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ROOM-SCALE TESTS WITH EXPOSED TIMBER

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ABSTRACT: The influence on fire growth from varying the amount of exposed timber at both the wall and ceiling has been studied through completion of room-scale fire tests, utilizing test standard NFPA 286, *Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*. Three tests were completed that had exposed timber consistent with the 2021 International Building Code (IBC). To understand the impacts on early fire growth conditions, four additional tests with exposed timber at the ceiling consisting of 40%, 60%, 80% and 100% of the floor area, were conducted. Instrumentation included thermocouples, a heat flux transducer, a heat release rate exhaust hood and for each test the propane burner profile was identical. Based on the time to flashover criteria in the standard, flashover was not observed in any of the tests meeting the 2021 IBC limits. By increasing the area of exposed to timber at the ceiling to 40% and 60% of the floor area, flashover was also not observed. Where the exposed timber was 80% and 100% of the floor area (at the ceiling), conditions for flashover were met. The outcomes of the room-scale fire testing are an indicator of expected performance, and these initial tests are carried out to demonstrate that the relatively cost-effective fire experiments can assist in decision making prior to undertaking a large scale experimental series, or to be able to provide refinement and repeatability to completed large-scale results.

KEYWORDS: Timber buildings, room corner test, fire growth, flashover

1 – INTRODUCTION

As mass timber structures continue to be prevalent globally, growing in size, height and complexity, building regulations, codes and standards change to adapt. Building owners and architects desire the timber to be visually seen and to be exposed throughout a building, creating a new engineering problem for fire safety. Buildings with exposed mass timber continue to be researched and studied to determine how the area, location, and type of mass timber impacts fire development and fire decay, an important factor for determining the safety for mass timber structures, especially high-rise buildings.

To assist with the on-going research on exposed mass timber and the connection between room-scale and full-size experiments, the authors have investigated using room-scale testing to study the influence of different areas of exposed timber on fire development. Large scale experiments are costly and take significant time to set up, resource, and complete. Methods to understand how mass timber impacts a fire at a room scale have been studied by the research community for over 15 years [1-7]. This paper presents the initial work from this study where early fire growth to flashover is considered.

2 – BACKGROUND TO TESTING

The International Building Code (IBC) [8], the model building code adopted and amended in all US states and territories, has always allowed exposed timber as a structural material and as an interior finish. Structural timber is permitted under construction types, III, IV and V, and can remain fully exposed. For buildings constructed prior to the 2021 edition of the IBC, the height limit for structural timber was 25.9 m and the exposed timber was not subject to the limitations for flammability of interior finishes, given the buildings would be fully sprinkler protected if residential use, or over three floors in height for non-residential use.

Timber as an interior finish is more prevalent in the US given the IBC allows combustible materials as wall and ceiling finishes, with most restrictions relaxed where sprinkler protection is installed. The interior finish limitations allow timber to be used as a wall or ceiling

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finish throughout all occupied spaces of residential, office, assembly and educational buildings, without needing to be fire retardant treated, or require any flammability reducing coatings. Limitations on flammability of interior materials including timber, occur for exits and exit paths. This differs from other countries that have stricter limitations on combustible finishes and restrict the use of timber, i.e. European criteria through meeting EN 13501-1 [9], where most untreated timber would meet Euroclass D and require treatment to be used within occupied spaces.

The IBC was updated in 2021 after a near five-year process of committee deliberations, task group activities and full-scale fire testing. As a result of that process, mass timber buildings are allowed up to 18 stories, through three new construction types, IV-A, B and C. The new requirements allow structural timber to be exposed up to 12 floors and 54.9m. During the code change process, the impact of exposed timber on fire growth was an item of discussion, with regard to the impact on occupant evacuation and firefighting. The IBC provides criteria for interior finish materials to limit the initial fire hazard of combustible materials, and the interior lining flammability requirements are required to be met for the new type IV-B and C construction implemented with the 2021 IBC update (IV-A does not have mass timber exposed).

As part of the 2021 IBC code changes, an experimental program was implemented to support the code changes with five full-scale fire tests, with four of those fire tests including areas of exposed mass timber [4], and two of those four testing the performance of sprinkler protection. Testing at full-scale is expensive and takes significant resources to set up, prepare for, complete, and assess the results. Time and budgets limited the number of experiments including differing areas of exposed timber discussed in sub-committee work, and a compromise outcome was decided on with only two experiments occurring with exposed timber and being allowed to proceed well past the point of flashover. The two fire experiments that went to flashover with exposed mass timber on the ceiling or walls exposed to a fire that was not controlled by sprinkler protection, or with firefighting intervention, to understand how exposed timber impacts life safety, firefighting and changes the heat release rate. Based on the results of the fire testing, mass timber buildings up to 12 stories were permitted with limited amounts of exposed mass timber, being 20% of the floor area at the ceiling, and 40% of the wall area. Also, the early fire hazards were considered to be of importance with the inclusion of exposed timber flammability criteria, a difference from existing requirements, noting the impact of sprinkler protection.

Understanding how areas of exposed timber impacted occupant tenability and time to flashover was not studied further within the committee process, given that timber as an interior finish was already permitted by the IBC, and therefore existing flammability test methods and limitations were considered to suitably address the exposed mass timber. The large-scale fire testing also did not show any change to the time of flashover between Tests 1 (fully encapsulated), Test 2 (partially exposed ceiling) and Test 3 (exposed wall). Discussion regarding the appropriate test method to determine when exposed timber influenced occupant tenability and time to flashover were to be studied at a future date.

The influence of exposed timber on the time to flashover was a somewhat unanswered question from committee work, and not possible to evaluate by further large-scale testing, given timing and budgets. Of interest was how an increasing area of exposed mass timber would influence flashover, especially when that exposed timber is at the ceiling. Hence, the motivation for this work was based on that outstanding question regarding how increasing area of mass timber at the ceiling detrimentally impacts flashover, and also from actual high-rise mass timber projects where building and fire authorities would ask the same question. The lack of data-based information is a gap that needs to be filled.

2.1 - WHY IS FLASHOVER IMPORTANT?

Flashover is an important marker for fire growth and development, producing conditions when the room of fire becomes untenable and indicating a change to the fire, where it has reached full development. It is defined in different ways by different authors, though is normally considered to be the point where all combustibles have been ignited and are in the process of being consumed by the fire [10, 11]. Flashover is also an important indication for firefighting intervention, given the personnel and water resources needed to control and suppress a growing fire are much less than the resources needed to suppress a flashed over fire.

The IBC requirements for exposed timber are not explicitly connected with limits on combustible interior finishes, even though exposed timber can impact fire spread behaviour and the time to flashover (ignoring the positive impact of sprinkler protection, where installed). For any room where there is a growing fire, having more timber exposed as an interior finish will increase the fire growth rate and will result in incrementally adverse conditions, with a decreased time to flashover [12, 13].

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2.2 - EXPERIMENT MOTIVATION

The aim of the experimental work was to compare areas of timber exposure that were consistent with the 2021 IBC and with larger areas beyond what the 2021 IBC allows and determine the impact of exposed timber on the time to flashover, at room-scale. The experimental results are aimed at determining the influence of large areas of exposed timber on flashover, where that timber may be located on the wall, or ceiling, or a combination of walls and ceiling. When compared to a room with non-combustible finishes, it is known and expected that the introduction of exposed timber will reduce the time to flashover. A question that has not been addressed in a substantive way is how much exposed timber starts to impact flashover substantially. The aim of the experiments was to investigate when the exposed timber has a significant influence on time to flashover and do this at a reduced scale.

Upon researching methods to determine flashover, it became apparent that test approaches are limited and are based on bench-scale testing or room-scale testing. A room-scale test was chosen as it can provide data on how exposed timber can impact early fire development, and do this with a clearer demonstrable method and resultant data. This approach is also able to be completed without large-scale fire experiments, hence faster and substantially more cost-effective.

The room-scale testing is also beneficial to evaluate options, and future work aims to address items such as: 1) Methods to improve performance by reducing flammability, such as pressure treatments, coatings and thermal treatments; 2) Evaluate other mass timber products, for example the impact of horizontal cut-outs in the outer layer of cross laminated timber (CLT) for acoustic performance, where the closely spaced cut-outs can be included to assist with reducing interior sound. The use of cut-outs, slots and other articulations have been questioned as to their impact on fire spread on walls and ceilings; 3) Provide the basis for finite element modelling that can be used to scale results to estimate behaviour in full-size fire compartments.

2.3 SCALING IN FIRE

Scaling is helpful for all fields and provides a means by which to expand on experimental results and assist with parametric studies or defining the factors to be experimented on prior to a large-scale experiment. Historically, bench- and intermediate-scale fire experiments have been used to evaluate material or assembly fire performance and/or flammability and to investigate different experimental configurations at a lower cost. There are several ways to scale fire experiments including specimen dimensions, fire exposure, or energy released. Once developed and easily replicated, some scaled tests become standardized and are used as an indicator of relative change when compared to a baseline.

Scaled fire tests that incorporate the use of exposed timber occurred recently in conjunction with the uptick in the use of mass timber as a construction material. Karannagodage et al., used scaled compartments (0.5 m by 0.5 m by 0.5 m and 0.5 m by 1 m by 0.5 m) to investigate the influence of different exposed timber configurations and areas on the compartment fire dynamics and noted that the presence of exposed timber on the walls influenced the temperature development and the fire duration and that self-extinguishment was a function of geometry, openings and moveable fuel load [14]. Experiments on 24 medium-scale compartments (50 cm by 50 cm by 37 cm) with varying opening factors concluded that previous notions pertaining to fire regimes (e.g., fuel controlled or ventilation controlled) are not applicable when timber elements are exposed and involved in the fire [6]. Scaled 1/8 test compartments were conducted by Northard et al. to evaluate the role that the timber plays in accelerating the transition from a travelling fire to fully developed behaviour [15].

2.4 – INTERIOR FLAMMABILITY AND FLASHOVER TESTING METHODS

The IBC requires combustible materials used as interior finishes to be tested to either NFPA 286 *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth* [16] or ASTM E84 *Standard Test Method for Surface Burning Characteristics of Building Materials* [17], or UL 723 *Test for Surface Burning Characteristics of Building Materials* [18]. NFPA 286 is known as the "room corner" test, for determining the contribution of interior finish materials to room fire growth for specified fire exposure conditions. NFPA 286 evaluates materials based on their performance within a room set-up, with the materials in their vertical or horizontal orientation. This test differs significantly from both ASTM E84 and UL 723 that utilize the Steiner Tunnel and test materials in a horizontal configuration only, with the material mounted as a ceiling. ASTM E84 and UL 723 are used more commonly for material testing, though has limited applicability as it tests in the horizontal configuration only, not representative of exposed timber on walls, and only tests fire spread across a limited width of sample. While technically full-scale, the room corner test can be considered intermediate-scale (or room-scale) when

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compared to large-scale tests such as those conducted by Zelinka et al [4] for the 2021 IBC code changes.

The IBC also specifies NFPA 286 as the test method to determine how combustible materials influence flashover within a space. Building regulations, codes and standards do not typically name a fire test for the determination of flashover and hence the IBC is different. Interestingly, the results from how combustible materials influence flashover are not used and the time to flashover does not change the required fire protection or fire safety measures.

As a brief description, NFPA 286 is based on a standard room with a door at the front of the room and a gas burner located at the rear (Fig 1). Materials to be evaluated are located on the walls, or ceiling, or both. Surfaces that do not include the tested materials are covered with a non-combustible sheathing, typically fire grade gypsum board. With a maximum duration of 15 minutes, flashover is considered to occur when two of the following five parameters are reached: heat release rate (HRR) exceeds 1 MW, heat flux at the floor exceeds 20 kW/m^2, average upper gas layer temperature exceeds 600°C, flames exit doorway, and a paper target on the floor auto-ignites. Measuring the time to flashover in any room experiment will always have variability, due to the normal nonuniformity of fuel packages, ignition, ventilation and configuration of fuels.

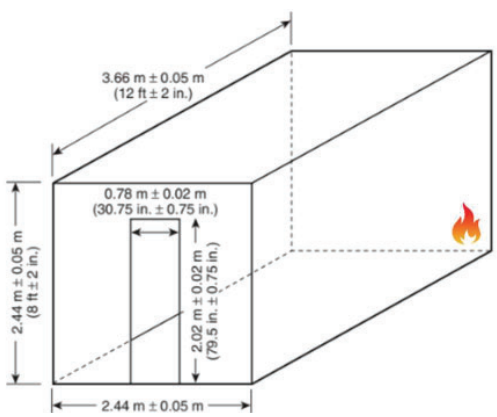

Figure 1: Room dimensions with gas burning in back corner.

3 – EXPERIMENTAL SET-UP AND ROOM CONFIGURATION

Tests were conducted in accordance with NFPA 286 with varying amounts and configurations of exposed timber. All experiments were undertaken at the Forest Products Laboratory where an exhaust hood (2.44 m by 2.44 m) is located immediately adjacent to the door of the fire test room with the bottom of the hood level with the top surface of the room. The interior dimensions of the fire test room were 2.44 m by 3.66 m by 2.44 m in height (Fig 1). The doorway was 0.78 m by 2.02 m. The walls and ceiling were framed with wood studs that were protected with fire-rated gypsum wallboard (Fireguard Type X) with a nominal thickness of 16 mm.

For each test, the ignition source in the back corner of the fire test room was a propane burner with a nominal 305 mm by 305 mm porous top surface and the net heat output was controlled to 40 kW for the first 5 minutes of the test and 160 kW for the remaining 10 minutes.

3.1 TEST MATRIX

A total of seven tests were carried out (see Table 1). The first three tests included 20% of the floor area exposed on the ceiling, 40% of one long wall exposed, and a combination of 8% of one long wall and 16% of the floor area exposed on the ceiling separated horizontally. These three tests are consistent with the exposed mass timber criteria set forth for Type IV-B construction in the 2021 IBC and provide benchmark conditions. Tests 4 through 7 evaluated incremental increases in exposed timber on the ceiling near the rear of room closest to the burner including 40%, 60%, 80% and 100% of the floor area. No timber was exposed on the walls. The increase in exposed timber on the ceiling could then be compared to the baseline conditions in Tests 1 through 3 to understand the impacts on early fire growth conditions. Ultimately, tests 4 through 7 are consistent configurations with the recently revised 2024 IBC [19].

TABLE 1: TEST CONFIGURATION AND SET UP

Test	Description	Area of timber
1	20% exposed timber to ceiling meeting 2021 IBC IV-B, set out from rear of room	1.8m^2
2	40% exposed timber to one long wall meeting 2021 IBC IV-B, set out from rear of room	3.6m^2
3	8% exposed to one wall and 16% exposed at ceiling, meeting 2021 IBC IV-B, set out from rear of room	0.74m^2 wall, and 1.4m^2 ceiling
4	40% exposed timber to ceiling, set out from rear of room	3.6m^2
5	60% exposed timber to ceiling, set out from rear of room	5.4m^2
6	80% exposed timber to ceiling, set out from rear of room	7.1m^2
7	100% exposed timber to ceiling	8.9m^2

3.2 TIMBER PANELS

One of the limitations with the room-scale testing is the need to move all materials to be evaluated through the room opening. The limitations of the room enclosure need to be addressed in a practical way for the mass

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timber products being evaluated, given their weight. To address the limitations, exposed timber panels were fabricated to represent the first ply of CLT were made from western yellow pine lumber with dimensions of 19.5 mm by 139 mm attached to 12.7 mm thick plywood with phenol–resorcinol–formaldehyde (PRF) adhesive (Hexion Cascophen LT-75 with Cascoset FM-282) and nails (Fig 2).

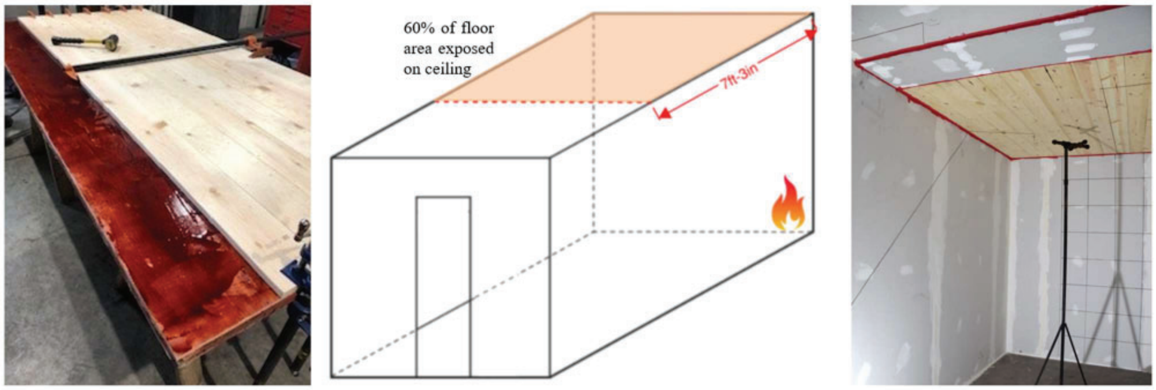

Figure 2: Left to right: Timber panel fabrication with adhesive on plywood. Schematic (not to scale) of Test 5. Timber panel representing 60% of the floor area installed on ceiling prior to conducting Test 5.

The panels were installed over the Type X gypsum board interior surfaces of the fire test room and screwed directly to the wood framing. Fixings were located at 300 mm centres. A Type X gyp boarder and firestop sealant (Hilti, FS-One Max) was installed at the interface of the timber panel with the gypsum board. Firestop sealant was also installed at the wall to ceiling intersections (Fig 2).

3.3 OBSERVATIONS & DATA COLLECTION

The room was instrumented with thermocouples, a heat flux sensor, and heat release rate (HRR) hood in accordance with NFPA 286 and as shown in Fig 3. The ceiling thermocouples (Omega, GG K 24 SLE) were installed 102 mm below the ceiling. Additional thermocouples were installed in the centerline of the doorway with one thermocouple at 102 mm below the top of the door frame, one at 1 m below the top of the door frame, and a third 26 mm above the floor. A Schmidt-Boelter heat flux sensor (Medtherm Corporation, 64-5SB-18) was installed 26 mm above the center of the floor, facing upward. The exhaust collection system was instrumented with oxygen, CO and CO_2 gas sampling and analysis system to obtain the heat release rate.

In addition to the instrumentation, paper targets consisting of a single crumbled sheet of newspaper were placed on the floor at 1.2 m from both the rear and front walls along the centreline. Additionally, images and videos were recorded during the tests to observe potential ignition of the paper targets on the floor and flames through the door.

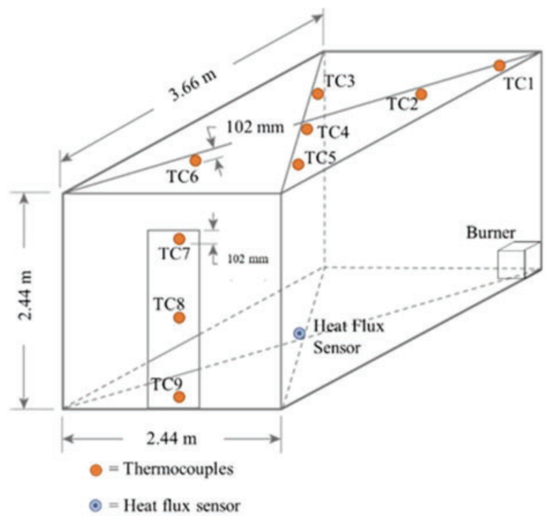

Figure 3: Instrumentation locations within the fire test room.

4 – RESULTS & DISCUSSION

Tables 2 and 3 identify major results, rounded to the nearest whole number, that occurred during each experiment. These results are specifically related to the five different requirements of flashover established in NFPA 286 occurred. Note that, for all seven tests, the paper targets on the floor did not ignite at any point during the tests so this parameter is not included in the tables. All times are provided such that time = 0 seconds is when the burner was turned on and the test started. For observational purposes, Test 2 was extended to 20 minutes while all other tests were terminated at 15 minutes.

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TABLE 2: RESULTS SUMMARY OF AVERAGE CEILING TEMPERATURES AND TIME TO FLAMES TRHOUGH DOOR

Test	Average Ceiling Temperature			Flames through door
	Time to 600℃ [s]	*Max. T [℃]*	*Max. T Time [s]*	*Time [s]*
1	-	526	886	-
2	-	537	361	-
3	-	516	353	-
4	574	607	575	-
5	461	723	511	-
6	483	735	536	544
7	449	724	520	496

TABLE 3: SUMMARY OF HEAT FLUX AND HRR RESULTS

	Heat Flux		Heat Release Rate	
	Max. HF [kW/m²]	*Max. HF Time [s]*	*Max. HRR [kW]*	*Max. HRR Time [s]*
1	8	675	302	873
2	8	1183	353	362
3	7	727	298	341
4	7	576	360	514
5	13	529	576	518
6	15	529	642	532
7	15	510	589	522

Flashover per NFPA 286 did not occur in the first three tests with exposed areas of timber matching the IBC requirements. Of the four tests with additional area of exposed mass timber, the NFPA 286 flashover criteria was not met with 40% and 60% of the floor area as exposed timber at the ceiling. Flashover did occur (based on flames through the door and ceiling temperatures) when 80% and 100% of the floor area as exposed timber at the ceiling was tested. Despite Test 2 running the burner longer than required (40 kW for 5 minutes and 160 kW for an additional 15 minutes for a total test duration of 20 minutes), none of the above criteria for flashover were met.

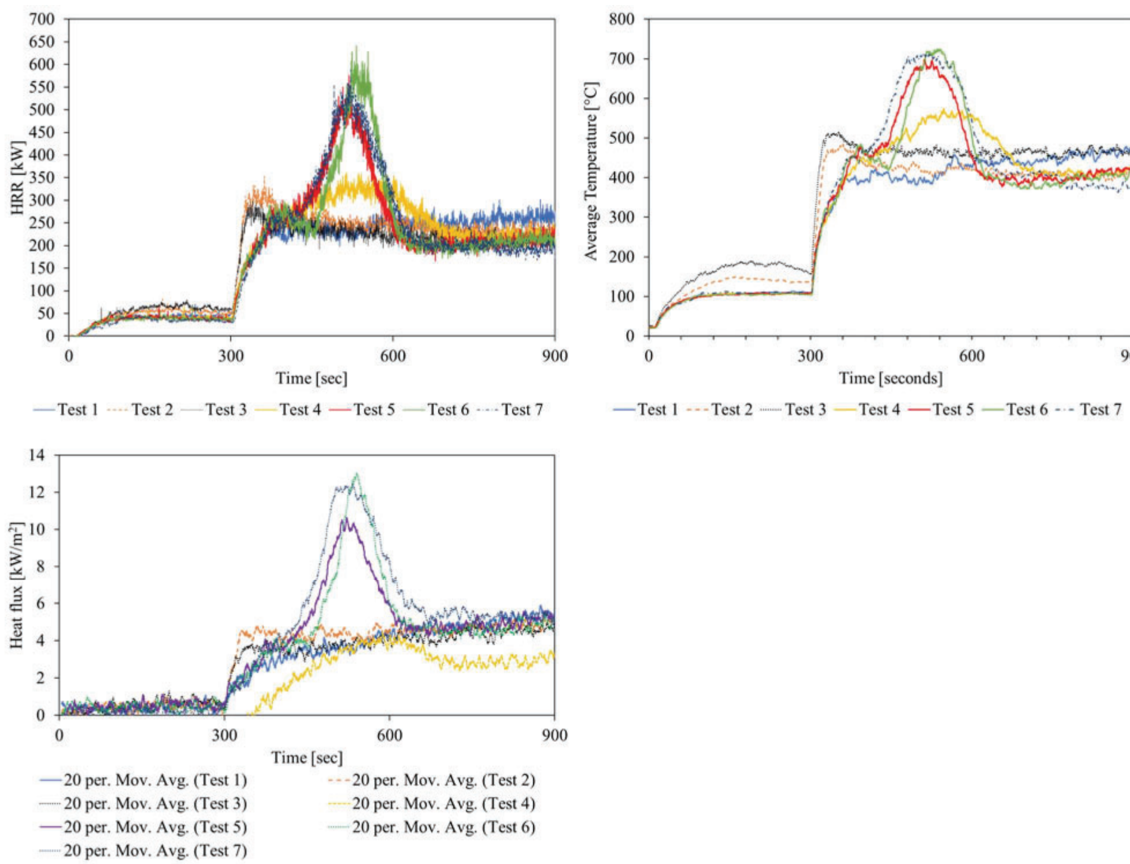

Figure 4: Heat release curves for each test with respect to time (top left), average ceiling temperature with respect to time (top right), and heat flux presented as the moving average over a period of 20 seconds (bottom left).

Fig 4 provides the curves for HRR, average ceiling temperature, and heat flux with time. Tests 1 through 4 show similar behaviour with maximum HRR all below 400 kW, maximum average temperatures below 575°C, and the maximum heat flux less than 8 kW/m^2. While the maximum average ceiling temperatures in Test 5 did reach 698°C, a secondary criterion of flashover was never met. In Test 6, flames crossed the doorway at 544 seconds into the test and the maximum average temperature was 735°C with the average ceiling temperature at or above 600°C for a duration of 105.5 seconds beginning at 483 seconds after the burner was turned on. For Test 7, flames crossed the doorway at 496 seconds after the burner was turned on. Additionally, the maximum average ceiling temperature was 724°C with the average temperature at the ceiling being at or above 600°C for a duration of 145 seconds beginning at 448 seconds after the burner was turned on. It should be noted that, due to freezing conditions on the test day, a flash back preventor froze, causing one of the two propane streams to falter between 16.5 and 114.75 seconds into the test. This resulted in a minor dip in the average ceiling temperature. After this, the propane was able to regulate as expected. Fig 5 provides images with respect to time for Test 6 from the initial burner output of 40 kW to an increase in 160 kW at 5 minutes and the burner off at 15 minutes. Visually, the flames spreading at the ceiling are observed between 7 minutes and 10 minutes, which is consistent with the increase in ceiling temperature and HRR. After 10 minutes, the ceiling temperatures decrease despite the burning remaining at 160 kW. This is due to the formation of a char layer at the ceiling.

Figure 5: Images during Test 6 showing burner and clock with time in mm:ss:ms.

Ultimately, several factors including compartment geometry, ventilation, fuel type, and fuel load will impact the time to flashover in a real compartment so the results in the rooms-scale will not always be an accurate reflection of the large-scale outcomes. However, the qualitative results are comparable to the results observed in large-scale tests showing that the cost-effective method can be used to show the indicators of influence. The second and third large-scale tests by Zelinka et al. [4] showed that the HRR increased to over 20 MW with exposed mass timber on either the ceiling or wall, when compared to the first test with no exposed mass timber and a peak HRR of 18.5 MW. Additionally, Brandon et al. [5] showed that the HRR more than doubled from a compartment with 100% of the ceiling exposed to a compartment with 100% ceiling, beam, and walls exposed.

Questions still exist regarding the safest location for exposed timber and whether walls with large areas of

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exposed timber result in less influence on flashover and fire development, than similar areas of exposed timber at the ceiling. With the room-scale tests, the exposed timber on the walls in Test 2 and 3 resulted in faster times to the maximum HRR and average ceiling temperatures when compared to the other tests (Figure 6). Overall, as more timber is exposed, the time to flashover decreases while the HRR, ceiling temperatures, and heat flux at the floor increase. Thus, both exposed timber at a ceiling or wall detrimentally impact the occupant tenability conditions by changing the fire development, though exposed timber at the ceiling may have a lesser impact than the same area at a wall.

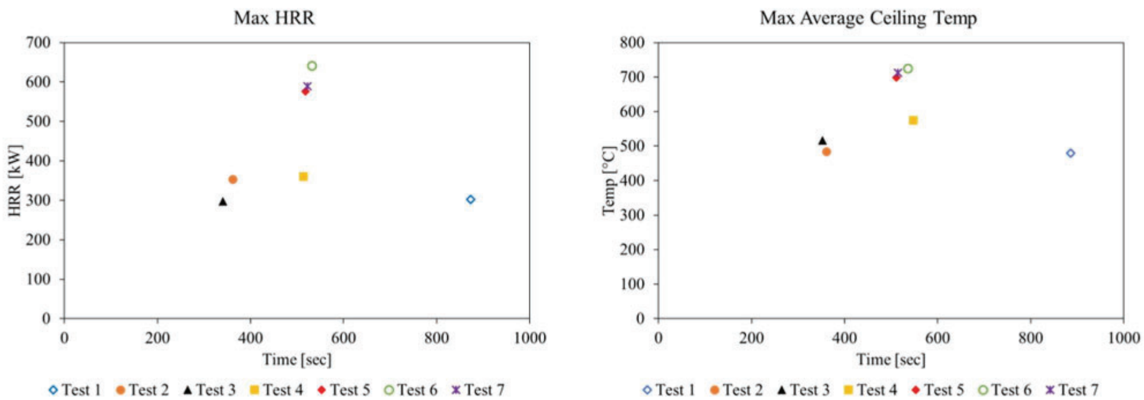

Figure 6: Times to maximum HRR (left and times to maximum average ceiling temperature (right).

Based on the results from the room-scale tests, it is possible that the 2024 IBC changes allowing close to 100% of mass timber to be exposed at the ceiling will results in a reduced time to flashover for a full-size compartment. However, impact on fire growth and reduction in time to flashover would be similar to exposed wood panels as an interior finish, which is already allowed in the IBC.

5 – CONCLUSION

The aim of this research was to utilize room-scale tests to explore how increasing the area of exposed timber limitations set by the 2021 IBC would impact fire growth and time to flashover. The data can then be used to determine if room-scale fire tests can be an effective approach for predicting full-scale experiments with differing areas of wall and ceiling timber exposed, different types of mass timber and different types of flammability protection.

For the tests consistent with the 2021 IBC criteria, flashover did not occur, suggesting that limitations will not substantially increase the fire growth within a full-size compartment.

An increase to 40% timber exposed on the ceiling had a marginal impact with elevated temperatures and HRR, but did not result in flashover. Over 60% exposed timber at the ceiling detrimentally influenced the fire growth conditions with over 80% exposed timber area resulting in flashover. Additionally, the timber on the wall had a greater influence on the initial fire growth than the same area of timber at the ceiling. These results indicate that adjacent exposed timber located at the wall and ceiling should be avoided, and that exposed timber at a wall will detrimentally increase fire growth, resulting in more severe conditions.

These room-scale test results can assist with both research and building design where decisions on exposed mass timber area are being undertaken. It is important to note that the standard room-corner test provides a specified fire exposure and in full-size compartments using real fuels, provided ventilation is available, flashover is highly likely to occur even without mass timber exposed.

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