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FULL-SCALE EXPERIMENTAL STUDY OF COMPARTMENT FIRES IN MASS TIMBER STRUCTURES

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ABSTRACT: The Canadian Wood Council partnered with key stakeholders to conduct five full-scale fire tests under the Mass Timber Demonstration Fire Test Program (MTDFTP) aimed toward advancing current understanding of compartment fire dynamics, fire safety during construction, and impact of exposed mass timber surfaces on fire severity and duration. The fire tests featured varying degrees of encapsulation, ventilation conditions, and fuel loads, and were performed in a two-storey structure constructed of cross-, dowel- and glued-laminated mass timber elements. The test structure's configuration and content intended to represent a mass timber building undergoing construction and areas with residential and open-plan office uses in a finished building. All fire tests were conducted without sprinkler protection or firefighter intervention, illustrating rare scenarios wherein suppression operations would be ineffective in controlling the size and spread of a fire. While the results for each test are discussed in greater detail, the following are some key observations common to all tests: the mass timber test structure remained stable after completing the test program, enduring a total of 19 hours of severe fire exposure; the average char depths in the exposed mass timber members were within the CSA O86:19 design allowance; and despite some exposed cross-laminated timber ceiling panels experiencing localized delamination during the cooling phase of the fire, this phenomenon did not result in re-ignition or fire regrowth.

KEYWORDS: mass timber, encapsulated mass timber construction, compartment fire dynamics, construction fire safety

1 – INTRODUCTION

All buildings constructed under the National Building Code of Canada (NBCC) are required to achieve a minimum level of fire and life safety through a combination of building height and area restrictions, limitations on the use of combustible materials, and various active and passive fire protection measures such as automatic sprinkler systems and compartmentation via fire separations [1]. In order to limit the potential contribution of structures to fire growth and spread, the NBCC has historically prescribed the use of noncombustible construction for buildings exceeding a certain size, based on their major occupancy classification (i.e., the principal occupancy for which a building is intended to be used). The 2020 edition of the NBCC introduced "encapsulated mass timber construction" as a new construction type, allowing tall wood buildings of Group C (residential) and Group D (business and personal services) major occupancies to be erected up to 12 storeys in building height, while maintaining an acceptable level of fire and life safety performance, equivalent to similarly sized buildings of noncombustible construction [2].

Compared to conventional building materials used in noncombustible construction (e.g., steel, concrete), building with mass timber offers several competitive advantages, such as significant reduction in carbon footprint [3], accelerated construction and procurement times facilitated by ease of installation and the possibility of prefabrication [4], and, when integrated into the finished building aesthetics, enhanced biophilic benefits conducive to human health and happiness [5]. Despite these compelling benefits, fire safety of mass timber as a primary structural material remains a concern among some stakeholders [6]. As such, in summer of 2022, the Canadian Wood Council collaborated with federal and provincial bodies and other key partners to conduct a series of full-scale fire tests under the Mass Timber Demonstration Fire Test Program (MTDFTP) aimed toward developing a better understanding of (i) fire dynamics in an open-plan mass timber office space and residential suites, (ii) fire safety during construction, and (iii) impact of exposed mass timber surfaces on fire severity and duration [7].

This paper summarizes the project background and objectives, methodology employed in the MTDFTP's full-scale fire testing series, key findings, and conclusions from this study.

2 – BACKGROUND

The primary purpose of the MTDFTP is to support the acceptance of encapsulated mass timber construction in Canada among architects, engineers, developers, authorities having jurisdiction (i.e., building and fire department officials), insurance professionals, Code committees, and other interested parties. The knowledge obtained from this project can be used to support the advancement of prescriptive Code and alternative

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solutions pertinent to the design and construction of tall wood buildings and the development of 'next-generation' performance-based Codes [8].

3 – PROJECT DESCRIPTION

A total of five full-scale fire tests with varying degrees of encapsulation (i.e., mass timber protection), ventilation conditions, and fuel loads were conducted in a large multi-compartment mass timber structure. The structure was instrumented with thermocouples, Gardon gauges, and infrared cameras to record time-resolved traces of temperature and heat flux profiles measured in and around the structure. Additionally, video cameras were utilized to capture the various stages of fire development during a test, with post-fire char measurements taken afterwards.

All five tests were performed in the absence of sprinkler protection and firefighting intervention, illustrating rare scenarios wherein an automatic sprinkler system would not operate or would be ineffective in controlling the size of a fire, and the fire service would fail to respond to a fire emergency [9, 10]. Therefore, the results of the MTDFTP's full-scale fire testing series should be interpreted within this context.

4 – EXPERIMENTAL SETUP

4.1 MASS TIMBER TEST STRUCTURE

The mass timber test structure employed in this project measured two storeys in height and 330 m^2 (3,550 ft^2) in gross floor area. It was constructed of glued-laminated timber beams and columns, and cross-, dowel-, and glue-laminated timber floor/ceiling panels, and included an exit stair shaft of cross-laminated timber construction. The cross-laminated timber panels used adhesives that met the elevated temperature performance requirements of the 2018 version of ANSI/APA PRG-320 [11]. All structural mass timber elements were designed and sized to provide at least 2-hour fire-resistance rating, following the effective cross-section calculation method described in Annex B, Fire resistance of large cross-section wood elements, of CSA O86:19, "Engineering design in wood" [12].

The test structure's layout (Fig. 1) and content intended to represent a mass timber building undergoing construction, as well as areas of a finished building with an open-plan office space and residential suites. More specifically, the first storey of the L-shaped mass timber test structure was configured as a four-bay open-plan office area, with each bay measuring 7.3 m by 7.3 m (24 ft by 24 ft), while the second storey was laid out as three separate residential units – suite 'A', 'B', and 'C' – located above the two middle bays on the first storey. A more comprehensive description of the structure's design details can be found in [7].

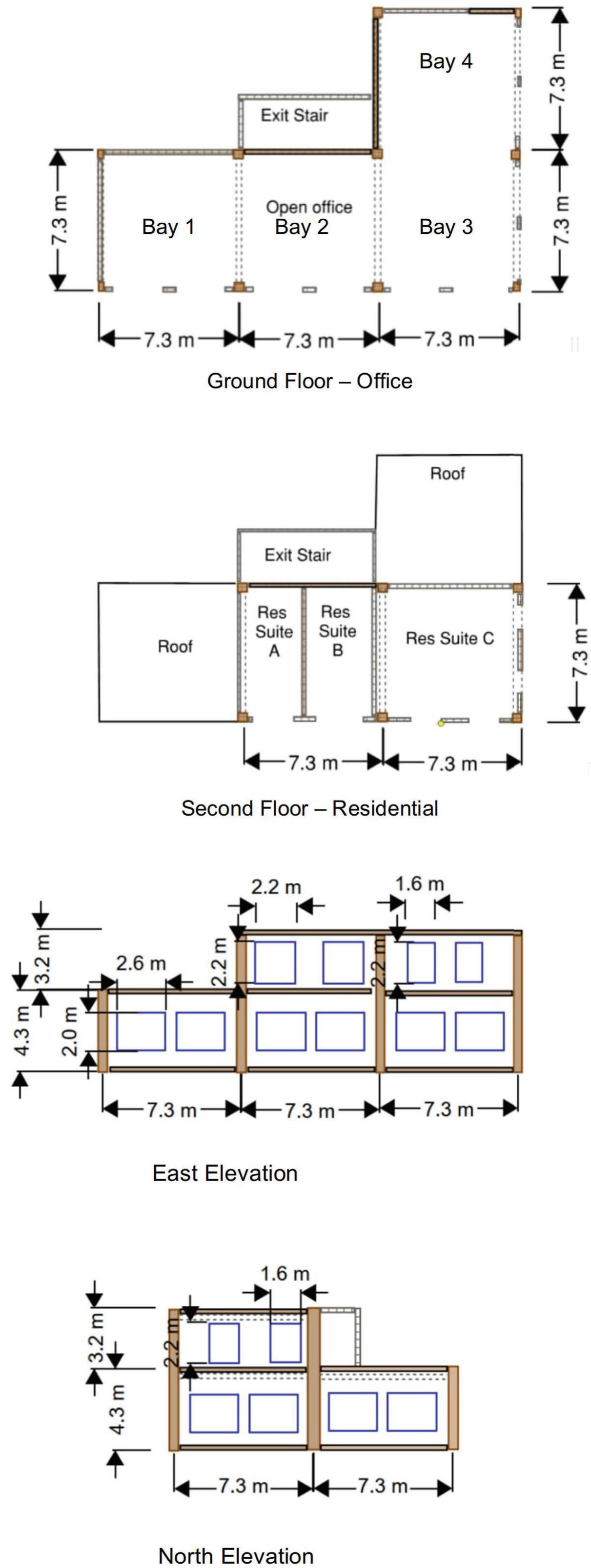

Figure 1. Mass timber test structure: schematic floor and elevation plans [7].

The finished structure (Fig. 2) featured 1-hour fire-resistance rated exterior wall assemblies, constructed in accordance with cUL Design No. U419 [13], with ten window openings on the first floor, and six window openings on the second floor.

Figure 2. Photograph of the finished mass timber structure prior to the first scheduled test.

Since one of the key objectives of the study was to gain insight into the impact of exposed mass timber surfaces on fire severity and duration, the use of fire rated exterior walls, which may not be required in most buildings, would reduce the probability of fire breaching to the exterior, therefore, retaining much of the heat generated inside the structure and allowing the tests to focus on the fire performance of exposed mass timber elements.

4.2 TEST MATRIX AND FIRE SCENARIOS

The test matrix and corresponding fire scenarios used in the MTDFTP's testing series are described in the following paragraphs. Where referenced, the term "combustible content" or "movable fuel load" refers to all combustible materials, including floor coverings, that are not part of the building's primary structure. The fuel loads used typical contents and arrangement found in residential suites, office spaces, or construction sites without including plastic and upholstered items containing foamed components (e.g., mattress, couch) in order to minimize smoke and environmental impact on the test site. Thus, all fire tests utilized wood-based materials for the fuel loads (see further details below). No structural load was applied, other than the self-weight of the test structure and the representative fuel loads.

Test 1 was conducted in residential suite 'B' and intended to replicate a Code-compliant baseline scenario for a building of noncombustible construction. As such, all structural mass timber elements within the suite, including the upper side of the mass timber floor, were protected with two layers of 15.9 mm ($^{5}/_{8}$ in) thick Type X gypsum board to prevent their involvement in the fire. The interior wall and ceiling surfaces were lined with a single layer of 25 mm (1 in) thick plywood and two layers of 12.7 mm ($^{1}/_{2}$ in) thick fire-retardant-treated plywood, respectively, as permitted by Division B, Article 3.1.5.12. of the 2020 NBCC. The total area of combustible interior finishes in the suite was around 72 m^2 (775 ft^2).

The fire compartment was fully outfitted with consumer furniture representing a studio apartment with sleeping, living, and dining areas, as shown in Fig. 3. The combustible content in suite 'B' had a fuel load density of 613 MJ/m^2 (54,000 BTU/ft^2), which was 10% higher than the similar fuel packages reported in previous tests [14–16]. The ventilation factor in suite 'B' was around 0.07 $m^{1/2}$. The purpose of this test was to provide baseline results for comparison to a similar fire in a residential unit of an encapsulated mass timber building (Test 2) with some exposed mass timber surfaces.

Figure 3. Photographs of the finished mass timber residential suites 'A' (Test 2), left image, and 'B' (Test 1), right image.

Test 2 involved a fire in a fully-furnished residential unit (suite 'A') of encapsulated mass timber construction with the same residential fuel package, furniture arrangement, fuel load density, interior floor dimensions, and ventilation factor as in Test 1 (Fig. 3). In Test 2, the residential suite featured various exposed mass timber elements, while the remaining portions of the mass timber surfaces were encapsulated with two layers of 15.9 mm ($^{5}/_{8}$ in) thick Type X gypsum board, including the mass timber shaft wall and the upper side of the mass timber floor, the latter of which would normally be protected with a 38 mm (1 $^{1}/_{2}$ in) thick concrete or gypsum-concrete topping in a finished building. Approximately 3 m^2 (32 ft^2) of mass timber column, 4 m^2 (43 ft^2) of mass timber beam, and 23 m^2 (248 ft^2) of mass timber ceiling surfaces remained exposed during the test. The aggregate area of exposed mass timber beam and column surfaces was equal to 12% of the total perimeter wall area of the suite, while the mass timber ceiling was completely exposed (i.e., 100% of the total ceiling area). The purpose of this test was to provide results for comparison to a similar baseline fire within a residential unit of noncombustible construction (Test 1), and to demonstrate the impact of exposed mass timber surfaces on fire severity and duration in a realistic occupied suite using greater exposed surfaces of mass timber elements than those currently permitted by Division B, Article 3.1.6.4. of the 2020 NBCC.

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Test 3 was conducted in the same residential suite 'B' as Test 2 wherein all mass timber elements were exposed and intended to replicate a realistic construction site fire scenario with a garbage bin fire source. More specifically, about 10 m^2 (108 ft^2) of mass timber shaft wall and 23 m^2 (248 ft^2) of mass timber ceiling and floor surfaces remained exposed in this test. The surface area of exposed mass timber wall was equal to 16% of the total perimeter wall area of the suite, while the mass timber ceiling and floor surfaces were fully exposed (i.e., 100% of the total ceiling/floor area).

The garbage bin fire source employed in this test was arranged by filling a 105-litre (28 gallon) steel garbage bin with a single 17 kg (38 lbs) wood crib, as shown in Fig. 4. The wood crib was constructed of 38 mm (1 $^1/_2$ in) square softwood lumber pieces cut to 300 mm (1 ft) in length with five pieces placed in a row such that the following row was perpendicular to the adjacent row, until the crib reached a total stack height of 17 layers. The garbage bin fire source, which provided a movable fuel load density of 15 MJ/m^2 (1,300 BTU/ft^2), was placed 25 mm (1 in) away from the base of the mass timber shaft wall located at the rear of suite 'B'. This garbage bin fire source alone can produce a peak heat release rate of 300 kW and a free burning time of 27 minutes.

Figure 4. Garbage bin fire source employed in Test 3.

Test 4 involved a fire in residential suite 'C' wherein all mass timber elements were exposed and intended to represent a more severe construction site fire scenario with a more aggressive fuel package than that used in Test 3. Around 13 m^2 (140 ft^2) of mass timber beam, 9 m^2 (97 ft^2) of mass timber column, 50 m^2 (540 ft^2) of mass timber ceiling, and 53 m^2 (570 ft^2) of mass timber floor surfaces in suite 'C' remained exposed during the test. The aggregate area of exposed mass timber beam and column surfaces accounted for 25% of the total perimeter wall area of the suite, while 100% of the total mass timber ceiling/floor area was exposed.

The movable fuel load employed in this test consisted of unprotected wood-framed interior wall partitions and six large wood cribs, each weighing approximately 50 kg (110 lbs), as shown in Fig. 5. The exposed interior partition walls were constructed using 300 kg (660 lbs) of 38 mm by 89 mm (1 $^1/_2$ in by 3 $^1/_2$ in) wood studs. The wood cribs were constructed of 38 mm by 89 mm (1 $^1/_2$ in by 3 $^1/_2$ in) softwood lumber pieces cut to 800 mm (2.6 ft) in length with six pieces arranged in a row such that the following row was perpendicular to the adjacent row, until each crib reached a total stack height of 8 layers [17]. The combustible content used in this test had a fuel load density of 224 MJ/m^2 (19,700 BTU/ft^2), which is higher than that typically found on mass timber construction sites. The ventilation factor in suite 'C' was around 0.11 $m^{1/2}$.

Figure 5. The movable fuel load employed in Test 4.

Test 5 was intended to represent a fire scenario in an open-plan office space of encapsulated mass timber building construction with some exposed mass timber elements. The test was conducted on the first storey of the mass timber structure, measuring around 200 m^2 (2,150 ft^2) in floor area. The ventilation factor on this floor was approximately 0.12 $m^{1/2}$. The exposed mass timber surfaces in this test were around 195 m^2 (2,100 ft^2) on the ceiling, 28 m^2 (300 ft^2) over the shaft wall, 33 m^2 (355 ft^2) over the columns, and 36 m^2 (390 ft^2) over the beams, for a total of 290 m^2 (3,120 ft^2). In other words, the mass timber ceiling was entirely exposed (i.e., 100% of the total ceiling area), and the aggregate area of exposed mass timber beam, column, and wall surfaces was equal to 35% of the total perimeter wall area of the fire compartment. The remaining portions of the mass timber walls that were not intended to contribute to the total area of exposed mass timber surfaces were encapsulated with two layers of 15.9 mm ($^5/_8$ in) thick Type X gypsum board on the interior side, while the upper side of the mass timber floor assembly was protected with two layers of 12.7 mm ($^1/_2$ in) thick Type X gypsum board, to prevent their involvement in the fire. Similar to Test 2, the total surface area of exposed mass timber ceiling in Test 5 was greater than that currently permitted by Division B, Article 3.1.6.4. of the 2020 NBCC.

The open-plan office space was fully-furnished with eighteen cubicles (i.e., workstations simulated with wood materials) separated by privacy partitions made of 19 mm ($^3/_4$ in) thick plywood sheets, as shown in Fig. 6. The workstations were outfitted with wood table tops constructed of nominal 38 mm by 140 mm (1 $^{1}/_{2}$ in by 5 $^{1}/_{2}$ in) and 38 mm by 184 mm (1 $^{1}/_{2}$ in by 7 in) dimensional lumber, while the floor covering in each cubicle area was lined with 19 mm ($^{3}/_{4}$ in) thick plywood sheets, placed over the gypsum board, to replicate carpeting and similar textile flooring and underlayment typically used in a contemporary office. Other consumer furniture (e.g., upholstered office chair) and ancillary office supplies (e.g., paper, electronic equipment, shelving unit, waste basket) were substituted with discrete piles of 25 kg (55 lbs) wood cribs providing an equivalent calorific content [17]. As such, each cubicle featured a small wood crib constructed of 38 mm by 89 mm by 800 mm (1 $^{1}/_{2}$ in by 3 $^{1}/_{2}$ in by 2.6 ft) softwood lumber pieces arranged in rows of six and stacked to 4 layers high. Additional strips of 38 mm by 38 mm by 2.4 m (1 $^{1}/_{2}$ in by 1 $^{1}/_{2}$ in by 8 ft) softwood lumber pieces were distributed across all cubicles and placed below the table tops. The combustible content used in this test had a fuel load density of 362 MJ/m^2 (31,900 BTU/ft^2), which was within the historical range of fuel packages reported in the literature [18, 19].

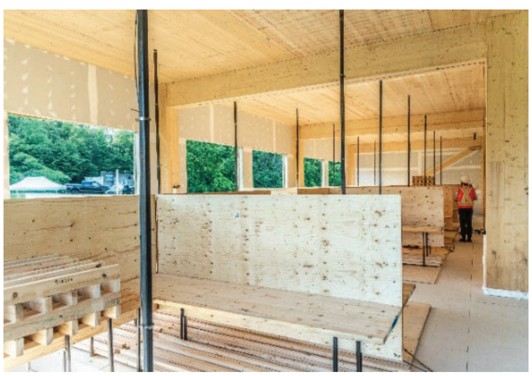

Figure 6. Photograph of the open-plan office space in Test 5.

Test 5 involved the largest fuel load, compartment size, and ventilation factors in this demonstration fire test program. The fire was ignited in Bay 1 of the L-shaped test structure and left to spread (uninterruptedly) throughout the entire space on the ground floor. Unlike the majority of exposed mass timber compartment fire tests conducted to date, which had predominantly focused on residential occupancies, this test was intended to provide insight into the impact of exposed mass timber surfaces on fire severity and duration in a typical occupied open-plan office space of a finished mass timber building.

As mentioned previously, all fire compartments in this testing series were instrumented with thermocouples, water-cooled heat flux meters, video and infrared cameras to capture various stages of fire development during a test and to record time-histories of temperature and heat flux profiles measured inside and outside the mass timber structure. A more detailed description of the instrumentation employed in each of these tests can be found in [7].

Please note that the numerical order of the tests serves only as an identification and does not reflect the true temporal sequence of the tests conducted. Test 5 was performed first, followed by Tests 1, 2, 4, and 3. The test results presented in this paper are documented in a chronological order, reflecting the actual testing schedule.

5 – RESULTS

5.1 TEST 5

By design, Test 5 combined several severe testing conditions including an aggressive ignition source and fuel package as well as the absence of automatic sprinkler protection and firefighting intervention during the 4-hour test. In reality, the likelihood of all these conditions occurring simultaneously is extremely low.

The initial fire growth, from ignition to flame impingement on the ceiling, took 3 minutes and 40 seconds, as can be seen from the temperature-time plot shown in Fig 7. This rapid fire progression was likely caused by the aggressive ignition source, high fuel load and ventilation openings in the test. Fig. 8 shows a plume due to the ignition source alone impinging on ceiling by design, which significantly accelerated the initial fire growth.

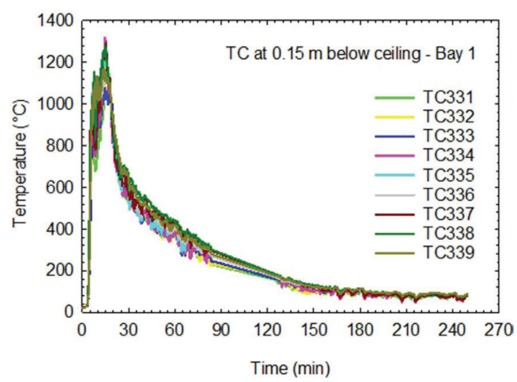

Figure 7. Temperature vs. time in the upper region of the fire compartment, recorded across multiple locations in Bay 1 (fire origin), 0.15 m below the ceiling level [7].

Once the flames from the fire impinged on the ceiling (Fig. 8), they spread across the exposed ceiling surface within 2 minutes at an average speed of 140 mm/s (5.5 in/s). The radiative heat feedback from the ceiling flames to the fuel bed on the floor was sufficiently large to ignite the cubicles consecutively at an average speed of 100 mm/s (3.9 in/s). Similarly, the aggressive ignition source and high fuel package used in this test, along with abundance of oxygen supply, likely accelerated the rate of flame spread across the ceiling. The entire open-plan office area, from floor to ceiling, was fully engulfed in flames during 7 to 18 minutes following the onset of ignition. During this time, large fire plumes issued from

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the window openings, as shown in Fig. 9, extending up to 7.5 m (24.6 ft) high and 10 m (32.8 ft) out the openings.

Figure 8. Photograph of the flame impingement on the exposed mass timber ceiling in Bay 1 (fire origin).

Figure 9. Photograph of the fire plumes ejected from the window openings during Test 5.

The thermal environment throughout the large open space was highly stratified, with a marked difference in temperatures of around 400°C (752°F) between the upper and mid-compartment height layers. The fire began to decay after 18 minutes. By 21 minutes, no visible flaming was observed on exposed mass timber surfaces, and, by 30 minutes, the fuel bed had significantly reduced in size, leaving only glowing debris on the floor (Fig. 10), which was completely consumed by 60 minutes. At no point during the test did the temperatures measured inside the mass timber stairwell exceed 36°C (97°F). The maximum temperatures recorded inside the residential suites on the second storey (window openings of which were protected during Test 5) ranged from 30°C (86°F) to 65°C (149°F), depending on the location.

During the subsequent three hours of the test, the open-plan office space continuously cooled down, yet smouldering in several mass timber joints appeared to persist as the temperatures recorded in the mass timber connections continued to rise due to thermal lags. Some portions of the cross-laminated timber ceiling panels near the shaft experienced localized delamination after 190 minutes, yet this phenomenon did not cause re-ignition or fire regrowth.

Figure 10. Photograph of the glowing fuel bed debris on the floor.

Post-test char measurements revealed that the average char depths in the exposed mass timber members were well within the CSA O86:19 design allowance (i.e., 78 mm (3 in) for one-dimensional charring and 84 mm (3 $^{15}/_{16}$ in) for notional charring) for 2-hour fire-resistance rated structural members – namely, 24 mm ($^{15}/_{16}$ in) for the cross-laminated timber ceiling, 42 mm (1 $^{21}/_{32}$ in) for the cross-laminated timber stairwell wall panels, and 29 mm and 39 mm (1 $^{5}/_{32}$ in and 1 $^{17}/_{32}$ in) for the glued-laminated timber beams and columns, respectively, with the vertical mass timber members exhibiting deeper charring profiles than the horizontal elements.

More profound charring depths were observed near the connections and at the mass timber beam, column, and ceiling junctions. Deep-seated burnt pockets were also found at several junctions of the ceiling panel butt joints of glue-laminated timber panels on top of the beams and at the bottom of the cross-laminated shaft wall beside the column. This was likely due to the challenges encountered during the construction of the test structure such as incomplete firestop system installation, compounded by the absence of normally used concrete or gypsum-concrete topping on the floor assemblies, and less precise hardware connection fit between various mass timber members, which were supplied from different manufacturers across Canada [7]. Furthermore, the test structure was not built as airtight as a typical finished mass timber building. The lack of firefighting intervention during the four-hour test further exacerbated these factors, which, ultimately, appeared to compromise the continuity of fire separations, allowing hot gases to migrate through the structural elements, thus, causing the mass timber joints and connections to smoulder. It is important to note that these issues were unique to the test structure. In a typical encapsulated mass timber building, computer numerical control (CNC) technology would be employed to produce mass timber structural elements and install connection hardware with greater precision and tighter fits. Moreover, concrete or gypsum-concrete topping would be poured on the upper surface of the mass timber floor assemblies, and the building envelope would be airtight to limit air leakage and thermal transfer, at a minimum, as required by the National Energy Code of Canada for Buildings (NECB) [20].

Overall, the mass timber test structure demonstrated remarkable stability and integrity after enduring more than four hours of severe fire exposure. Following the test completion, suppression operations, conducted by the municipal fire brigade on site, were devoted to addressing the hidden hot spots in some mass timber joints and connections, which were subsequently fully extinguished. Post-test fire watches confirmed that no further smouldering combustion or hot spots were evident.

5.2 TESTS 1 AND 2

Tests 1 and 2 were conducted to compare the fire performance of a mass timber residential suite, featuring exposed mass timber columns, beams, and ceiling, relative to a Code-conforming noncombustible baseline scenario. The goal of these tests was to demonstrate the outcome of using greater areas of exposed mass timber surfaces (in Test 2) than those currently permitted in the 2020 NBCC. As mentioned previously, Test 1 intended to represent a severe fire scenario in a fully-furnished residential unit (suite 'B') of noncombustible construction with combustible linings on the ceiling and three interior walls. The total area of combustible interior finishes in Test 1 was around 72 m^2 (775 ft^2). In contrast, Test 2 was conducted in a realistic occupied residential unit (suite 'A') of encapsulated mass timber construction with some exposed mass timber surfaces, for a total of approximately 30 m^2 (323 ft^2). Both tests included the same fuel package (i.e., identical room content and furniture arrangement), fuel load density (613 MJ/ m^2 (54,000 BTU/ft^2)), interior floor dimensions (22 m^2 (237 ft^2)), and ventilation factor (around 0.07 m$^{1/2}$).

Overall, the fire development across these tests was quite similar. Following the onset of ignition, compartment flashover occurred at nearly the same time in both tests (4 minutes 48 seconds in Test 1 and 4 minutes 44 seconds in Test 2), accompanied by over 6 m (19.7 ft) high fire plumes emerging from the window openings, as shown in Fig. 11. During the fully-developed phase of the fire, the compartment temperatures in both tests reached 1,200°C (2,190°F) (Fig. 12). The compartment fire entered the decay phase as the combustible content in both tests approached near-full consumption. The fire began to decay earlier and more rapidly in Test 2 compared to Test 1, at 25 and 30 minutes after ignition, respectively, due to the additional fuel from the plywood linings in Test 1. By the end of both tests, compartment temperatures decreased to below 200°C (392°F). Due to the large quantity of combustible interior linings used in Test 1, the remaining debris continued to burn on the floor with glowing embers until the end of the 4-hour test. In contrast, Test 2 showed no sustained flaming on the mass timber elements after 45 minutes, although small flickering flames intermittently appeared on the exposed ceiling and beam surfaces. While some portions of the exposed cross-laminated timber ceiling panels experienced localized delamination during the cooling phase of the fire in Test 2, this phenomenon did not result in re-ignition or fire regrowth. Overall, the fire environment in the mass timber residential suite (Test 2) appeared to be less severe than that in the Code-conforming noncombustible baseline scenario (Test 1). The temperatures measured in the mass timber exit stair shaft remained below 32°C (90°F) for the entire duration of the tests, indicating that the compartment fires in either test did not adversely affect the tenability conditions in the adjacent stairwell.

Figure 11. Photographs of the peak fire plumes issued from the window openings during Test 1 (left image) and Test 2 (right image).

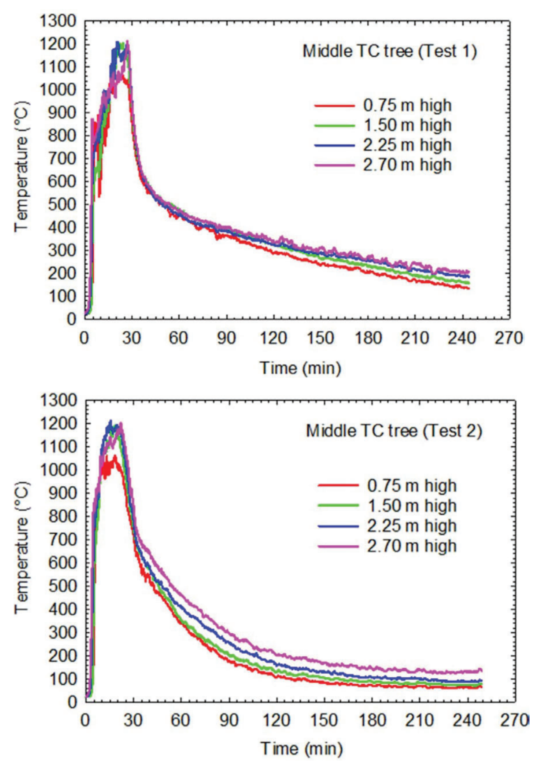

Figure 12. Time-histories of room temperatures in Test 1 (top plot) and Test 2 (bottom plot), recorded at four measurement positions on the middle thermocouple rake [7].

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The average char depths in Test 2 were 40 mm (1 $^9/_{16}$ in) for the mass timber ceiling panels, 70 mm (2 $^3/_4$ in) and 57–67 mm (2 $^3/_4$ – 2 $^5/_8$ in) for each exposed side of glued-laminated timber beam and columns, respectively. More profound charring depths, however, were observed near the connections and at the mass timber beam, column, and ceiling junctions, with some deeper-seated hidden hot spots. This was partly due to the test structure not being built as airtight as a typical finished mass timber building. Post-test firefighting operations were necessary to ensure that all hot spots were fully extinguished.

5.3 TEST 4

Test 4 was performed in a 7.1 m (23.3 ft) wide by 7.5 m (24.6 ft) long by 3.0 m (9.8 ft) high space (suite 'C') replicating a severe construction fire scenario. The fire compartment included exposed mass timber ceiling, floor, column, and beam surfaces for a total of approximately 125 m^2 (1,346 ft^2). The fuel package employed in this test consisted of unprotected wood-framed interior wall partitions and six large wood cribs, which collectively provided a fuel load density of 224 MJ/m^2 (19,700 BTU/ft^2). The severe test conditions were further exacerbated by strong winds present on the test day.

Following the onset of ignition, the fire grew in size for about 8 minutes, transitioning into the fully-developed stage where sustained flaming remained at its peak extent for almost 10 minutes (Fig. 13). During this period, the temperatures recorded in the compartment exceeded 1,100°C (2,012°F), while fire plumes issued from the window openings reached over 6 m (19.7 ft) high, as shown in Fig. 14. The fire started to decay at around 18 minutes after ignition when virtually all combustible content was either consumed or fallen onto the floor. By 19 minutes, the flames ceased to eject from the openings, and, by 30 minutes, no visible flaming was observed on exposed mass timber surfaces. The compartment temperatures decreased to between 300°C and 400°C (572°F and 752°F) around one hour after ignition. However, the fire did not reach a point of complete self-extinguishment as the compartment temperatures gradually ascended to around 600°C (1,112 °F) and intermittent flaming persisted in the mass timber wall-to-ceiling junctions. The test was terminated at around 2.5-hour mark and all deep-seated localized hot spots were manually extinguished by the fire brigade on site. The test was terminated earlier than planned due to smoke migrating toward the occupied buildings on site. The temperatures recorded in the mass timber exit stair shaft were below 22°C (72°F) throughout the entire test, demonstrating that the fire severity in the adjacent compartment did not compromise the tenability conditions experienced in the stairwell.

During Test 4, the mass timber test structure endured approximately 20 minutes of flaming combustion followed by 120 minutes of smouldering combustion. The average post-fire char depths were well within the CSA O86:19 design allowance for 2-hour fire-resistance rated structural members, namely, 70 mm (2 $^3/_4$ in) for the dowel-laminated timber ceiling, and 34–53 mm and 56–73 mm (1 $^{11}/_{32}$ – 2 $^3/_{32}$ in and 2 $^7/_{32}$ – 2 $^7/_8$ in) for each exposed side of glued-laminated timber beams and columns, respectively. Similar to previous tests, more profound charring depths were observed near the connections and junctions, with some deeper-seated hidden hot spots, which subsequently warranted post-test suppression operations for full extinguishment.

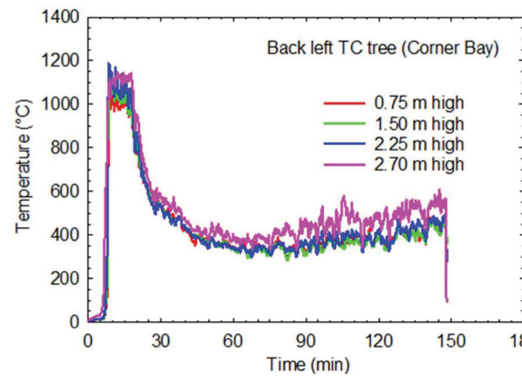

Figure 13. Time-histories of room temperatures in Test 4, recorded at four measurement positions on the rear left (corner bay) thermocouple rake, closest to the fire origin [7].

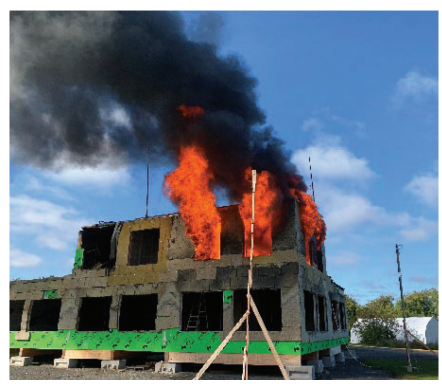

Figure 14. Photograph of the peak fire plumes issued from the window openings during Test 4.

5.4 TEST 3

Test 3 was conducted in a 3.2 m (10.5 ft) wide by 7.0 m (23 ft) long by 3.0 m (9.8 ft) high space (suite 'B') representing a portion of a mass timber building under construction. The fire compartment featured exposed mass timber ceiling, floor, and shaft wall surfaces for a total of around 55 m^2 (592 ft^2). A 105-litre (28 gallon) steel garbage bin filled with a single 17 kg (38 lbs) wood crib was used as the fire source, which provided a fuel load density of 15 MJ/m^2 (1,300 BTU/ft^2).

Following the onset of ignition, it took over 20 minutes for the flames of the garbage bin fire to grow and impinge

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on the exposed mass timber ceiling. Flame spread on the ceiling of the compartment and subsequent flashover was observed at around 23 minutes after ignition with the room temperatures rising to above 1,000°C (1,832°F) almost instantaneously (Fig. 15). However, the compartment flashover was short-lived as the flames significantly diminished in size within only a minute, ceasing to eject from the window opening. By 25 minutes after ignition, there was no visible flaming on the mass timber ceiling, and, as can be seen from Fig. 16, by 30 minutes, the compartment temperatures dropped to below 160°C (320°F). It was evident that the garbage bin fire source did not have sufficient quantities of fuel to sustain prolonged steady-state burning in the compartment. The remaining debris in the waste bin self-extinguished by 35 minutes. At the end of the 4-hour test, the room temperatures were well below 30°C (86°F). At no point during the test did the temperatures measured in the mass timber stairwell exceed 18°C (64°F).

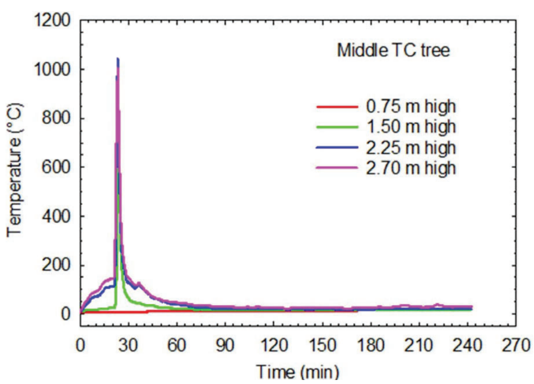

Figure 15. Time-histories of room temperatures in Test 3, recorded at four measurement positions on the middle thermocouple rake [7].

During the test, the exposed mass timber ceiling, floor, and wall surfaces experienced less than three minutes of sustained flaming exposure, which resulted in minimal char depths; mostly surface charring of just a few millimetres, as shown in Fig. 16. However, the char depth was up to 20 mm ($^{25}/_{32}$ in) on the ceiling directly above the garbage bin, along the junction of the mass timber ceiling and wall. In the top right rear corner of suite 'B', where the mass timber ceiling and two walls met, the char depth exceeded 20 mm ($^{25}/_{32}$ in), with localized hot spots and glowing combustion still remaining in these junctions at the end of the test. Thorough firefighting operations were conducted after the test to ensure that all hot spots were fully extinguished.

Despite having a limited movable fuel load in Test 3 compared to that in Test 4, the garbage bin fire in Test 3 was designed to be as severe and repeatable as possible by creating ventilation slots and configuring wood pieces in the bin. The results of this test indicate that controlling the quantity of combustible materials on a construction site is crucial for minimizing potential fire hazards. Additionally, if a garbage bin fire occurs on a construction site, early detection and the availability of operable and readily accessible fire extinguishers could provide workers with an opportunity to extinguish the fire promptly.

Figure 16. Test 3: the post-fire state of exposed mass timber ceiling (top image) and shaft wall (bottom image) surfaces [7].

6 – CONCLUSION

Mass timber offers several competitive benefits in construction, making it an increasingly popular choice for sustainable and aesthetically pleasing building projects. Despite these compelling benefits, fire safety of mass timber as a primary structural material remains a concern among some stakeholders. As such, the Canadian Wood Council collaborated with federal and provincial bodies and other key partners to conduct a series of five full-scale fire tests under the Mass Timber Demonstration Fire Test Program (MTDFTP) aimed toward developing a better understanding of mass timber compartment fire dynamics in residential suites (Tests 1 and 2) and open-plan office spaces (Test 5), fire safety during construction (Tests 3 and 4), and impact of exposed mass timber surfaces on fire severity and duration (Tests 1–5). All five fire tests were performed in the absence of sprinkler protection and firefighting intervention, illustrating rare scenarios wherein an automatic sprinkler system would not operate or would be ineffective in controlling the size and spread of a fire, and the fire service would fail to respond to a fire emergency in a timely manner.

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This paper provided an overview of the project background, objectives, and methodology employed in the MTDFTP's full-scale fire testing series, as well as key findings and conclusions from this study. While the results for each test were discussed in greater detail, some key observations common to all tests included the following findings: (i) the mass timber test structure remained stable and solid after five full-scale tests, enduring a total of 19 hours of severe fire exposure; (ii) the average char depths in the exposed mass timber members were well within the CSA O86:19 design allowance for 2-hour fire-resistance rated structural members; (iii) the conditions in the mass timber stair shaft were not adversely affected in any test; and (iv) despite some exposed cross-laminated timber ceiling panels experiencing localized delamination during the cooling phase of the fire, this phenomenon did not result in re-ignition or fire regrowth.

The knowledge obtained from this project can be used to support the advancement of prescriptive Code and alternative solutions for the design and construction of tall wood buildings, and to assist in the development of 'next-generation' performance-based Codes and construction fire safety guidelines.

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