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WOODWISE: LARGE-SCALE COMPARTMENT FIRE TESTS EXAMINING SUSTAINABILITY, SMOLDERING, AND EMISSIONS

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ABSTRACT: In the United States, timber is a common building material in low and medium-rise construction, up to 25.9m (85ft). Through research and innovation, code changes were enacted in 2021 that eliminated barriers to high-rise mass timber buildings. However, some stakeholders have observed that major technical barriers remain. Specifically, the structural performance of timber during all phases of a fire and resulting emissions from buildings using combustible construction. This paper summarizes a multi-disciplinary research program designed to address the challenges in a holistic and systematic manner through four large-scale fire tests within mass timber compartments with fuel loads of 798 MJ/m^2 of real furnishings, with and without encapsulation. The results of this research will be used to improve engineering design methodologies and demonstrate the role these structures play in meeting the sustainability targets of the building construction industry.

KEYWORDS: Fire safety, mass timber, compartment fires, smoke.

1 – INTRODUCTION AND BACKGROUND

Buildings contribute nearly 40% of the total global greenhouse gas emissions, with 11% directly attributed to building materials. Mass timber products are a potential solution to reducing these emissions through structures that sequester carbon and promote healthy forest management techniques. Despite these benefits, projects are still experiencing approval issues. Recently, the California State Fire Marshal prevented the use of mass timber applications in hospitals citing a lack of research to meet Immediate Occupancy performance objectives in fire [1]. This stipulation demonstrates the need to further the understanding of fire propagation through mass timber buildings under real fire scenarios so that engineers can design for these performance objectives.

Projections of the building construction industry conclude that the number of mass timber buildings in North America will double every two years starting in 2020 [2]. For this market increase to be actualized, modern architectural and developer needs require an increase in the amount of mass timber that is exposed within a structure. Highlighting the mass timber by exposing it meets biophilic design goals as well as sustainability goals through the reduction of additional materials (e.g. non-combustible gypsum board fire protection). Exposing the mass timber also provides a differentiator in a competitive construction market. In high-rise structures, mass timber is currently required to be concealed with non-combustible board fire protection, also referred to as encapsulation. Reducing the encapsulation and increasing the exposed mass timber has spurred conversation and concern around the changes to structural flammability that may come with these modifications. Specifically, unlike traditional high-rise building materials (concrete and steel), the structure of a mass timber building may become involved in a fire, increasing both the fuel load and the products of combustion produced. Adding to this, current prescriptive codes developed over a 100 years ago [3, 4], fall short in realistically handling contemporary fire scenarios and post-fire structural evaluation of mass timber buildings.

Previous large-scale fire tests of mass timber structures utilizing cross-laminated timber (CLT) provided data to quantify the contribution of exposed CLT to the total heat release rate (HRR) [5, 6], demonstrated the fire safety of fully protected compartments [5-10], contributed to the development of performance standards for adhesives [5, 7], and characterized the effects of varying the area of

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unprotected timber [8-10]. Despite these efforts to evaluate the fire performance of mass timber structures, several barriers remain in the way of adoption of mass timber structures including fire decay and smouldering and the potential generation of toxic emissions.

To address these barriers and develop new knowledge for the engineering community to move past them, the authors performed four large-scale compartment fire tests at the National Fire Research Laboratory at the Bureau of Alcohol, Tobacco, Firearms, and Explosives in Beltsville, Maryland (USA). The goals of the tests were to address the fire performance of mass timber, structural and serviceability performance of mass timber during realistic fire scenarios and improve emissions and sustainability practices for mass timber construction. This paper will provide an overview of the test setups, fuel load, and testing methods in addition to some preliminary results. Specifically, the analysis presented within this paper will meet the following research objectives:

(1) Quantify the effect of encapsulation on average maximum compartment temperatures, and

(2) Explore the effect of using furniture as fuel over wood cribs on the compartment temperatures and variability

2 – TEST SETUP

The project team constructed three, single-floor mass timber compartments with 5-ply CLT walls and ceilings under a 20 MW HRR hood and performed four tests on these compartments (one compartment was used twice). Each compartment was 2.8 m wide by 5.9 m deep by 2.4 m high and had a single opening of 1.7 m wide by 1.9 m high, corresponding to an opening factor of 17.1 m^1/2 (Figure 1). Even though structural loads were not applied throughout the tests, the compartments were designed per current codes and standards [8] for structural loads as though the compartment was a part of a high-rise mass timber building.

Each compartment was constructed of 5-ply Southern Yellow Pine (SYP) cross laminated timber for the walls and the ceiling. The floor of each compartment was 3-ply SYP CLT with two layers of 25.4 mm cement board to protect the floor. The floor was supported on 3-ply, 0.9 m wide CLT stringers that spanned the short span of the compartment. This detail enabled the movement of the compartments within the laboratory. Two Spruce-Pine-Fir (SPF) glue laminated (glulam) timber columns (311 mm x 406 mm) were located at the midpoint of the long dimension of the compartment. A 311 mm x 610 mm glulam beam connected these two columns together using a Simpson Strong Tie concealed beam hanger CBH2.37x5.5C-KT connection to each end of the beam. An additional standalone glulam column (406 mm x 406 mm) was placed at the front of the compartment and instrumented with thermocouples.

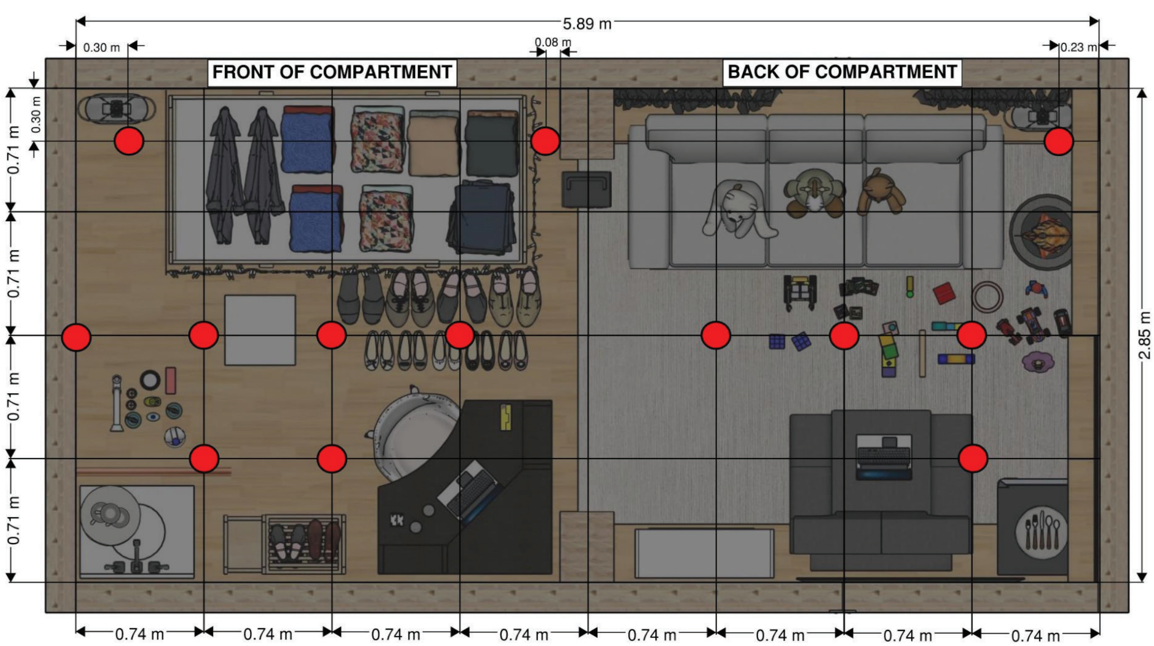

Figure 1. Plan view of typical large-scale compartment with thermocouple tree locations (red dots). Not all sensors shown for clarity.

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The mass timber was fully encapsulated in two of the fire tests, partially encapsulated in one test, and fully exposed in the remaining test. Tests #1 and #4 used the same compartment and consisted of fully encapsulated fire protection within the compartment. Encapsulation of these two tests was achieved with three layers of 15.9 mm thick fire resistant Type-X gypsum board. Test #2 had all the walls within the compartment, the ceiling, and the glulam columns and beam exposed. Test #3 had two layers of 15.9 mm thick Type-X gypsum board on the long span walls only. The back and front walls, the ceiling, and the glulam columns and beam were left exposed. The inclusion of the glulam beam and columns located at the midpoint created a physical impediment to hot gases circulating within the compartment. In addition, when furniture was used as fuel, the fuel within the back and front of the compartments were different (Fig. 2).

Furniture was used as the within-compartment fuel load for Tests #1 to #3, while Test #4 used wooden cribs to meet the fuel load of 798 MJ/m^2. These variations enabled the project team to compare fire behaviour, material response, and emissions during all phases of a fire between fuel types and encapsulation variations. Fire caulking was applied at each of the CLT ceiling-to-wall connections as well as the CLT panel-to-panel joint spline connections for the walls and the ceiling that were located at 4.41 m from the inside face of the front of the compartment. The test structures were highly instrumented including, but not limited to:

- Heat release rate to evaluate the fire growth.
- Thermocouples to capture compartment and material temperatures.
- Differential flame thermometers to measure heat flux to mass timber surfaces.
- Water-cooled heat flux sensors next to the structure.
- Infrared cameras to detect smouldering combustion.
- Post-test measurements of remaining cross-sections.
- Combustion emissions measurements inside and escaping from the compartment.
- Analysis of soot and heavy metal content post-fire.
- Load cells to measure mass loss throughout the test.

For brevity, this paper will only address the resulting temperature measurements throughout the compartment as measured through thermocouple trees. Thermocouple trees were installed throughout the compartment (Fig. 1) comprised of Type K thermocouples to measure the temperature distributions throughout the fire from the finished floor elevation to the ceiling. Thermocouples were placed every 0.61 m from the finished floor to the ceiling to measure the vertical spatial distribution of temperatures throughout each of the experiments. The horizontal distribution of the thermocouples throughout the compartment fitted a grid pattern, as shown in Fig. 1. Thirteen thermocouple trees were placed throughout the compartment with eight being in the back of the compartment and five being in the front of the compartment.

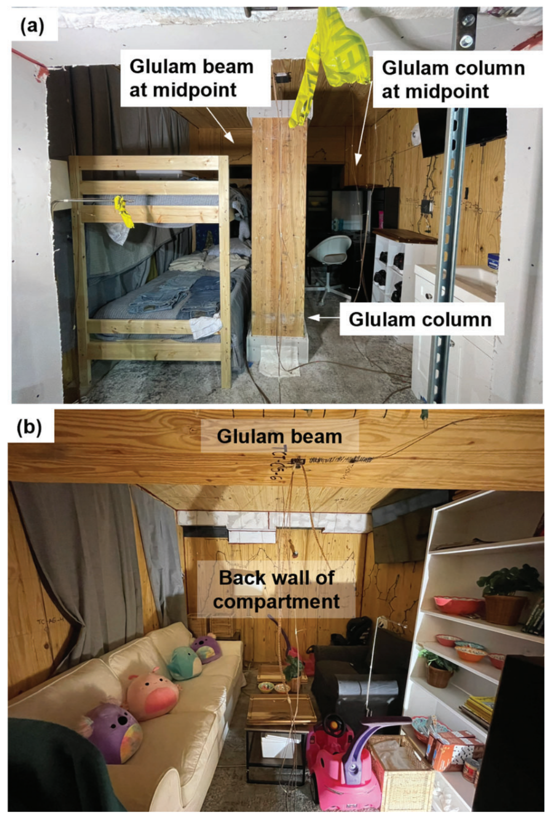

Figure 2. Photos of fuel within the compartment for Test #2 (a) back of compartment and (b) front of compartment

3 –RESULTS AND DISCUSSION

The results from these experiments will be presented in terms of the spatial temperature distributions within the compartment. This includes both vertically within the compartment as well as a comparison of the temperatures from the back of the compartment and the front of the compartment throughout the fires. The temperatures will then be compared across tests of full encapsulations (Tests #1 and #4) and tests with exposed mass timber (Tests #2 and #3). The goal is to draw conclusions on the effect of encapsulation on the spatial temperatures within a compartment when fuel load and ignition points are held constant, but the type of fuel (furniture versus wood cribs) and the amount of encapsulation are varying. For brevity, only the thermocouple data for the thermocouples located 0.61 m and 1.83 m from the finished floor within each thermocouple tree will be reported.

Figure 3. Photos of compartment fire tests (a) Test #2 (fully exposed mass timber with furniture) (b) Test #4 (full encapsulated mass timber with wood cribs)

3.1 – COMPARTMENT TEMPERATURES

For Test #1 (fully encapsulated), the maximum temperatures in the front of the compartment begin to steadily decrease at about 40 minutes while the maximum temperatures in the back of the compartment remain constant, with occasional spikes in temperature, from about 45 minutes to 120 minutes (test termination) (Fig. 4). Additionally, in the front of the compartment, the temperatures closer to the finished floor were approximately the same maximum temperatures as the temperatures closer to the ceiling, with the maximum temperature at 0.61 m above the finished floor averaging 2℃ higher than the temperatures at 1.83 m above the finished floor. In the back of the compartment, maximum temperatures occurred closer to the finished floor. The temperatures at 0.61 m above the finished floor had maximum temperatures that were, on average, 140℃ higher than the maximum temperatures measured 1.83 m above the finished floor.

For Test #2 (all timber exposed), the average maximum temperatures between the front and back of the compartment were similar, with the average maximum temperature of the front of the compartment being 11.8% and 12.9% higher than the back of the compartment at a height of 0.61 m and 1.83 m, respectively. The maximum temperatures in the front of the compartment in Test #2 were only slightly higher than those of Test #1, with the average maximum temperatures of Test #2 approximately 17℃ higher at 0.61 m and 74℃ higher at 1.8 m above the finished floor. On the other hand, the maximum temperatures in the back of the compartment in Test #2 were lower than those of Test #1, with the average maximum temperatures of Test #1 being 207℃ higher and 71℃ higher at 0.61 m and 1.8 m above the finished floor, respectively.

Table 1. Average maximum temperatures within each compartment both front and back at 0.61 m and 1.83 m from finished floor and standard deviations.

Test No.	Front/Back	Average Max. Temperature (°C)	
		0.61 m	1.83 m
Test 1	Front	1085 ∓ 76	1183∓114
	Back	1193∓205	1053∓69
Test 2	Front	1102∓62	1109∓89
	Back	986∓36	982∓39
Test 3	Front	1081 ∓ 70	1172∓179
	Back	1012∓37	1015∓30
Test 4	Front	1236∓157	1295∓87
	Back	1076∓51	1083∓52

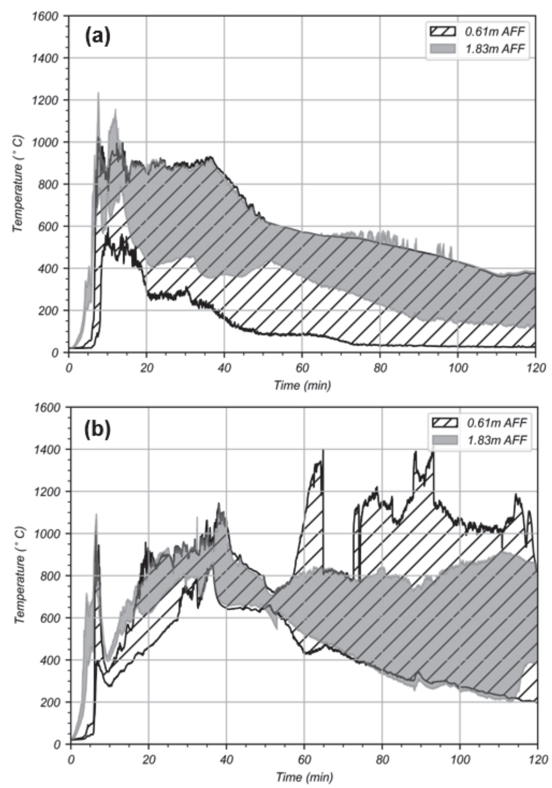

Figure 4. Thermocouple tree data for 0.61 m and 1.83 m above finished floor for Test #1 (a) front of compartment and (b) back of compartment

The temperatures within both the front and back of the compartment for Test #2 differed little with respect to the height above the finished floor (Fig. 5). In the front of the compartment, the average maximum temperature 1.83 m above the finished floor was only 7℃ higher

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than that of the 0.61 m above the finished floor. Similarly, in the back of the compartment, the average maximum temperature 1.83 m above the finished floor was 4℃ lower than that the average maximum temperature 0.61 m above the finished floor.

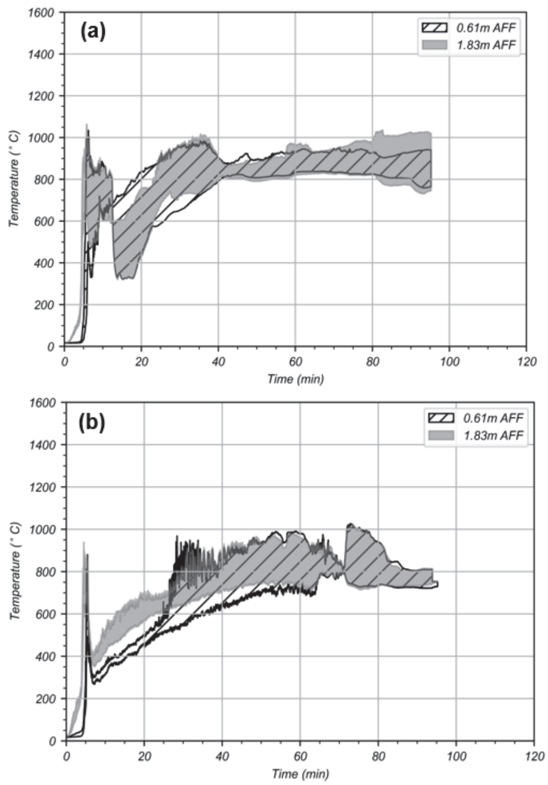

Figure 5. Thermocouple tree data for 0.61 m and 1.83 m above finished floor for Test #2 (a) front of compartment and (b) back of compartment

The average maximum temperature at the front and back of the compartments for 0.61 m and 1.83 m above finished floor are shown in Table 1 along with the standard deviations. The variability for Test #2 was significantly smaller than the variability for Test #1.

For Test #3 (partly exposed timber), the average maximum temperature between the front and back of the compartment were similar (Fig. 6), with the average maximum temperature of the front of the compartment being 6.8% and 15.5% higher than the back of the compartment at a height of 0.61 m and 1.83 m, respectively. Additionally, the temperatures within the height of the compartment were very similar indicating flashover occurred. The variability in temperature was higher in the front of the compartment than the back (Table 2).

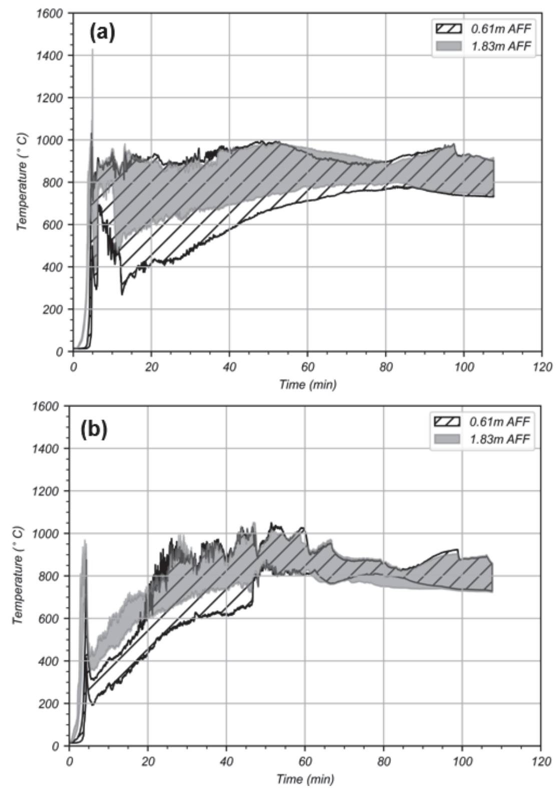

Figure 6. Thermocouple tree data for 0.61 m and 1.83 m above finished floor for Test #3 (a) front of compartment and (b) back of compartment

For Test #4, (fully encapsulated, wood crib fuel) the maximum temperatures in the back of the compartment begin to decrease at about 50 minutes and continued to decrease until test termination (233 minutes) (Fig. 7). The maximum temperatures in the front of the compartment, however, began to decrease at about 60 minutes, but increased again at 0.61 m at about 140 minutes. The temperatures within the front of the compartment were higher than the back of the compartment. The average maximum temperature in the back of the compartment was 1076 ℃ at 0.61 m above the finished floor, whereas the average maximum temperature in the front of the compartment was 1236 ℃ at the same height (15% difference). There was an even greater difference at 1.83 m above the finished floor with an almost 20% difference in the average maximum temperatures between the front and back of the compartment. For Test #4, the variability of the temperature in the front of the compartment was higher than the variability in the back.

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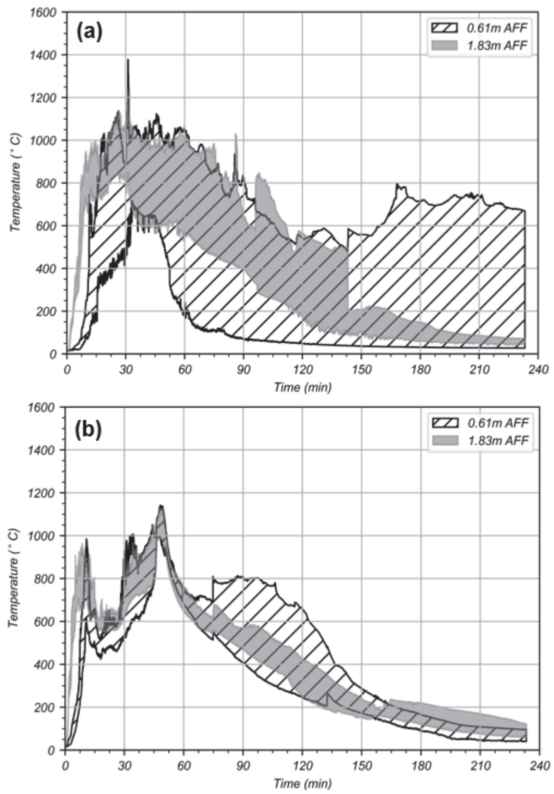

Figure 7. Thermocouple tree data for 0.61 m and 1.83 m above finished floor for Test #4 (a) front of compartment and (b) back of compartment

3.2 – CEILING TEMPERATURES

Plots of the average ceiling temperatures as measured by the thermocouples located at 2.4 m above the finished floor are provided in Fig. 8. The overall average is from 22 thermocouples located on the ceiling. The front average is taken as the average of 12 thermocouples located on the ceiling in the portion of the compartment between the opening and the glulam beam/column assembly. The back average is calculated as the average of 10 thermocouples on the ceiling from the glulam beam/columns to the back wall opposite the opening. For all tests, both the front and back average ceiling temperatures increased initially with flashover. However, the back average ceiling temperature immediately decreased while the front average ceiling temperature remained high. This is due to the depth of the beam located across in the middle of the compartment and the air from the opening not reaching the back of the compartment until later in each test when the back average ceiling temperatures increase again. With the modern mobile fuel load in Tests #1 through #3, the initial peak average temperature for the in the back of the compartment occurred between 4 and 6 minutes and lasted approximately 2 to 6 minutes.

The first peak in temperature for Test #4, with the wood cribs, had a duration of 15 minutes with the peak occurring at 10 minutes into the test. The differences in peak durations speak to the ignitability and ease at which many of the modern fuels burn.

However, despite the differences in peak heat release rates (Table 2), the average ceiling temperatures for all four tests were close and never exceeded 945ºC in Tests #1 through #3 and the average peaked at 1071°C in Test #4 with wood cribs. When comparing Test #1 with no exposed mass timber to Tests #2 and #3 with exposed mass timber, again, the average ceiling temperatures reached similar maximums. The back average ceiling temperatures for Tests #1, #2, and #3 were similar for the first 40 minutes at which time Test #1 began to decay while the exposed mass timber in Tests #2 and #3 continued to contribute to the fully developed fire. In the front of the compartment, the average ceiling temperatures for Tests #1 through #3 were similar for the first 20 minutes, at which point the temperatures for Tests #2 and #3 increased to approximately 900°C and then plateaued for the remainder of the tests while Test #1 began to decay.

Table 2. Peak heat release rate per test

Test Number	Peak Heat Release Rate (HRR) [MW]
1	7.3
2	9.6
3	8.9
4	6.0

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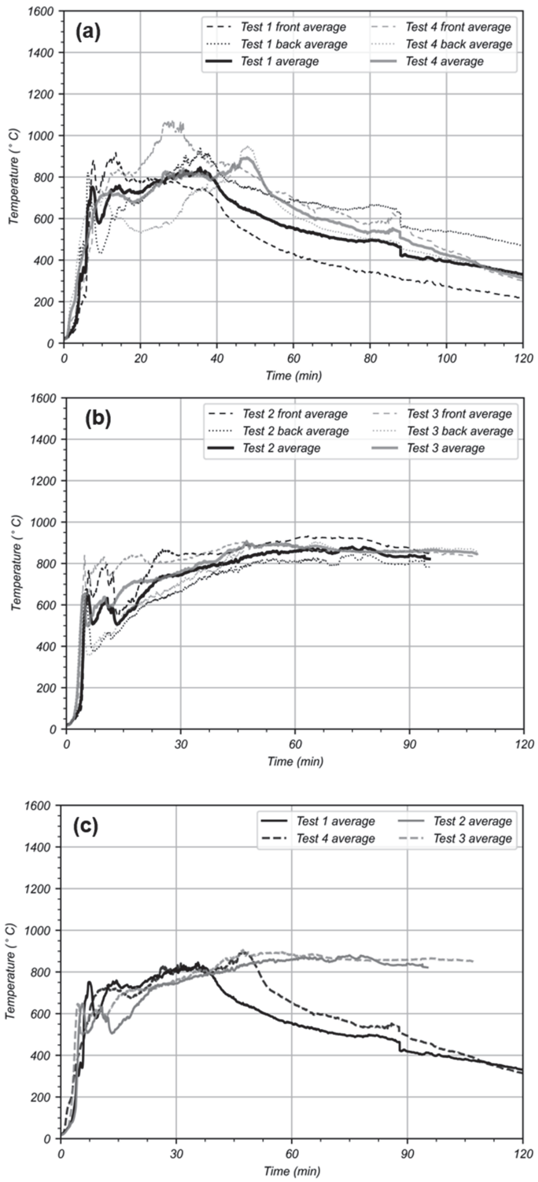

Figure 8. Average ceiling temperatures of (a) Test #1 and Test #4, (b) Test #2 and Test #3, and (c) all tests combined

3.3 – COMPARISON BETWEEN TESTS #1 & #4

In Test #1, temperatures in the front of the compartment began to decrease at about 40 minutes while the temperatures in Test #4 did not start to decrease until about 60 minutes. Furthermore, the average maximum temperature 0.61 m above the floor was higher for the front of the compartment of Test #4 than Test #1. The average maximum temperature in the front of the compartment was 14% and 9.5% higher in Test #4 for thermocouple heights of 0.61 m and 1.83 m, respectively.

The maximum temperatures in the back of the compartment of Test #4 begin to decrease at about 50 minutes and continued to decrease until test termination (233 minutes). However, in Test #1, the maximum temperatures in the back of the compartment remained constant, with occasional spikes in temperature, from about 45 minutes to 120 minutes (test termination). The variability in temperature in the back of the compartment in Test #4 was lower than the variability in temperature in Test #1. In the back of the compartment, Test #4 had 9.8% lower temperatures than Test #1 at 0.61 m from the finished floor. However, the maximum average temperature in the back of the compartments were approximately the same at 1.83 m above the compartment floor between the two tests (2.8% difference).

3.4 – COMPARISON BETWEEN TESTS #2 AND #3

The temperatures in the front and back of the compartment in Test #2 and Test #3 were very similar with all average maximum temperatures being within 6% of one another. The average maximum temperature in the front of the compartment at 0.61 m and 1.83 m above the finished floor for the two tests only differed by 21°C and 63°C, respectively. The variability in temperatures for Test #3 was larger than Test #2 in the front of the compartment, as can be seen in Table 1. Neither test demonstrated signs of cooling in the front of the compartment. At 30 minutes of burning during Test #2, temperatures in the front of the compartment were constant which continued until test termination (minute 95). The same behaviour was observed for Test #3 where the temperatures in the front of the compartment remained constant soon after ignition, at about minute 8 until test termination (minute 107).

The temperatures in the back of the compartment in Test #2 and Test #3 are very similar. The average maximum temperature at 0.61 m and 1.8 m above the finished floor for the two tests only differed by 26°C and 33°C, respectively. The temperature variability in the back of the compartments for Tests #2 and #3 were very similar, as can be seen in Table 1. Neither test demonstrated decreasing temperatures in the back of the compartment. The temperatures in the back of the compartment for Test #2 became constant at about minute 40 and continued until test termination (minute 95). Similarly, the temperatures in the back of the compartment for Test #3 became constant at about minute 35 and continued until test termination (minute 107).

4 –CONCLUSIONS

The four large-scale compartment fire tests described within this paper varied in levels of encapsulation to quantify the effect of varying levels of encapsulation on the fire dynamics within the compartment. Difference between Test #2 and Test #3 average maximum temperatures in the front and back of the compartment were insignificant indicating that applying encapsulation to only the side walls of the compartment had little effect on the average maximum temperatures within the compartment. In addition, temperatures generally decreased from Test #1 (fully encapsulated) to Tests #2 and #3; however, the difference between the average maximum temperatures was within 7% of each other. The exception was for the average maximum temperature at 0.61 m above finished floor in the back of the compartment. These temperatures decreased by 17.4% and 15.2% from Test #1 to Tests #2 and #3, respectively.

Tests #1 and #4 were both fully encapsulated with the only difference being that Test #1 used furniture and Test #4 used wood cribs. The resulting effect of this difference was larger than the effect of the amount of encapsulation. Temperatures in the front of the Test #4 (wood cribs) compartment increased by 13.9% and 9.5% at heights 0.61 m and 1.83 m above finished floor, respectively. On the other hand, temperatures in the back of the Test #4 (wood cribs) compartment decreased by 9.8% at 0.61 m above finished floor and increased by only 2.8% at 1.83 m above finished floor. In addition, the variability of the temperatures in Test #1 with furniture as fuel was higher than when wood cribs were used for fuel load.

These results demonstrate that varying levels of encapsulation may not have a large impact on the average maximum temperatures within the compartment. However, there are many other fire dynamic factors that should be explored to fully understand the effect of varying levels of encapsulation on fire dynamics within a compartment (e.g., heat flux, depth of charring).

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5 –REFERENCES

[1] CBC (2022). California building code (CBC). *International Code Council*: Washington, DC.

[2] Forest Business Report. 2022 International Mass Timber Report. https://www.masstimberreport.com/?utm_source=Kaiser+%2B+Path&utm_campaign=5b6bf2c748-EMAIL_CAMPAIGN_2020_06_08_05_10_COPY_01&utm_medium=email&utm_term=0_6dbba1a997-5b6bf2c748-208039942

[3] Law, A. and Bisby, L. (2020). “The rise and rise of fire resistance”. *Fire Safety Journal*, 116, 103188.

[4] Babrauskas, V. and Williamson, R. B. (1978). “The historical basis of fire resistance testing—Part I”. *Fire Technology*, 14(3), 184-194.

[5] Li, X., Zhang, X., Hadjisophocleous, G., and McGregor, C. (2015). “Experimental Study of Combustible and Non-combustible Construction in a Natural Fire.” *Fire Technology*, 51(6), 1447–1474.

[6] McGregor, C. (2013). “Contribution of cross laminated timber panels to room fires.” MASc thesis, Carleton University, Ottawa, Ontario, Canada.

[7] Janssens, M. (2015). *Full-Scale Tests in a Furnished Living Room to Evaluate the Fire Performance of Protected Cross-Laminated and Nail Laminated Timber Construction*. SwRI Project No 01.21428.01.001, Southwest Research Institute, San Antonio, Texas, 85.

[8] Su, J., Lafrance, P.-S., and Hoehler, M. S. (2018a). *Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 2 & 3 – Cross Laminated Timber Compartment Fire Tests*. Fire Protection Research Foundation, Quincy, MA, USA.

[9] Taber, B. C., Lougheed, G. D., Su, J. Z., and Bénichou, N. (2014). *Solutions for mid-rise wood construction: Apartment fire test with encapsulated cross laminated timber construction (Test APT-CLT)*. A1-100035-01.10, National Research Council of Canada, Ottawa, Ontario, Canada, 112.

[10] Zelinka, S. L., Hasburgh, L. E., Bourne, K. J., Tucholski, D. R., and Ouellette, J. P. (2018). *Compartment fire testing of a two-story mass timber building*. FPL-GTR-247, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, FPL-GTR-247.

https://doi.org/10.52202/080513-0522