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INFLUENCE OF FUEL TYPE AND LOAD ON FIRE INTENSITY: RESULTS FROM FULL-SCALE FIRE TESTS FROM THE WOODWISE PROJECT

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ABSTRACT: Over the past decade, several large-scale fire tests have been conducted by research teams across the world to evaluate the fire performance of mass timber structures to support the adoption of larger and taller mass timber structures. However, the tests conducted to date have a mobile fuel load of 680 MJ/m^2 or less. Additionally, the mobile fuel load used was often cellulose-based and made of either wood furniture or wood cribs. The WOODWISE project aims to enhance the understanding of fire dynamics in mass timber structures with the inclusion of modern mobile fuels and higher fuel loads. Four large-scale mass timber compartment fires were conducted in the fall of 2024. For the tests, the mobile fuel load was 798 MJ/m^2, which includes everything except the fixed structure (mass timber). This higher fuel load more closely represents an average dwelling. Three of the tests included furniture, electronics, appliances, and household chemicals and are compared against one test with wood cribs. The heat release rate and gas layer temperatures are measured to evaluate the fire dynamics and provide results to compare between each compartment and previous tests.

KEYWORDS: Mass timber, cross laminated timber, fuel load, fire curve

1 – INTRODUCTION

Over the past decade, large-scale fire tests of mass timber compartments have been conducted to quantify changes in compartment fire dynamics when mass timber is exposed and to evaluate the fire performance of the timber elements. These tests, reviewed by [1, 2, 3], generated temperature and heat release rate (HRR) data that describe the fire environment within the compartment, quantify the contribution of exposed cross laminated timber (CLT) to the total heat released, demonstrates the fire safety of fully protected compartments, contributes to the development of codes and standards, evaluates traveling fires, and characterizes the effects of varying the area of unprotected timber. The results of this body of research have been valuable for the fire engineering field and provide benchmarks for mass timber stakeholders. However, all the tests were conducted with mobile fuel loads of 680 MJ/m^2 or less, with 550 MJ/m^2 being the most commonly used fuel load. The average mobile fuel load for dwellings has been shown to be closer to 780 MJ/m^2 [4] and the amount of fuel (load) within a compartment will influence both the temperatures and duration of the fully developed phase [5].

Additionally, the mobile fuel loads in previous fire tests were largely comprised of cellulose-based materials (wood furniture, books, cotton, and wood cribs). However, the type of fuel in a compartment alters fire

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behaviour including the time it takes for a fire to reach critical stages, the duration of these stages, and the range and duration of emissions produced. Modern fuels, including electronics, appliances, and household chemicals, will produce more toxic combustion products.

To understand the effects of higher fuel loads and modern fuels on the fire dynamics within mass timber compartments both with and without non-combustible encapsulation, the authors performed a series of large-scale compartment fire tests as a part of the WOODWISE project. The data presented here to quantity the influence of a modern fuel load include the HRR, gas species production, and mass loss.

2 – TEST METHODOLOGY

2.1. TEST COMPARTMENTS

A total of three CLT compartments (Fig. 1) with interior dimensions of 5.9 m by 2.8 m, with a floor-to-ceiling height of 2.4 m were constructed of 5-ply Southern Yellow Pine (SYP) cross laminated timber for the walls and the ceiling and 3-ply SYP CLT with two layers of cement board for the floor. Ventilation was supplied by an opening, 1.8 m in width and 1.9 m in height, located in one of the shorter walls resulting in an opening factor (OF) of 0.062 $m^{1/2}$, as calculated in [6]. A glulam beam/column assembly was located in the middle of each compartment. The beam had dimensions of 30.5 cm by 61 cm and the columns had dimensions of 30.5 cm by 40.6 cm. Tests #1 and #4 had three layers of 16 mm thick Type X gypsum board covering all mass timber surfaces while Tests #2 and #3 had varying amounts of exposed mass timber surfaces (Fig. 2). For Test #2, the ceiling, walls, and the glulam beam/column assembly were exposed for a total of 113% of the floor area and 276% of the floor area was exposed mass timber on the ceiling and walls, respectively. Test #3, the ceiling, back wall, and glulam beam/columns were exposed such that 113% of the floor area was exposed on both the ceiling and the walls. The side walls in Test #3 were protected with two layers of 16 mm thick Type X gypsum board.

To monitor gas temperatures, timber temperatures, heat fluxes, and flow fields at the opening, the compartments were heavily instrumented with thermocouple trees, embedded thermocouples in the CLT, directional flame thermometers, and velocity probes. The preliminary results presented herein will focus on heat release rate and mass loss.

The compartment fire tests were performed under the Fire Products Collector (FPC) located at the Fire Research Laboratory at Alcohol, Tobacco, and Firearms (ATF) in Beltsville, MD. Each test structure was constructed under the 19.8 m by 19.8 m collection hood as show in Fig. 1. The primary fire characteristics calculated from the FPC include HRR and smoke production which includes both particulate and gas-phase species production. HRR measurements are based on the principle of oxygen consumption calorimetry. Gas species production, specifically O_2, CO and CO_2, is calculated based on the measured gas concentrations flowing through the FPC. Additionally, measurements were made in the exhaust duct to assess the emissions of toxic compounds (not reported here).

Each compartment was placed on top of eight 22.2 kN (5 kip) load cells (Load Cell Berman Low Profile Disk Model BTWM) sampling at 1 Hz for the duration of the experiment (Fig. 3). The load cells were placed at the center of the CLT stringers supporting the compartment floor. The first set of load cells were located 0.46 m from the outside compartment edge in the longitudinal direction. The remaining load cells were spaced at 1.78 m on center in the longitudinal direction. All load cells were placed approximately 0.46 m from the outside compartment edge in the transverse (short) direction.

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Figure 1: *The three test structures during construction all located under the Fire Products Collector. During testing, the structures not being tested were protected with gypsum board and ceramic batting on the exposed exterior.*

Figure 2: Varying amounts of exposed mass timber in back portion of Test #2 (left) and Test #3 (right) prior to testing..

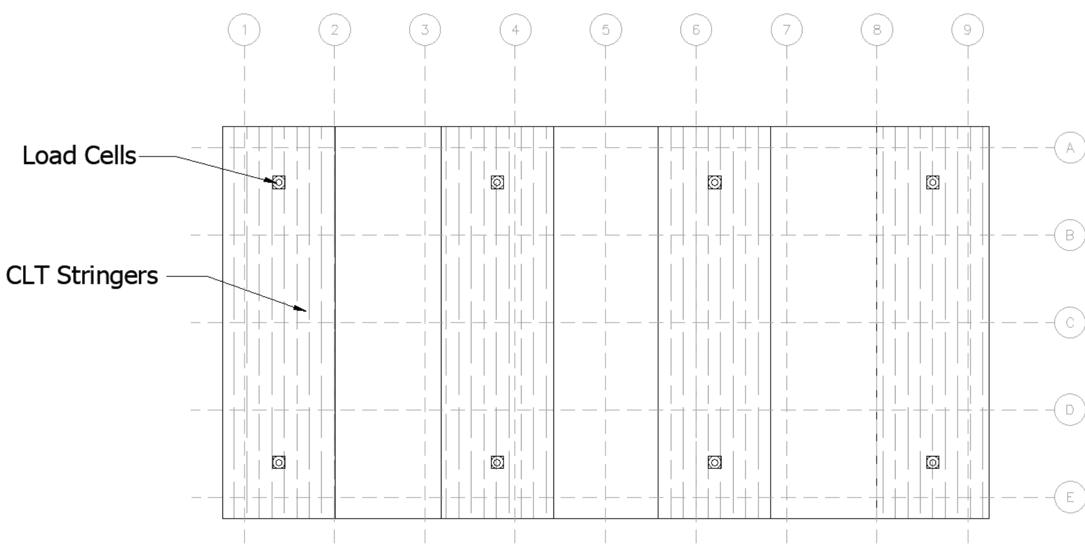

Figure 3: Locations of load cells and CLT stringers.

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The dimensions of the WOODWISE compartments were chosen to be comparable with test series conducted by the National Research Council of Canada (NRC) in collaboration with the National Institute of Standards and Technology (NIST) [11]. Additionally, the NRC/NIST tests compartment sizes were used to develop ANSI/APA PRG 320 [12], which is the North American standard that covers the manufacturing, qualification, and quality assurance requirements for CLT. For comparison purposes, the interior dimensions from [11] were 9.1 m by 4.6 m, with a floor-to-ceiling height of 2.7 m. Two different ventilation sizes were evaluated in [11]: 1.8 m by 2 m (OF = 0.032 $m^{1/2}$) and 3.6 m by 2 m (OF = 0.065 $m^{1/2}$).

2.2. FUEL LOAD

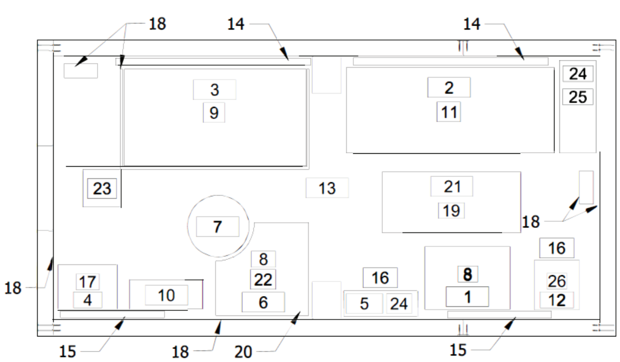
The fuel load was 798 MJ/m^2 consisting of two types of fuel. For Tests #1 through #3, modern mobile fuel was used and for Test #4, the fuel load was entirely Douglas-fir wood cribs.

2.2.1 Modern Mobile Fuel Load

The modern fuel load consisted of combustible and non-combustible materials including potential catalytic materials. The fuels were distributed throughout the compartment as shown in Fig. 4.

Most of the modern mobile fuel load consisted of multiple components. For instance, the vanity included plumbing components such as a chrome fixture, polyvinyl chloride (PVC), copper tubing, and solder. Additional materials typically found within a residence were distributed throughout the compartment and included fipronil (pesticide), triclopyr (herbicide), nitrogen phosphate fertilizer (fertilizer), latex paint, cyfluthrin (pesticide), bleach, shampoo and conditioner, mouthwash, a microwave, butcher blocks, fake plants, storage bins, cotton textiles, and zinc phosphide (rodenticide).

All items were weighed prior to placement into the compartment, and the composition was determined from product information or estimated. Energy content was calculated using heat of combustion values from the Society of Fire Protection Engineers Handbook for Fire Protection Engineering [10] or from the literature to calculate the total heat in MJ. The overall composition of the fuel load is provided in Table 1.



FURNITURE LEGEND		
ID	ITEM	DESCRIPTION
1	CHAIR	FRAME, CUSHIONS
2	SOFA	FRAME, CUSHIONS
3	BUNK BED	FRAME, PUF MATTRESS, PILLOWS
4	VANITY	CABINET, BASIN, FAUCET
5	BOOK SHELF	BOOKCASE
6	DESK	
7	DESK CHAIR	
8	LAPTOP	TWO UNITS
9	MISCELLANEOUS	CLOTHES, BLANKETS, CUTTING BOARDS, PLASTIC CONTAINERS
10	SHOE RACK WITH SHOES	SHOES WITH METAL STIFFENING PLATES
11	TOYS	POLYESTER FIBERS, THERMOPLASTIC
12	REFRIGERATOR	
13	RUG	POLYPROPYLENE FIBERS, NYLON, UNDERLAY
14	DRAPES	POLYESTER, POLYURETHANE BACKING
15	TV	
16	TOY CAR	PLASTIC
17	HOUSEHOLD CHEMICALS	PESTICIDES, CLEANERS, PAINT, PLUMBING
18	LIGHTNING	METAL LAMP, LED LIGHT STRANDS
19	MISCELLANEOUS	CUTTING BOARDS, PLATES, PLASTIC CONTAINERS, FAKE PLANT
20	MISCELLANEOUS	PLATES, CUPS, CUTTING BOARDS, PACKAGED FOOD, BODY WASH
21	COFFEE TABLE	
22	THRASH CANS	
23	INSTRUMENTED COLUMN	GLULAM 16"X16"
24	MISCELLANEOUS	PLATES, CUPS, PACKAGED/CANNED FOOD, BOOKS/MAGAZINES, WOVEN BASKET, TOWELS, CUTTING BOARDS, FAKE PLANT
25	MISCELLANEOUS	WOVEN BASKETS, TOWELS, PLASTIC CONTAINERS
26	CAR SEAT	

Figure 4: Schematic of modern fuel load layout for Tests #1 through #3.

Table 1: Modern Mobile Fuel Load Composition

Material	Mass (kg)	Mass (%)	Energy (MJ)	Energy (%)
Wood (kg)	297.8	55.7%	5717.5	45.1%
Paper	16.7	3.1%	212.2	1.7%
Polyurethane Foam	42.9	8.0%	1098.6	8.7%
Polyester	8.3	1.6%	189.8	1.5%
Melamine	2.3	0.4%	42.4	0.3%
Polyethylene or Polypropylene	65.7	12.3%	2839.0	22.4%
Other Plastic	78.1	14.6%	2264.6	17.8%
PVC	1.5	0.3%	14.8	0.1%
Natural Textile (Cotton)	15.7	2.9%	290.3	2.3%
Hydrocarbon	0.4	0.1%	19.5	0.2%
Metal	4.8	0.9%	0.0	0.0%
Total	534.2	100%	12688.7	100%

2.2.2 Wood Cribs

Test #4 was conducted with only wood cribs as the mobile fuel load (Fig. 5) to provide a baseline for emissions measurements between the modern fuels and cellulose-based fuel. The wood cribs were similar to those used by [7] and [8] with the dimensions of each stick being 38 mm by 90 mm by 800 mm long and were constructed with grade #1 or better Douglas-Fir Larch species group dimensional lumber. Each crib included 48 sticks with six sticks for each of the eight layers. Within one layer, the sticks had a spacing of 114 mm such that the porosity factor as characterized by Heskestad [9] was 0.23. Stainless steel nails (#10 x 12.7 cm) were used to fabricate the cribs.

Based on mass and literature values for the heat of combustion (19 MJ/kg [10]), one crib would have a total heat release value of approximately 1233 MJ. A total of 10 cribs were placed in the compartment for Test #4 (Fig. 6).

3 – RESULTS AND DISCUSSION

One objective of the WOODWISE test series was to evaluate the effect of modern fuel types and larger fuel loads on the development of compartment fire dynamics in compartments with and without mass timber exposed. The HRR and compartment temperatures time series (i.e., initiation, duration, peaks, etc.) were evaluated and compared against previous comparable large-scale test results.

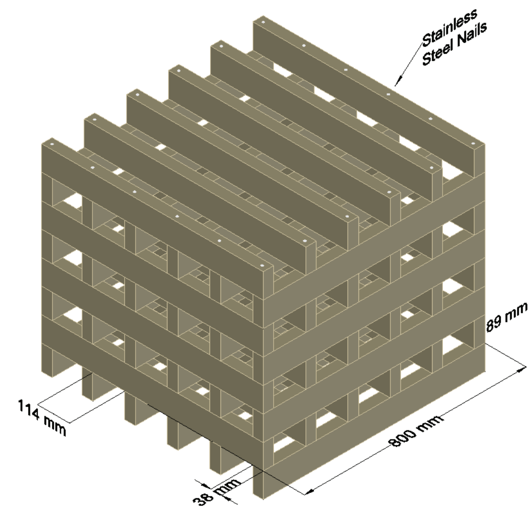


Figure 5: Schematic of wood cribs.

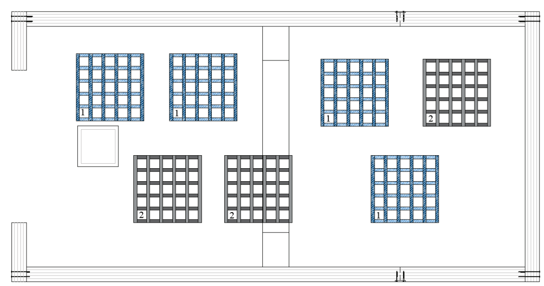


Figure 6: Schematic of wood cribs layout for Test #4. Locations with a blue crib and "1" indicate only one crib placed there. Locations with a gray crib and "2" indicate two cribs were stacked in that location.

3.1 HEAT RELEASE RATE

The heat release rate curves from Tests #1 through #4 are presented in Fig. 7. In Test #1, there is some regrowth of the fire around 40 minutes. This occurred due to the failure of a gypsum board wall/ceiling joint near the back of the compartment above the couch. Tests #2 and #3 never decayed due to the high fuel load and the large amount of exposed mass timber available to sustain the fully developed phase of the fire. Tests #1 and #4 with the mass timber entirely protected with gypsum board decayed despite the higher mobile fuel loads implemented in this test series compared to other test series. The peak HRR and time to the peak HRR for each test is provided in Table 2.

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Table 2: Peak Heat Release Rate Results

Test	Peak HRR (MW)	Time to peak HRR (min)
1	7.3	8.7
2	9.6	6.0
3	8.9	5.0
4	6.0	22.6

The results in Table 2 are consistent with the findings from Su et al. [11] showing that exposed CLT surfaces within a compartment will contribute to the total heat released and the more CLT exposed, the greater the contribution. This additional contribution of exposed CLT will likely result in increased flow velocities through the opening such that the hot gasses exit faster, drawing in air quicker to sustain burning of the CLT surfaces.

The wood cribs (Test #4) significantly affected both the fire growth and fully developed phases of the fire compared to the modern fuel load. For Test #4, the growth of the fire took 15 minutes to transition from the incipient phase to the fully developed phase. By comparison, the modern mobile fuel load (Test 1) transition from incipient to fully developed phase took only 4 minutes, resulting in a 275% increase in time.

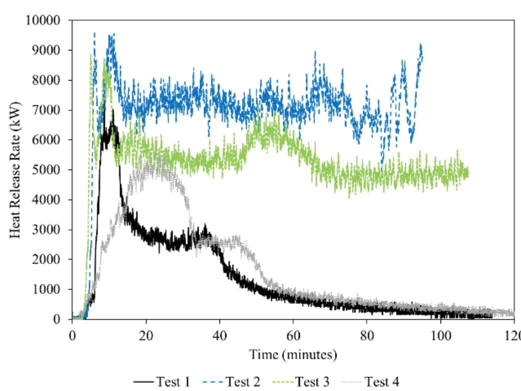

Figure 7: Heat release rate curves from WOODWISE Tests #1 through #4.

3.2 HRR COMPARISON WITH OTHER LARGE-SCALE EXPERIMENTS

Fig. 8 provides a comparison of WOODWISE Tests #1 and #4 to NRC/NIST Tests 1-1 and 1-2 [11]. The mass timber was fully encapsulated for all four of these tests but the mobile fuel load for the NRC/NIST test was 550 MJ/m^2 and largely consisted of cellulose-based materials along with a minimal amount of PU foam included in cushions and a mattress. Ventilation plays a significant role on the duration of each fire phase. The dimensions of the opening for the WOODWISE compartments were similar to NRC/NIST 1-1 but the WOODWISE OF was closer to the OF for NRC 1-2. The incipient phase of the fire for WOODWISE Test #1 was only 4 minutes when compared to almost 12 minutes for the NRC/NIST test (200% increase), likely due to the type of fuels located directly near the initial ignition. For the WOODWISE tests, the ignition package, consisting of 10 sheets of paper towel, gauze, and 250 ml of gasoline in a plastic bag, was placed on the couch with plastic-based toys nearby. In the NRC/NIST tests, the ignition was a natural gas burner located near a wood console table with wood cribs on the shelves. Though the fuel load, type, and ignition varied, all tests were ventilation limited and ultimately decayed when the mobile fuel load was consumed. The cellulose-based fuel loads from Test #4 and both NRC/NIST tests took longer to consume such that the fully developed phases were two to five times longer in duration when compared to the modern mobile fuel load from Test #1.

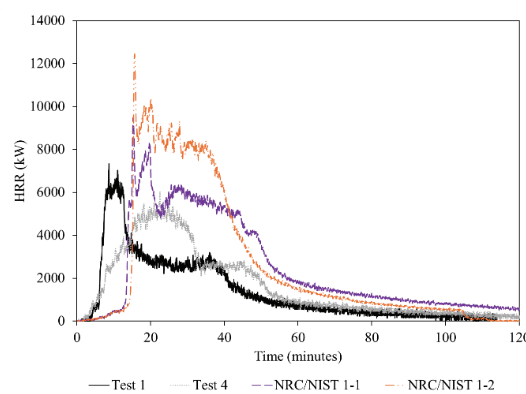

Figure 8: Heat release rate curves from WOODWISE Tests #1 and #4 compared to NRC/NIST Tests 1-1 and 1-2.

3.3 COMBUSTION EFFICIENCY

Combustion efficiency can be estimated by calculating the ratio of CO/CO_2 over the course of the test. The lower the CO/CO_2 ratio, the more complete the combustion. Utilizing the gas analysis equipment in the FPC, the CO/CO_2 ratio was calculated for the duration of each test. In all tests, the CO/CO_2 ratio rapidly increased as the fire became established then decreased shortly before the peak HRR was observed (Fig. 9). The CO/CO_2 peak for the modern fuels (Test #1 through #3) was only 1 to 1.5 minutes in duration and reached a maximum value of 0.26 to 0.32 before decreasing to 0.02 for most of the test. The wood cribs had a substantial impact on the CO/CO_2 ratio. Test #4 had a

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lower peak value of 0.15 that remained elevated for nearly ten times longer than with the modern fuel. The CO/CO_2 ratio increased in the latter part of Tests #1 and #4 when the mass timber underneath the gypsum began to smoulder.

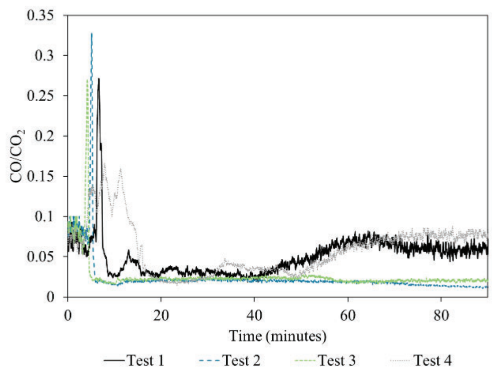

Figure 9: CO/CO_2 curves from WOODWISE Tests #1 through #4.

3.4 MASS LOSS

Mass loss time series of each test further illuminates the details of the combustion dynamics in the compartments (Fig. 10). The percent of mass lost, though not identical, does demonstrate a near constant rate of change for the first 20 minutes. However, it is after 20 minutes that Tests #1 and #4 (mass timber protected with gypsum board) begin to slow in their percent of mass lost. This timing correlates well with the start of the decay phase for both tests (Fig. 7). Conversely, Tests #2 and #3 (mass timber exposed) continue to lose mass at a fairly constant rate. It is worth noting that Test #3 (partially exposed mass timber) begins to decrease slightly in percent mass lost after 60 minutes, which again correlates well with a slight decrease in heat release rate (Fig. 7).

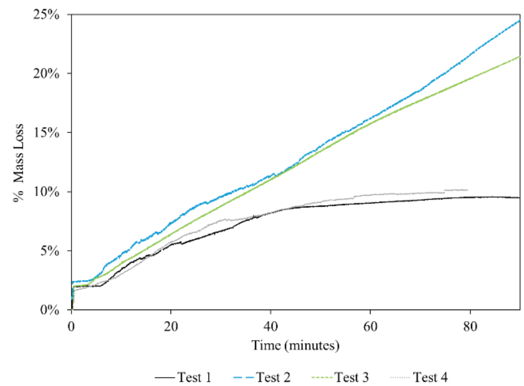

Figure 10: Percent mass loss curves from WOODWISE tests 1 - 4.

Interestingly, although the amount of exposed mass timber on the ceiling between Tests #2 and #3 were the same, Test #3 had 60% less exposed mass timber on the walls. Despite this, at 90 minutes into both tests, Test #2 had lost 24% while the percent mass loss for Test #3 was 21%. The fire in Test #3 was expected to decay with the increased amount of gypsum board, which would have resulted in less mass lost. However, since this did not occur, the gypsum likely failed due to the fire environment from the modern fuels and the CLT was undergoing combustion behind the gypsum. From post-test images it is clear that the protected CLT walls charred. Fig. 11 is an image from Test 3 showing the differences in char patterns between the exposed ceiling and back wall to the "flatter" char pattern that occurred on the CLT wall that was protected with gypsum. However, further analysis of residual depths for every panel is underway to determine how much of the exposed timber versus the protected timber remains in Test #3, which can then be compared to Test #2 to illuminate where most of the compartment mass loss stems from.

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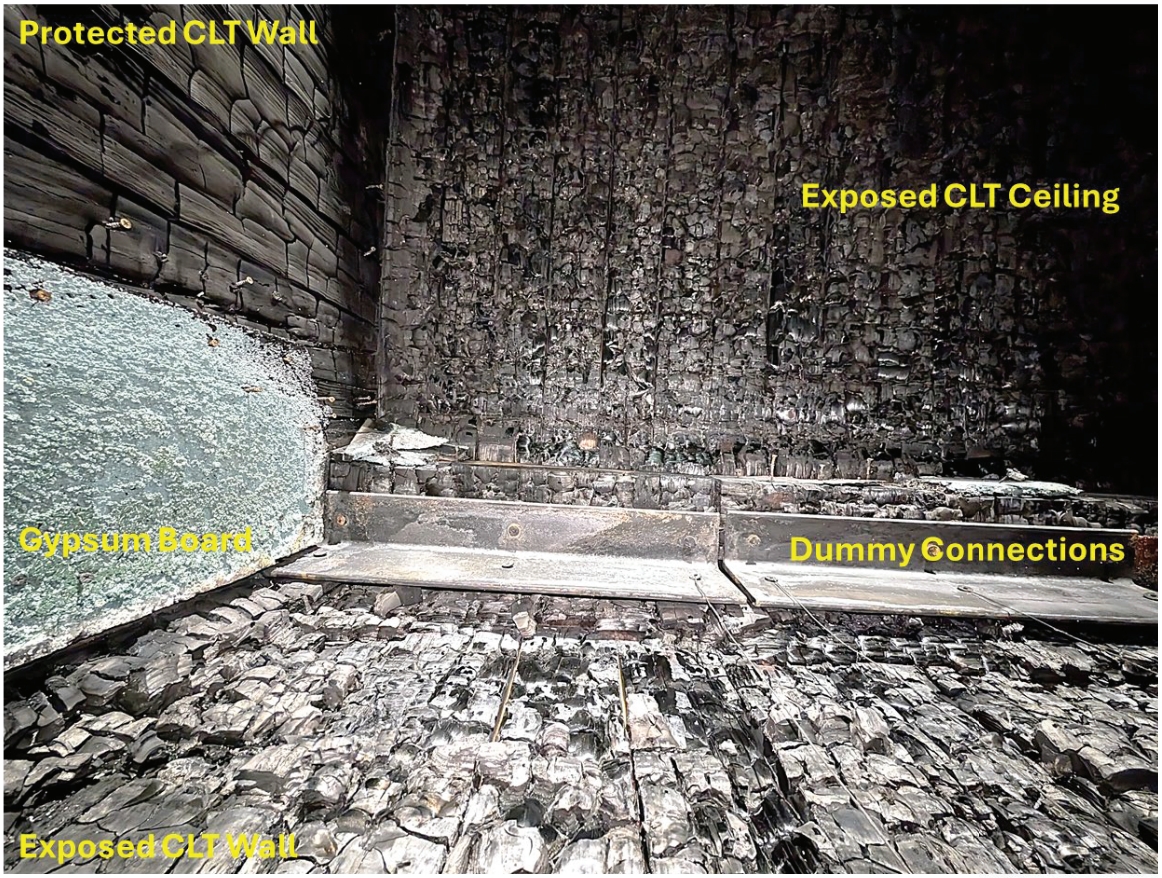

Figure 11: Charring patterns from different surfaces in Test 3.

4 – CONCLUSION

This paper evaluated the preliminary findings of the effect of modern fuel types and larger fuel loads on the development of compartment fire dynamics in compartments with and without mass timber exposed.

The HRR with respect to time highlights the impact the modern mobile fuels have on the fire development when compared to cellulose-based materials. The modern fuels decreased the time to the peak heat release rate and the fully developed phase when compared to the wood cribs. The modern fuels were also consumed quicker, resulting in a shorter duration for the fully developed phase when compared to the wood cribs. This is further highlighted in the CO/CO_2 ratio where CO production from the cellulose-based materials extended 10 minutes beyond that of the modern mobile fuels.

Ultimately, the modern fuels generated a different type of fire growth, when compared to wood cribs, with a more severe fire. The modern fuels resulted in a much longer decay time in their burnout phase, with many of the fuel packages (such as the car seat) continuing to combust and flame for the full duration of the experiment compared to wood cribs. The modern fuels also impacted the compartment fire by creating conditions that reduced the effectiveness of the encapsulation, with charring occurring behind the encapsulation, even with the encapsulation remaining in place.

The onset of the decay phase in Tests #1 and #4 is clear from not only the inflection point of the heat release rate curves but also the percent mass loss curves. The larger fuel load of 800 MJ/m^2 used did not greatly affect the heat release rate results when compared to results from a compartment with a fuel load of 550 MJ/m^2. This is because the compartment is ventilation limited. Tests #2 and #3 displayed a near constant percent mass loss and heat release rate throughout the tests. The addition of exposed mass timber was the only difference between these tests and Test #1. Wood cribs are not representative of modern fuels and should be used with

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caution for experiments that are investigating post-flashover fires, as they underrepresent fire conditions.

Full scale compartment tests are prohibitively costly, making replicates difficult at best to perform. Scaling these down appropriately to preserve the key physical processes that impact compartment dynamics is desirable. Yet questions remain as to the role of scaling when choosing an appropriate opening factor, fuel load, and amount of mass timber used just to name a few. Future work will address these gaps by leveraging data collected from the full-scale compartment tests presented here.

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