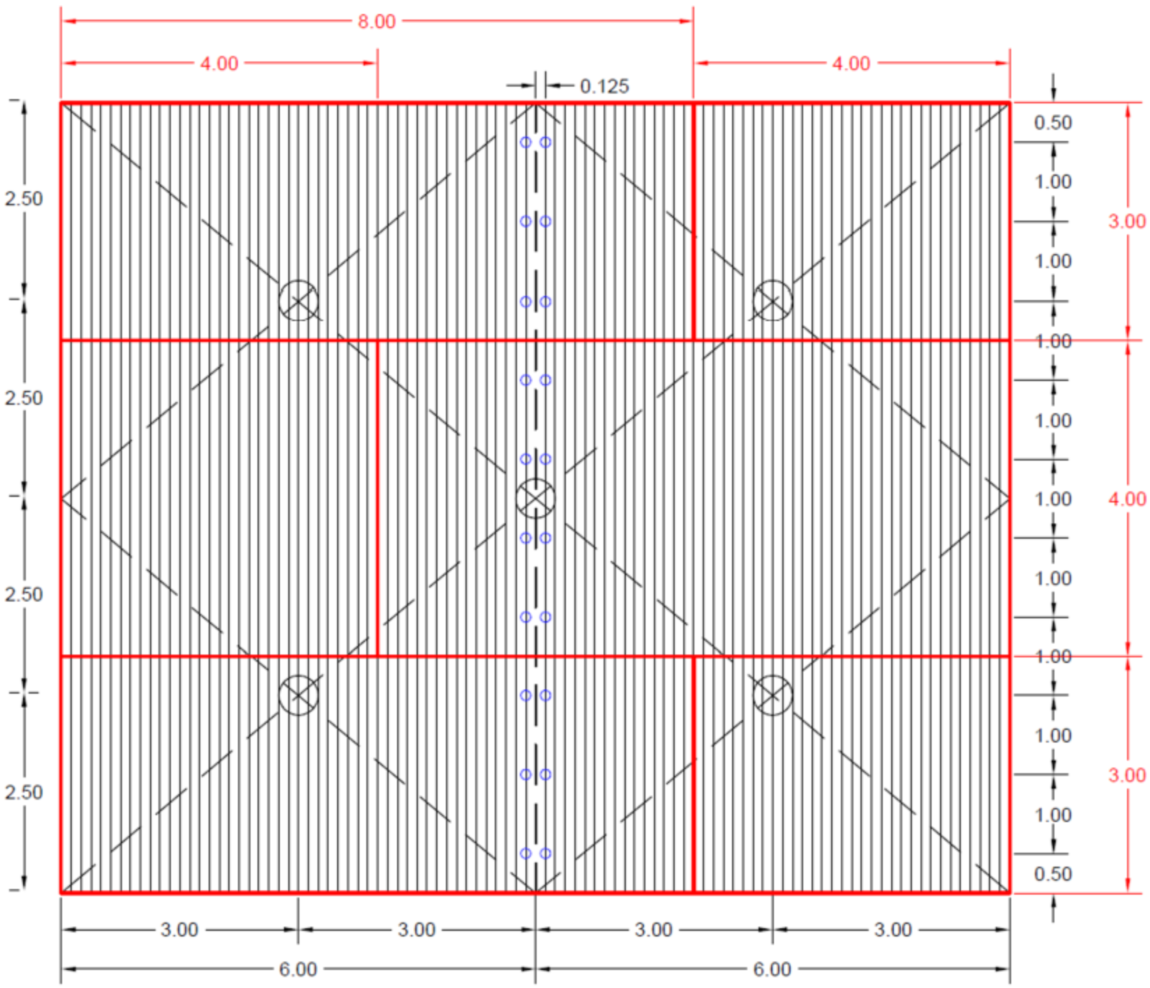
[7] "National Building Code of Canada Proposed Change 1027. NBC15 Div.B 3.1. Encapsulated Mass Timber Construction," Canadian Commission on Building and Fire Codes, 2017.

[8] "CAN/ULC S146. Standard Method Of Test For The Evaluation Of Encapsulation Materials And Assemblies Of Materials For The Protection Of Structural Timber Elements. Under Development," Underwriters Laboratories Canada Inc., Ottawa, ON, 2018.

# APPENDIX I – 2X6 WALL PLYWOOD DETAIL

## 2x6 NLT Wall

Plywood Layout. Dimensions in ft.

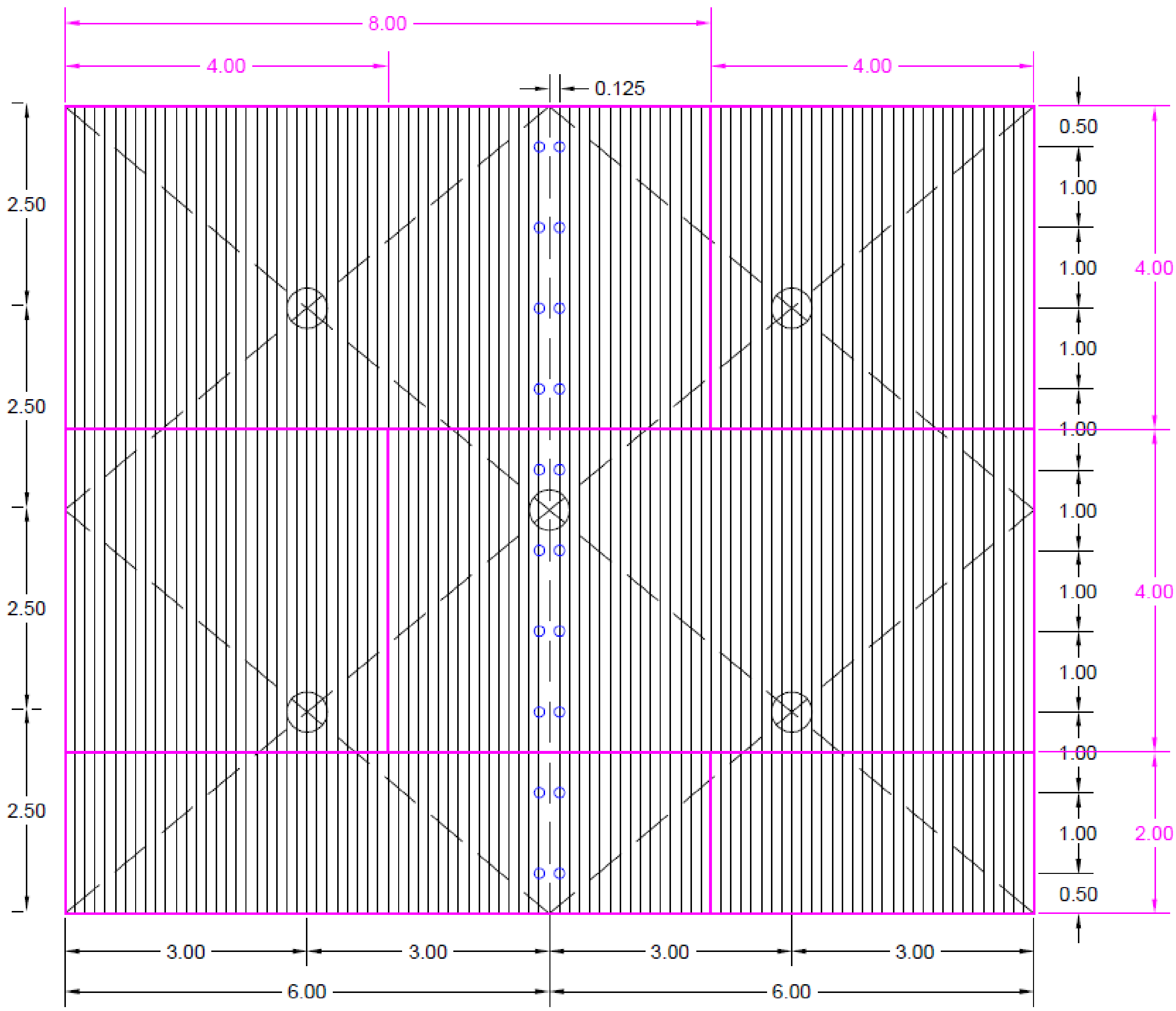


# APPENDIX II – 2X8 NLT WALL GYPSUM DETAIL

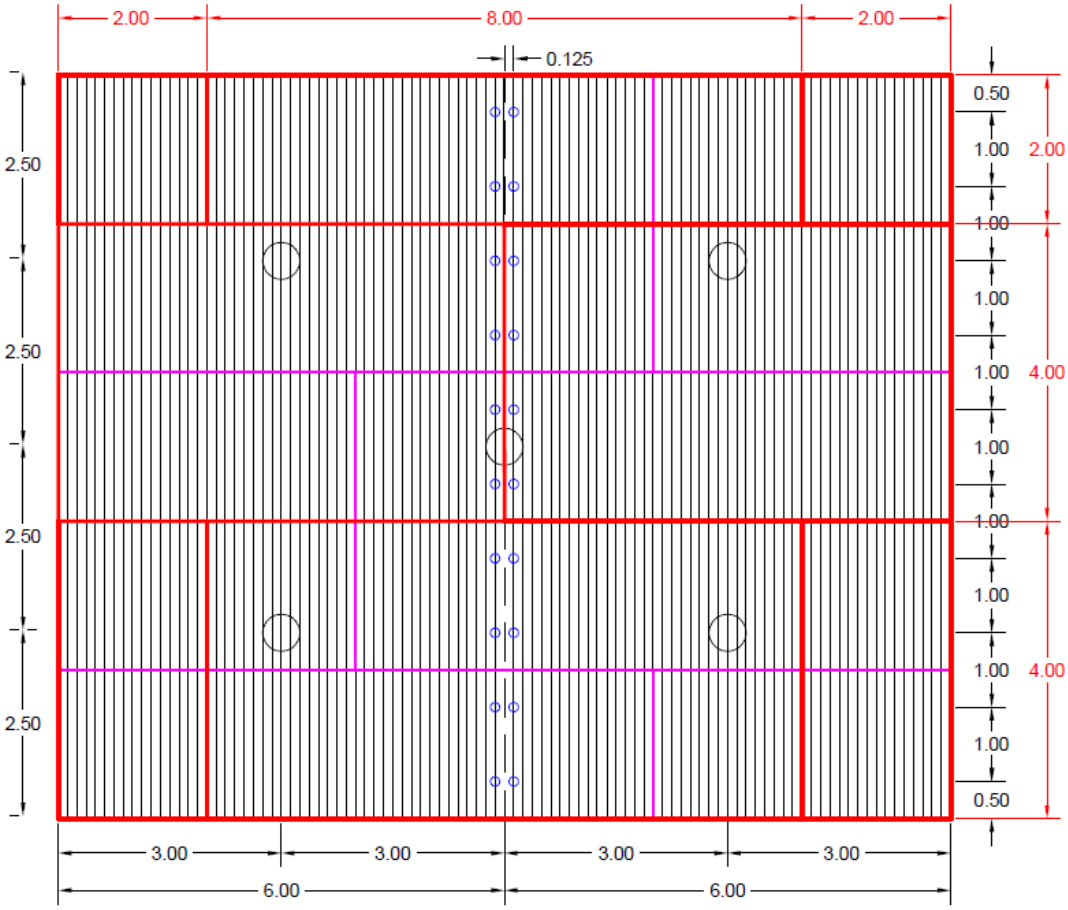
## 2x8 NLT Wall

12.7 mm (½”) Type C Gypsum Layout. Dimensions in ft.

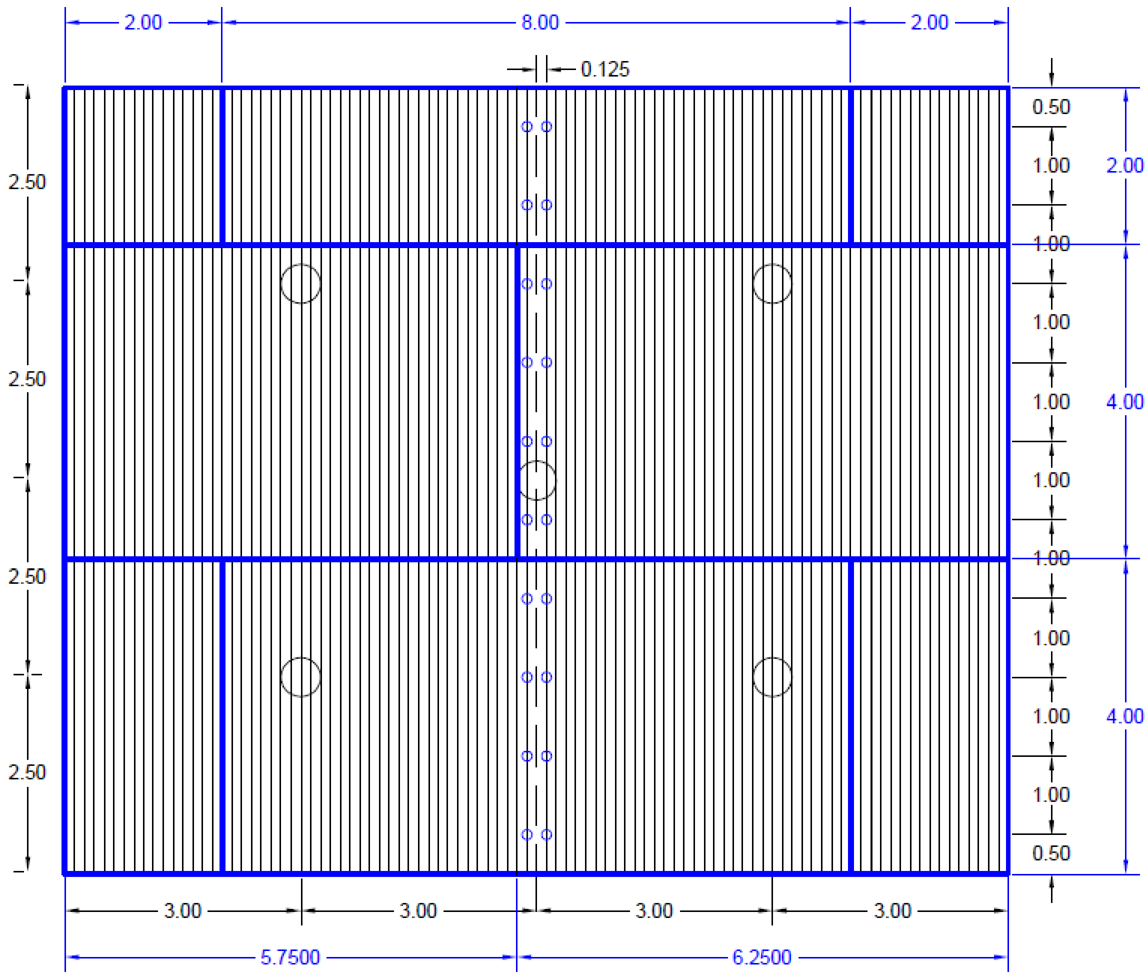
Exposed Base Layer



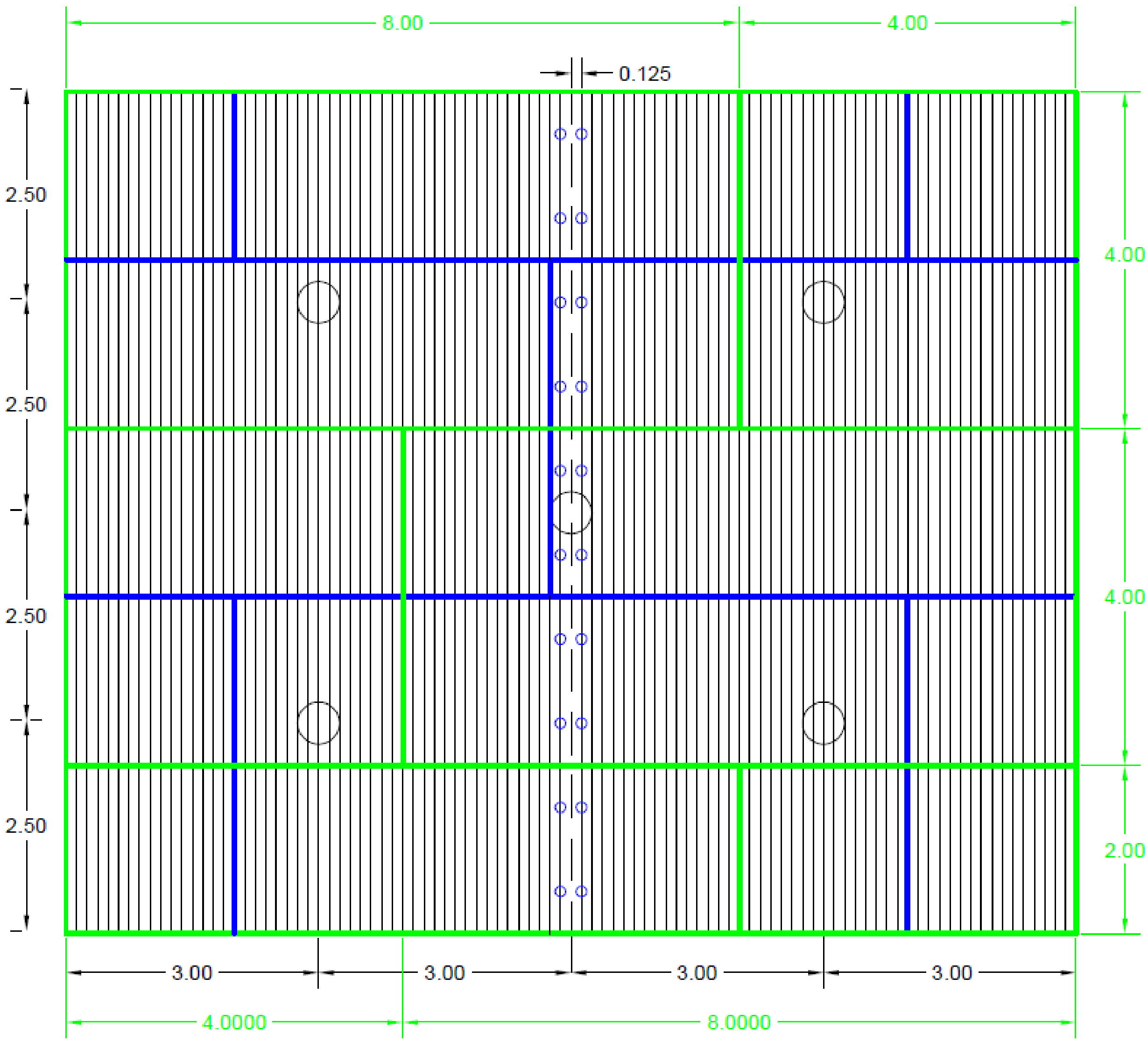
## Exposed Face Layer



Unexposed Base Layer



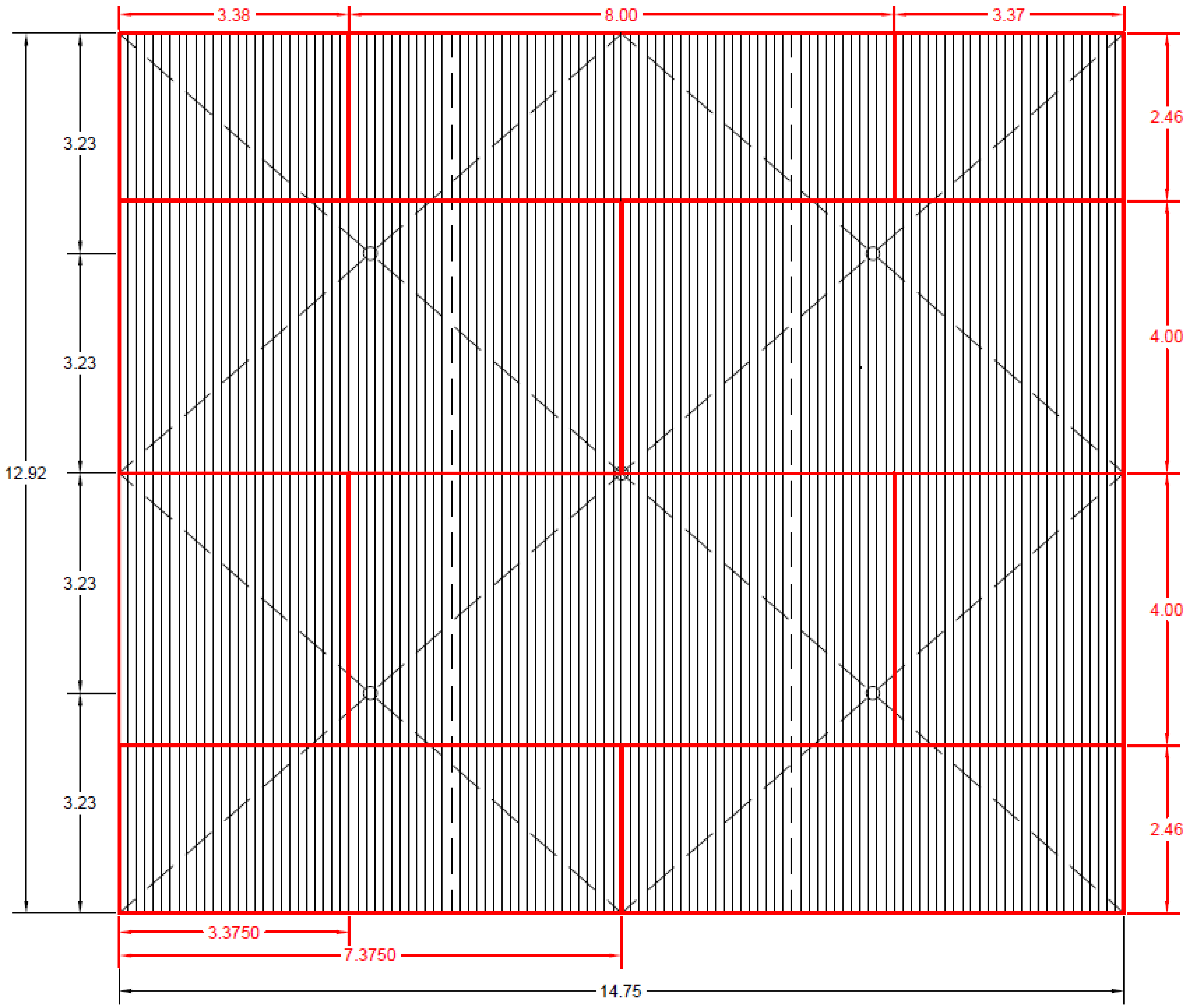
Unexposed Face Layer



# APPENDIX III – 2X6 NLT FLOOR PLYWOOD DETAIL

## 2x6 NLT Floor

12.7 mm (½”) Plywood Layout. Dimensions in ft.



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