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Large-Scale Fire Tests of A Mass Timber Building Structure for MTDFTP

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Executive Summary

The Mass Timber Demonstration Fire Test Program (MTDFTP) included two series of experiments: the pilot scale demonstration tests in summer 2021 in Richmond, BC and the large scale fire tests in summer 2022 in Ottawa, ON. This report documents the series of large scale fire tests on a mass timber structure conducted to study fire safety during construction, fire dynamics and performance in an open plan office space and residential suites, as well as influence of exposed mass timber structural members on fire severity and duration.

Five large scale fire tests were conducted in a two-storey, four-bay mass timber structure constructed of glued-laminated timber (Glulam) columns and beams, cross-laminated timber (CLT), dowel-laminated timber (DLT) and glue-laminated timber (GLT) floor/ceiling panels. The structure had a total floor area of 334 m^2 (3,600 ft^2) with layouts and contents intended to represent business and residential occupancies as well as construction sites in different tests. The first storey of the structure was an open plan office space. The second storey was configured as three residential units, which were either fully furnished or at the construction stage. A CLT exit stair shaft was included in the test structure. Mass timber structural elements were designed and sized to provide at least 2-hour fire-resistance rating, as calculated per Annex B of CSA O86 Engineering Design in Wood.

These fire tests were conducted without sprinklers and without firefighting intervention for extended hours, representing rare scenarios in which sprinkler systems would not operate or would be ineffective in controlling the fire and the fire department would fail to respond to the fire emergency. Such a probability of sprinkler failure and fire department response failure would be extremely low for completely constructed buildings. For buildings under construction where sprinklers have not been installed, the probability of fire department failing to respond for extended hours would also be very low. Therefore, the results of the MTDFTP large scale fire tests should be interpretated within this context.

This report describes the large scale fire tests, including the fire scenarios, fuel loads, experimental setups, instrumentation, measurements and procedure used in the tests, and provides experimental data and results. (Note: this report documents the tests in a chronological order; the numerical numbering of the test serves only as an identification and does not reflect the actual sequence of the test). The analysis of the experimental data and results has produced the following key findings and conclusions.

<u>Test 5 – Fully furnished open office space</u>

Test 5 represented a fully furnished open plan office space with 204 m^2 floor area and a total of 291 m^2 exposed mass timber columns, beams, wall and ceiling. The mass timber ceiling surfaces were entirely exposed (100% of the total ceiling area). The aggregate exposed surface area of the mass timber beams, columns and wall was equal to 35% of the total wall area of the perimeter of the compartment. The office space was furnished with 18 working cubicles as the movable building contents with the fuel load density of 362 MJ/m^2, which is believed to be above the average of today’s fuel load density in the open plan offices.

By design, Test 5 represented a worst case scenario combining several severe testing conditions including a high fuel load, an aggressive ignition package, rough openings with high ventilation and oxygen supply (instead of real windows), the absence of sprinklers, and the absence of firefighting intervention during the test. Test 5 was conducted under these severe conditions and lasted for more than four hours to uninterruptedly demonstrate the fire dynamics and performance of the mas timber structure.

- Test 5 used the aggressive ignition package in order to ensure the initial flame would impinge on the 4-m high ceiling. With the aid of the aggressive ignition package, the initial fire growth – from ignition to flame impingement on the ceiling – took 3 min 40 s. Once the ceiling jet was formed above the ignition location, the fire spread across the exposed ceiling within 2 min and fully engulfed the entire open plan office space within 3 min. If real windows had been used instead of the rough openings, it would have taken some time for heat to build up to break the window glass in order to obtain enough oxygen supply for combustion.
- A comparative analysis of the fire development in conjunction with data from other tests (Test 3 and Test 4) indicated that the aggressive ignition package used in Test 5 (wood cribs stacked to 1.8 m high) was likely to have impacted the fire development in two ways. Firstly, the initial fire growth from ignition to flame impingement on the ceiling was accelerated. Secondly, once the flame impinged on the ceiling, the speed of fire spread across the ceiling was likely to have accelerated by approximately 50%, relative to unstacked wood cribs. The primary impact would be on the timing of the initial flame impingement on the ceiling but a quantitative estimate was not feasible.
- Thermal radiation reached the building facades above the rough window openings and the surrounding area at distance, with the peak heat fluxes reaching 37-50 kW/m^2 at 3.5 m height above the openings, 58 kW/m^2 at 3 m away and 28-39 kW/m^2 at 4.5 m away from the test structure.
- Fire dynamics in this large open plan office space exhibited a highly heterogeneous temperature distribution. The fire started to decay after 18 min of fully-developed burning, visible flaming combustion was ceased completely by 30 min from the ignition and the office space was continuously cooled down until the end of the test which lasted for more than four hours.

<u>Test 1 – Noncombustible construction (baseline) versus Test 2 – Mass timber construction</u>

Test 1 simulated a code-prescribed noncombustible construction baseline residential suite with code-compliant combustible interior linings (25 mm thick plywood) on the ceiling and three interior walls; the total combustible linings were 72.2 m^2. Test 2 involved a residential suite constructed of exposed mass timber columns, beam and ceiling with greater exposed surfaces than allowed by the National Building Code of Canada 2020. The mass timber ceiling was 100% exposed and the aggregate surface area of the exposed mass timber beam and columns was equal to 12% of the total wall area of the perimeter of the suite. The total exposed mass timber surfaces were 29.7 m^2. Each test used a fully furnished residential suite of 22.4 m^2 floor area with the same room contents at the fuel load density of 613 MJ/m^2, which is slightly above the average fuel load density in modern residential suites. Both tests lasted for more than four hours. The results of the exposed mass timber suite (Test 2) were compared with the code-prescribed noncombustible construction baseline (Test 1) in terms of the fire dynamics and performance.

- In general, the fire in the mass timber suite behaved similarly to the fire in the baseline suite for the residential test scenario, including the growth, full developed and decay stages during more than four hours of testing.
- In both Test 1 and Test 2, flashover occurred at similar times, the fire plumes reached similar heights, and the room temperatures peaked at 1200 °C with similar temperature distributions both temporally and spatially during the fully developed fire stage.

- The fire severity in the mass timber room test was not any greater than the baseline test. In fact, the fire decayed earlier and quicker in the mass timber suite (5 min earlier) than in the baseline suite.
- Both tests presented similar external fire exposures. Test 1 was more under-ventilated inside and resulted in more vigorous exterior combustion due to the greater quantity of combustible interior lining than the exposed timber Test 2.

Test 4 – A severe construction site fire

Test 4 represented a portion of a mass timber building under construction. The space was 52.5 m^2 and 3.0 m high, and included exposed DLT ceiling, CLT floor, Glulam columns and beams with a total of 124.6 m^2 exposed mass timber surfaces. The mass timber ceiling and floor surfaces were completely exposed (100% of the total area). The aggregate exposed surface area of the mass timber beams and columns was equal to 25% of the total wall area of the perimeter of the suite.

Test 4 was designed to study a severe construction site fire scenario. Simulated construction debris and light wood open framing were positioned in the test space at the fuel load density of 224 MJ/m^2. Today's mass timber construction projects are dominated by prefabrication and do not have much other combustible products on site. Test 4 used a higher fuel load density than those typically found on the mass timber construction sites. The test lasted for two and half hours. There was no firefighting intervention during the test in order to uninterruptedly demonstrate the fire dynamics of a severe construction site fire. The severe test conditions were exacerbated by the strong wind on the test day.

- After ignition, the fire took approximately 8 min to fully involve the compartment and followed by a 10-min period of fully-developed burning. The construction site fire reached the decay stage at 18 min. Visible flaming mostly ceased on the mass timber elements after 30 min. The compartment temperatures decreased to 300-400 °C at 60 min. However, the decay became stagnant after 60 min with glowing floor and intermittent small flames in the joints and junctions until the end of the test.
- Thermal radiation reached 33 kW/m^2 at 3.5 m above the opening on the building facade and 15 kW/^{2} at 4.5 m from the leeward side of the building in the wind.

Test 3 – A garbage bin fire on construction site

Test 3 also represented a portion of a mass timber building under construction to simulate a realistic construction site fire scenario with a garbage bin fire. The test space was 22.4 m^2 and 3.0 m high, and included an exposed CLT ceiling, CLT floor and CLT wall with a total of 55.2 m^2 exposed mass timber surfaces. The mass timber ceiling and floor surfaces were completely exposed (100% of the total area). The exposed surface of the mass timber wall was 16% of the total wall area of the perimeter of the suite. A 28-gallon steel garbage bin filled with 17 kg lumber pieces (arranged as a wood crib) was used as the fire source, providing a moveable fuel load at the density of 15 MJ/m^2.

- This garbage bin fire scenario created a slow initial fire growth which took over 20 min to reach the ceiling height. The preheating of the ceiling for over 20 min allowed the quick ignition of the ceiling and subsequent flashover. Once the garbage bin fire formed a ceiling jet with the aid of fire spread via the CLT wall behind the bin, the fire quickly spread over the CLT ceiling and reached flashover at 23 min. However, the fire started to decay almost instantly. As soon as the garbage bin fire jet stopped hitting the ceiling, the flaming combustion disappeared quickly from all CLT surface at 24 min 10 s. The garbage bin fire source did not have sufficient energy to sustain the flaming combustion of the mass timber elements.

- The garbage bin fire was designed to be as severe and repeatable as practical for use in Test 3 although it had limited movable fuel load added to the space, compared to Test 4. The results show that controlling the quantity of combustible materials on the construction site is an important strategy to limit the potential fire hazard. Also, if this garbage fire scenario occurs on a construction site, there could be an opportunity for workers to extinguish the fire within the garbage bin if the fire could be detected early and operable extinguishers readily accessible.

Common findings in all tests

In addition to the findings and conclusions specific for each test, some common findings and general conclusions are as follows:

- The average char depths in the exposed mass timber members were well within the design allowance according to CSA O86-19 for the structural members of 2-hour fire-resistance rating in all the tests.
- Some exposed CLT ceiling experienced localized delamination in the cooling period during the tests but this did not cause any re-ignition or fire regrowth.
- Since deep-seated hot spots and smouldering remained after the fire tests, firefighting operations were required in order to ensure the hot spots were fully extinguished.
- The conditions in the stairwell were not adversely affected in any test.
- The test structure remained stable and solid after enduring the five severe fire tests with a total of 19 hours of fire exposure. This became more obvious in the demolition process of the test structure.

This series of the large scale fire tests produced new scientific data on the fire performance of mass timber in open plan office and residential buildings, fire safety at mass timber construction sites, as well as influence of exposed mass timber on fire severity and duration. This knowledge and data can be used to assist the fire safety design, evaluation and approval of alternative solutions for tall and large mass timber buildings; to assist the development of firefighting strategies in construction sites; and to assist the code development and harmonization pertinent to mass timber construction.

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1 INTRODUCTION

The Mass Timber Demonstration Fire Test Program (MTDFTP) included two series of experiments: the pilot scale demonstration tests in summer 2021 in Richmond, BC [1] and the large scale fire tests in summer 2022 in Ottawa, ON. The series of large scale fire tests on a mass timber structure were conducted to study fire safety during construction, fire dynamics and performance in an open plan office space and residential suites, and influence of exposed mass timber on fire severity and duration.

As part of its research to inform the advancement of safe and innovative solutions across Canada's construction industry, the National Research Council of Canada (NRC) conducted the technical work and science-based large scale fire tests to support the MTDFTP. NRC was responsible for instrumenting the test structure, setting up fire scenarios and fuel loads, conducting the large scale fire tests, analyzing test data and documenting the results.

This report documents the fire scenarios, fuel loads, experimental setups, instrumentation, measurements and procedure used in the large scale fire tests. The experimental data, results of data analysis, key findings and conclusions are provided in the report.

2 TEST SETUP

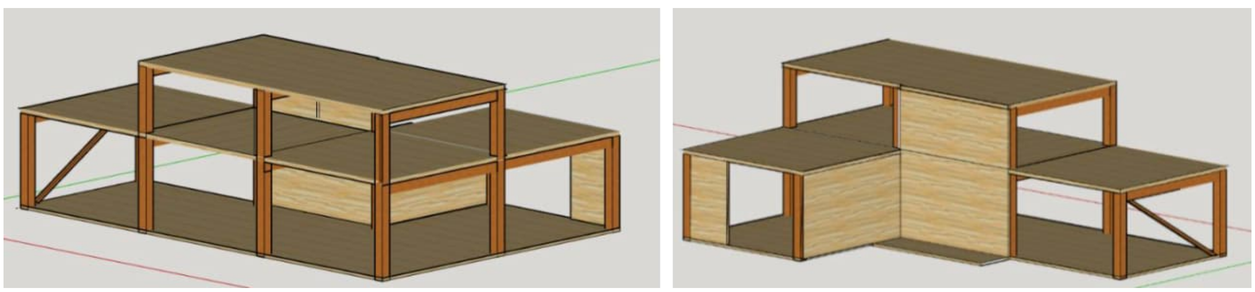
The MTDFTP Technical Working Group (comprising representatives of Canadian Wood Council, CHM Fire Consultants, GHL Consultants, Natural Resources Canada, NRC, FPInnovations, Ontario Ministry of Natural Resources and Forestry, Ministère des Forêts, de la Faune et des Parcs – Québec) developed a plan for the large-scale fire tests, including the design of a mass timber test structure, a test matrix and fire scenarios [2]. According to the test plan, NRC developed fuel loads and instrumentation and conducted the large scale fire tests at the Canadian Explosives Research Laboratory's (CERL's) outdoor testing field, located at 1 Haanel Drive, Ottawa, ON.

2.1 Mass Timber Test Structure

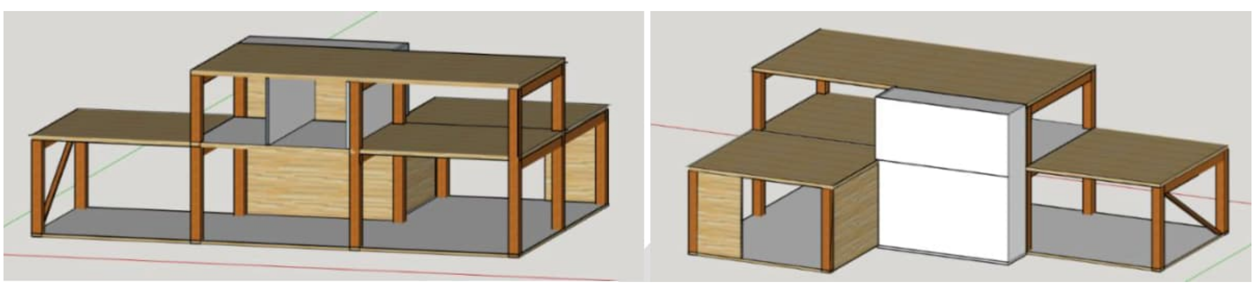
The mass timber test structure was a large two-storey, four-bay structure constructed of glued-laminated timber (Glulam) columns and beams, cross-laminated timber (CLT), dowel-laminated timber (DLT) and glue-laminated timber (GLT) floor/ceiling panels, with a total floor area of 334 m^2 (3,600 ft^2). As required in the National Building Code of Canada (NBC) 2020 [3], glulam elements were manufactured in plants conforming to CSA O177 [4] and CLT elements were manufactured in accordance with ANSI/APA PRG-320 [5]. Although there is currently no manufacturing standard for DLT products, they were conforming to ICC-ES ESR 4069 for use in the United States [6].

The structure had layouts and contents intended to represent business and residential occupancies as well as a building under construction in different tests. The first storey of the structure was an open plan office space. The second storey was configured as three residential units. A CLT exit stair shaft was included in the test structure. Mass timber structural elements were designed and sized to provide at least 2-hour fire-resistance rating, as calculated per Annex B of CSA O86 [7]. **Figure 1**, **Figure 2** and **Figure 3** illustrate the test structure. The design details of the test structure can be found in *Mass timber demonstration fire test project (MTDFTP), Large-scale test plan* [2].

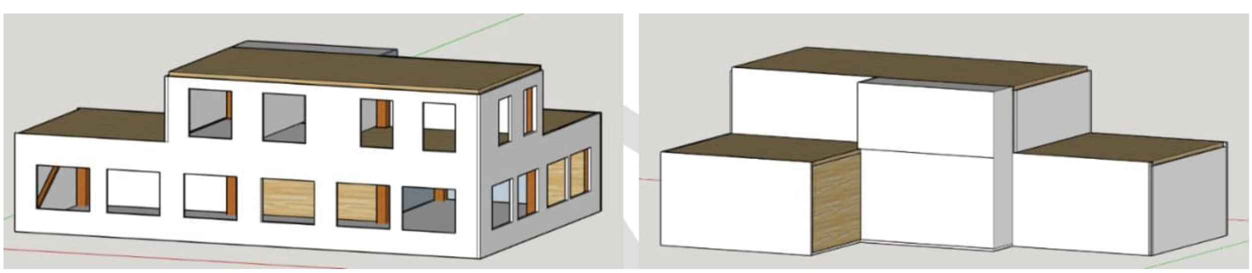
Since the purpose of the testing was to focus on the fire performance of exposed mass timber and for practicality purposes, most of the exterior wall assemblies used in this test structure were constructed of lightweight steel studs, gypsum board/sheathing and mineral wool insulation, providing a 1-hour fire-resistance rating in accordance with cUL Design No. U419. Outboard insulation (Rockwool Comfortboard 80) was also installed on the exterior façades that had rough window openings. Although most buildings may not require a fire-resistance rating for the exterior walls, the use of fire-rated exterior walls would reduce the probability that the fire breaches these exterior assemblies so that the tests could focus on the performance of mass timber structural elements and systems.



Mass timber structure



Structure with floor sheathing, exit shaft and interior walls



Structure with exterior walls

Figure 1. 3D model of mass timber test structure [2].

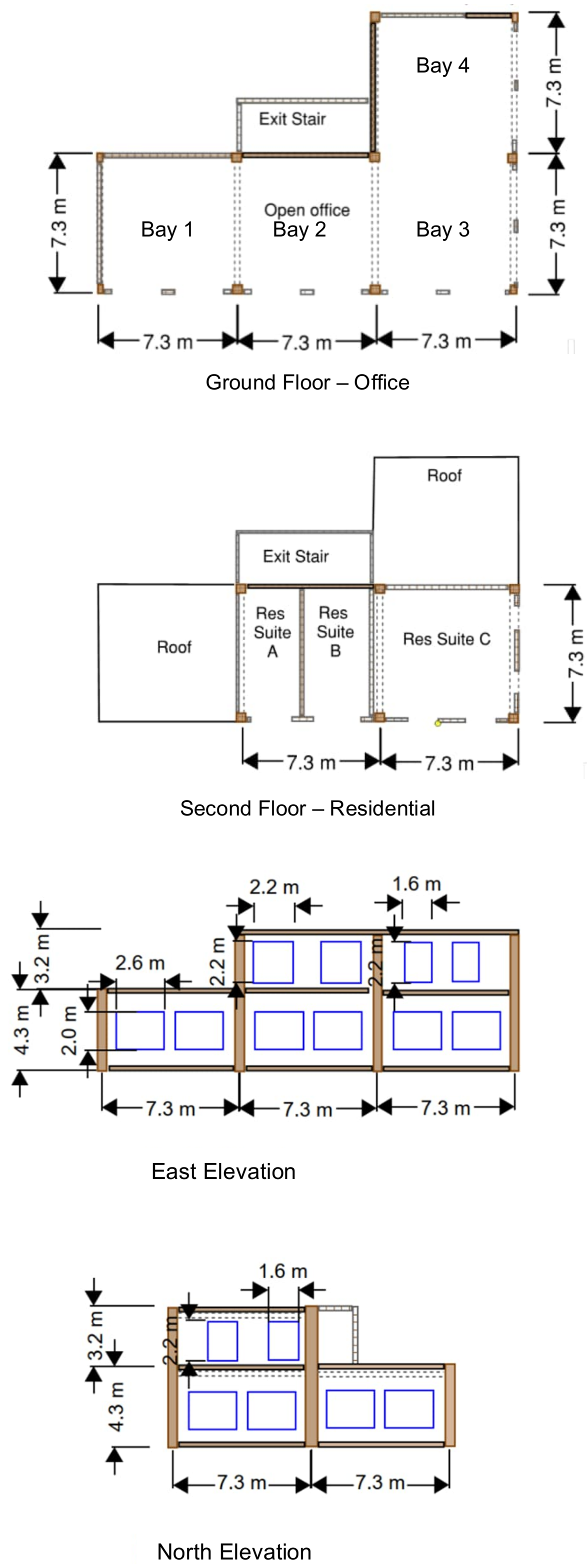


Figure 2. Mass timber test structure [2].

Figure 3. Photographs of mass timber test structure during construction.

During the erection of the mass timber structure, a bead of firestop caulking was applied between the following butt joints of the mass timber elements:

- panel-to-panel joints (in the floor assemblies and in the wall assemblies),
- panel-to-beam joints,
- panel-to-column joints, and
- wall-to-floor joints.

The construction phase encountered two rainy months in April and May 2022. The mass timber structure was erected in April and was not protected from the weather. Some of the firestop caulking was washed away by the rain. Non-structural exterior walls and suite separation walls were installed in May. The test structure was not fully protected from the weather until a waterproof roof membrane was installed on May 18-24. At the end of the construction phase, there was an obvious need to reseal some of the joints and to apply firestop caulking in the joints where the sealant was missing. Firestop caulking was applied to reseal or seal these joints. For those joints where large gaps existed, firestop caulking was applied in combination with firestop strips. Due to physical obstruction by the finished building elements, however, some of the joints could not be fully reached to ensure complete seal.

The test structure was not built as airtightly as normal buildings in order to speed up the construction process and to reduce the project costs. Instead of the normal concrete topping commonly used on the floor, two layers of 12.7 mm Type X gypsum board were placed on the floor of the open plan office space (Test 5), and two layers of 15.9 mm Type X gypsum board on the floor of the two residential suites (Test 1 and Test 2), as shown in **Table 1**. In addition, the exterior building envelope of the test structure, including its system components and interfaces, was not built to the requirements of the National Energy Code of Canada for Buildings (NECB) 2020 [8] for controlling air leakage and thermal transfer. Also, because the mass timber structural elements had to be supplied by multiple manufacturers and the connection hardware had to be manually installed on site, the advanced digital manufacturing technology (computer numerical control (CNC)) was not utilized for their fitting. Thus, the connections between various structural elements were not all tightly fit. Actual mass timber construction projects would fully utilize the CNC technology in the production of the mass timber elements and the installation of their connection hardware in the plant, achieving good fit and overall quality control. These differences are important in the understanding and interpretation of the test results.

2.2 Test Matrix and Fire Scenarios

Table 1 shows a test matrix and fire scenarios, which provided a basis for developing fuel loads for various tests. The combustible content or movable fuel load in an enclosure refers to all combustible materials (including flooring materials) that are not parts of a building structure. The movable fuel loads for use in the large-scale tests simulated typical combustible contents and arrangement found in occupied residential suites, open plan office spaces, and mass timber construction sites, respectively. As much as possible, consumer residential furniture, typical office work stations, and construction materials were used in the fuel loads. In order to minimize smoke and environmental impact on the test site, plastic and foam components in typical combustible contents were taken out of the fuel loads but their combustion energy was substituted with equivalent calorific contents using wood cribs. All tests used wood-based materials for the fuel loads. No structural load was used other than the self-weight of the structure and the representative fuel loads. The numerical numbering of the test serves only as an identification and does not reflect the actual sequence of the test (e.g., Test 5 was conducted first and Test 3 last). The tests are documented in a chronological order in this report.

2.3 Context of Fire Tests

One of the objectives of the MTDFTP large scale tests, among others, was to study the fire dynamics and fire severity resulted from exposed mass timber during the entire fire progression for the test scenarios. This requires that the fires be uninterrupted during the planned test duration. In order to achieve this objective, all five fire tests were conducted without sprinklers and without firefighting intervention for extended hours.

2.3.1 Sprinkler Reliability, Efficacy and Impact

The NBC 2020 requires that encapsulated mass timber construction for Group C and Group D buildings be fully sprinklered in accordance with NFPA 13 [9]. Properly designed, installed and maintained automatic sprinkler systems are reliable and effective in controlling fires to save lives, reduce injuries, and limit property loss. Reliability and efficacy are two primary parameters impacting the overall performance effectiveness of a sprinkler system in the event of a fire.

Sprinkler reliability indicates whether or not the sprinkler responds and delivers water to the fire when required. Sprinkler efficacy is a measure of whether or not the sprinkler system is effective to control the fire when operated. Assessing the efficacy of a sprinkler system whether or not the system is “effective” could be subjective. An objective analysis would be based on whether or not the system meets its design objective in confining the fire to the room of fire origin or, in the case of large un-compartmented spaces, to the hydraulic design area. The product of the two parameters, sprinkler reliability and efficacy, gives the overall performance effectiveness of the sprinkler system.

A recent National Fire Protection Association report [10] showed that the operation reliability of sprinklers was 92%, the fire control efficacy was 96% for various property uses based on U.S. fire statistics from 2015 to 2019, with an overall effectiveness of 88%. Fire spread was limited to the object or room of origin in 95% of reported structure fires with sprinklers present. The main cause for the 8% reliability deficit where sprinklers failed to operate was due to human factors/errors, such as systems being shut off. The 4% efficacy deficit where sprinklers were ineffective in controlling the fires was mainly due to that water did not reach the fire or inadequate water was discharged. This statistical data was not significantly different from the last two decades for U.S. and other countries [11, 12].

The NFPA report was based on the analysis of the statistic data collected by the US National Fire Incident Reporting System (NFIRS), which depends on firefighters to input the data in addition to their search, rescue and firefighting duties on the fire scenes. Since not all sprinkler systems were electrically monitored and supervised in the U.S., the unmonitored/unsupervised sprinkler systems were included in the U.S. data and could have significant weight in the reliability statistics [13].

Canada has required all sprinklered buildings to have monitored and supervised fire alarm systems which are designed to notify the fire department since the NBC 1995. This Canadian requirement should lead to higher reliability and efficacy of the sprinkler systems in newer buildings that require or provide a monitored and supervised fire alarm system (i.e., post NBC 1995), rendering a higher overall effectiveness of the automatic sprinkler systems for fire protection [13, 14].

The primary benefits of sprinkler systems are a reduction in the extent of fire spread resulting in a reduction in the loss of life and reduced property losses. With sprinkler protection, literatures indicate that fire is less likely to spread beyond the room of fire origin or the design area, and it is also less likely that fire services will be faced with a large fire situation in sprinklered buildings. This led to a significant reduction in life loss per 1,000 fires with an 82% reduction based on the

US fire experience [11] and a 92% reduction in residential occupancies based on the Province of British Columbia fire statistics [15].

British Columbia's building fire data between 2008 and 2013 was analyzed by Len Garis et al in relation to general construction type, including combustible construction, heavy timber construction and noncombustible construction [16]. They concluded that overall "there appears to be little difference with respect to fire spread, death, and injury rates as a function of building general construction type, provided these buildings have functioning smoke alarms and complete sprinkler protection."

There have been large scale fire tests conducted in evaluating the effectiveness of sprinklers and water mist systems in controlling and suppressing fires in buildings with exposed mass timber [17, 18]. These systems successfully controlled and extinguished the fires in the mass timber buildings as designed.

2.3.2 Performance Benchmarks for Fire Department Responses

Fire services are expected to respond to fire incidents within the level of service agreed to by the local municipality or community.

Recently, the Canadian Board for Harmonized Construction Codes' Working Group on Firefighter Rescue Operations conducted a study to quantify the times required for firefighters to respond to reported fires and to perform certain tasks of search and rescue operations at firegrounds [19]. The fire department response times were thoroughly analyzed using the benchmarks established from relevant standards and other recognized performance values as well as actual response data collected from the field. The fire department response time is the time from the notification of the fire by a public service answering point to the time of arrival of the first apparatus on the fireground. According to their report, the estimated response times from the receipt of the notification to the arrival of the first apparatus are expected to range from 7:21 to 18:06 min for career, volunteer and composite fire departments in various example jurisdictions in Canada.

Recognizing that mass timber buildings are required to be fully sprinklered and be equipped with fire alarm and detection systems with signals to notify the fire department, the notification should occur fairly quickly.

2.3.3 Risk of Failures of Both Sprinklers and Fire Department Responses

With electrically monitored and supervised fire alarm systems and sprinkler systems as well as expected levels of emergency response by fire department, the risk of fire developing to the stages potentially endangering the life safety and structural integrity in completed mass timber buildings is inherently low. Since the fire tests were conducted without sprinklers and without firefighting intervention for extended hours, they represented rare and conservative scenarios in which sprinkler systems would not operate or would be ineffective in controlling the fire and the fire department would fail to respond to the fire emergency. Such a probability of sprinkler failure and fire department response failure would be extremely low for completed mass timber buildings. For buildings under construction where sprinklers have not been installed, the probability of fire department failing to respond for extended hours would also be very low. Therefore, the results of the MTDFTP large scale fire tests should be interpreted within this context only.

Table 1. Large-scale demonstration fire tests (June – September 2022).

Test	Description	Location	Top of Floor Finish	Wall Finishes		Ceiling	Beams/ Columns	Percentage of exposed mass timber	Fuel Load	Ventilation Conditions
				Exterior Walls [(1)]	Interior Walls					
Test 1 (July 7)	Completed residential suite: A code prescribed solution for noncombustible construction	2nd storey residential Suite B	2 layers of 15.9 mm (5/8") Type X gypsum board	Steel stud and gypsum walls (cUL Design No. U419), 1-hour fire-resistance rating, 15.9 mm (5/8") Type X gypsum board inside, 15.9 mm (5/8") gypsum sheathing on exterior side, and mineral wool in-between (*for exterior walls with openings, 76 mm Rockwool Comfortboard 80 installed on the exterior sides*)	2 layers of 15.9 mm (5/8") Type X gypsum board with 25 mm (1") thick plywood as combustible lining	2 layers of 15.9 mm (5/8") Type X gypsum board with 25 mm (1") thick FRT plywood (FSR ≤25) as combustible lining	N/A	N/A	Residential fuel load (See Section 4.3)	Single opening 2.2 m W x 2.2 m H Ventilation factor approx. 0.07 $m^{1/2}$
Test 2 (July 14)	Completed residential suite: Exposed mass timber	2nd storey residential Suite A	2 layers of 15.9 mm (5/8") Type X gypsum board		2 layers of 15.9 mm (5/8") Type X gypsum board (also installed on mass timber exit stair wall for protection)	Exposed mass timber	Exposed mass timber	Ceiling: 100% Beams/columns: 12% of total perimeter wall area	Residential fuel load (See Section 4.3)	Single opening 2.2 m W x 2.2 m H Ventilation factor approx. 0.07 $m^{1/2}$
Test 3 (Sept. 29)	Construction site: Garbage bin fire source	2nd storey residential Suite B	Exposed mass timber		Exposed mass timber exit stair wall 2 layers of 15.9 mm (5/8") Type X gypsum board on suite separation walls	Exposed mass timber	N/A	Floor: 100% Ceiling: 100% Wall: 16% of total perimeter wall area	Garbage bin fire scenario (See Section 6.1)	Single opening 2.2 m W x 2.2 m H Ventilation factor approx. 0.07 $m^{1/2}$
Test 4 (Sept. 15)	Construction site: Exposed mass timber	2nd storey residential Suite C	Exposed mass timber		2 layers of 15.9 mm (5/8") Type X gypsum board on suite separation wall	Exposed mass timber	Exposed mass timber	Floor: 100% Ceiling: 100% Beams/columns: 25% of total perimeter wall area	Exposed light wood framing and wood cribs (See Section 5.1)	Four openings 1.6 m W x 2.2 m H Ventilation factor approx. 0.11 $m^{1/2}$
Test 5 (June 22)	Completed building: Open plan office floor with exposed mass timber	Full 1st storey	2 layers of 12.7 mm (1/2") Type X gypsum board		Exposed mass timber exit stair wall	Exposed mass timber	Exposed mass timber	Ceiling: 100% Wall: 10% of total perimeter wall area Beams/columns: 25% of total perimeter wall area	Fully-furnished office space (See Section 3.1)	Ten openings 2.6 m W x 2.0 m H Ventilation factor approx. 0.12 $m^{1/2}$

[(1)] *A portion of the exterior wall in Bay 4 on the first storey used CLT panels as shear walls where 2 layers of 15.9 mm (5/8") Type X gypsum board were installed over CLT on the interior side. Glulam bracing in Bay 1 was exposed on the interior side.*

3 TEST 5: OPEN PLAN OFFICE SPACE

Test 5 was intended to represent a fully furnished open plan office floor with exposed mass timber columns, beams, ceiling and stair shaft wall. **Figure 4** and **Figure 5** show a layout and photographs of the open plan office space with a floor area of 204 m^2. The exposed mass timber surfaces were 195 m^2 on the ceiling, 27.5 m^2 over the stair shaft wall, 32.5 m^2 over the columns and 36.2 m^2 over the beams for a total of 291 m^2. The mass timber ceiling surfaces were entirely exposed (100% of the total ceiling area). The aggregate exposed surface area of the mass timber beams, columns and wall was 35% of the total wall area of the perimeter of the compartment. Two cast iron pipes penetrated through the ceiling in Bay 1 and Bay 4 with firestop meeting 2-hour FH-rating tested in accordance to CAN/ULC-S115 [20].

Test 5 had the largest fire in this test program. The fuel load spread throughout the open office area on the ground floor of the test structure. Fire was ignited in Bay #1 of the test structure and left to spread through the space within the ground floor. Unlike the majority of exposed mass timber compartment fire tests conducted to date that had simulated residential occupancies, this test was intended to demonstrate the fire dynamics and performance of the exposed mass timber structure in a typical occupied open-office space of a mass timber building.

In Bay 4, two sections of the exterior walls (adjacent to the exit stairs and portion of the back wall) were constructed of CLT panels for structural purposes to resist in-plane lateral forces. These two exterior-wall sections were not intended to contribute to the exposed mass timber as part of the fire testing thus were protected using two layers of 15.9 mm Type X gypsum board on the interior side.

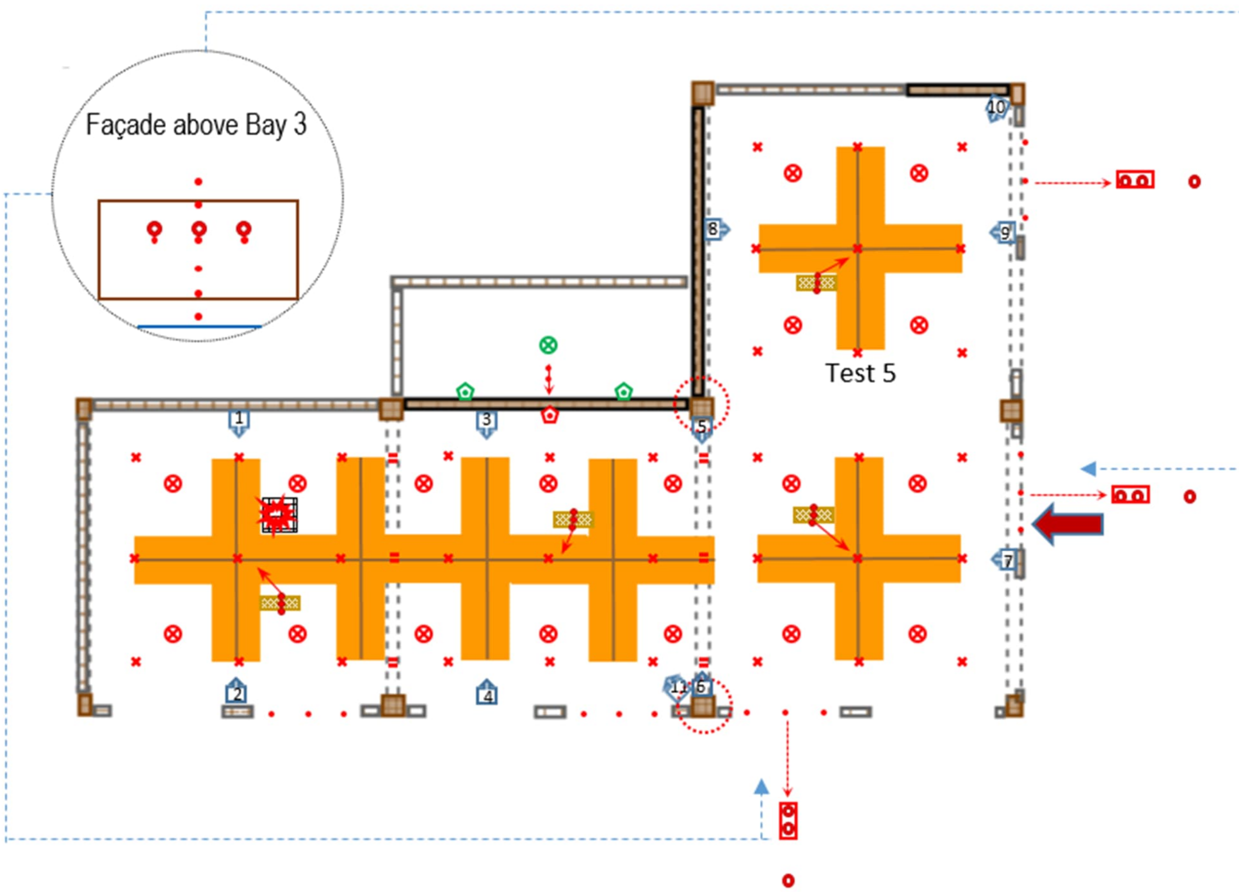
Instead of normally used concrete toping, the mass timber floor (CLT in Bays 1 and 2; DLT in Bays 3 and 4) was encapsulated with two layers of 12.7 mm Type X gypsum board, which is a prescriptive solution of the NBC 2020, Division B, Article 3.1.6.4 to provide a 50-minute encapsulation rating. This would prevent the mass timber floor panels from contributing to the fire, while simplifying and accelerating the construction process for the structure.

3.1 Fuel Load and Ignition

3.1.1 Fuel and Ignition Arrangement

The open plan office space was furnished with 18 cubicles separated by privacy panels, including 12 corner cubicles (2.4 m × 2.4 m each) and 6 U-shape cubicles (2.4 m × 3.0 m each). In order to minimize smoke and environmental impact on the site, the fuel load in the cubicles was wood-based materials without plastic and foam materials. The fuel load included wood-based table tops, flooring and privacy partition panels. Wood cribs were used to provide equivalent calorific contents of paper materials, plastic and foam materials, etc. A fuel load density of 362 MJ/m^2 was used in Test 5, including the following materials:

- Wood table tops of 660 mm depth were installed at 730 mm height and constructed using nominal 2 × 6 (38 × 140 mm) and nominal 2 × 8 (38 × 184 mm) dimension lumber;
- Privacy partitions were constructed using 19 mm × 1.2 m × 2.4 m plywood sheets with 0.3 m clearance from the floor;
- Plywood (19 mm × 1.2 m × 2.4 m) was used to simulate flooring materials in each cubicle area (placed on top of the gypsum board on the floor), which was equivalent to covering the whole ground floor with 9.5 mm (3/8”) thin wood-based flooring materials. This also simulated having carpet and underlay on the floor;



18 thermocouple trees, each with 5 TC's at 0.5, 1.0, 2.0, 3.0 and 3.85 m above floor in 10'x12'/12'x12' grid
Thermocouples 0.15 m below ceiling with 2.433-m (8-ft) even spacing
Thermocouples on bottom surface of beam
Thermocouple array inside the stair shaft, with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor
Embedded thermocouples in the ceiling centre at the depths of 25, 50, 75, 100 and 125 mm in the timber
Array of 5 thermocouples on the mass timber shaft surface in the office side at 0.5, 1.0, 2.0, 3.0 and 3.85 m above the floor
Array of thermocouples on the timber surface on the shaft side at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor
Embedded thermocouples in the shaft wall at the depths of 25, 50, 75, 100 and 125 mm at 2.0 m above the floor
Exterior thermocouples at top of the window opening (0.15 m below top of opening on centreline and 0.4 m to both edges) and on the façade at 0.75, 1.5, 2.5, 3.5, 4.5 above the top of the opening along centreline (extra TC at 0.5 m from the centreline on each side at 3.5 m). Note that the roof mast had five more thermocouples at 5.5 m, 6.5 m, 7.5 m, 8.5 m and 9.5 m heights above the window opening.
3 Gardon gauges on exterior façade at 3.5 m above top of opening aligned with centreline of the opening and 0.5 m from both sides of the centreline
3 Gardon gauges away from the structure, one facing the centre of opening at 3.0 m away, one 0.6 m above the top of opening at 3.0 m away, and facing the centre of opening at 4.5 m away
IR camera positioned outside the structure (another IR camera for bird view of the roof (not shown))
Video cameras mounted on wall or column inside (#1-#9 at 0.9 m above floor focusing on cubicles; #10-#11 at 1.6 m above floor focusing on ceiling
TC's at the beam-column connections (see next figure for details)

Figure 4. Fuel load and instrumentation for Test 5.

Figure 5. Open plan office space for Test 5.

- One small wood crib was placed in each cubicle to provide equivalent calorific contents of other combustible materials, such as books and paper files; plastics in electronic and computer equipment, waste baskets and shelves; fabric, upholster, foam and plastic materials in chairs, etc. The small wood crib consisted of 38 mm × 89 mm × 800 mm

SPF lumber pieces in rows of six stacked to 356 mm high (4 layers high) and weighed 25 kg [21];

- 288 lumber strips (2.4 m long nominal 2 × 2 (38 × 38 mm) dimension lumber) were distributed in the 18 cubicles and placed below the table tops.

Ignition started in one of the cubicles as shown in **Figure 4**. To facilitate the fire initiation, two large wood cribs (2 × 50 kg) were added in this cubicle, each consisted of 38 mm × 89 mm × 800 mm SPF lumber pieces in rows of six stacked to 712 mm high (8 layers high) [21]. The two large wood cribs and one small wood crib (with a total weight of 125 kg) were vertically stacked together to 1780 mm high (20 layers high) in order to ensure the fire plume would impinge on the 4-m high ceiling. The wood cribs were ignited from underneath with 1000 mL of methanol in shallow metal pans (this methanol ignition source had approximately a 40-kW heat output and 360-s free-burn time). A propane torch was manually applied for a short duration to ignite the methanol, which in turn ignited the wood cribs.

3.1.2 Comparison with Historical Fuel Load in Open Plan Offices

The office layout and fuel load used in Test 5 were developed based on available information of furniture arrangement and variable fuel load in common open plan office spaces.

Forty years ago, the International Council for Building Research Studies and Documentation (CIB) compiled fuel load density data for different occupancies. The average fuel load density was 420 MJ/m^2 for offices [22].

About 30 years ago, NRC conducted surveys of typical office buildings in North America to obtain data on open plan office arrangements. Typical office cubicles were 3 m × 3 m in size; each cubicle contained 131-176 kg of wood-based table top, 19-28 kg upholster materials in chairs, various quantities of books, paper files, fabric and wood frame in partitions being combustible materials [23]. Using the same amounts of the wood-based table tops and upholster materials in the cubicles of Test 5, the fuel load density would translate to 285-390 MJ/m^2 (not including various paper load in the survey).

National Institute of Standards and Technology (NIST) conducted a fire simulation of an open plan office space for the investigation of the World Trade Center (WTC) buildings collapse following the 9/11 event in 2001 [24]. Office cubicles commonly found in the WTC buildings were used in the fire simulation. Combustible materials in each cubicle were found to be 94.8-111.5 kg wood/laminate, 63.7 kg paper, 41.0-39.3 kg plastics and 34.2 kg carpet to a total of 233.7-248.7 kg combustible materials. Using these amounts of the combustible materials in the cubicles of Test 5, the fuel load density would translate to 364-394 MJ/m^2, to which the paper stock contributed approximately 20%.

In today's offices, with more electronic filing in place of paper filing, the average density of the variable fuel load today would likely be lower than the historical average of 420 MJ/m^2.

Arup recently conducted a fire test at Centre d'études et de recherches de l'industrie du béton (CERIB) to investigate fire dynamics in a large mass timber compartment [25, 26]. A fuel load was provided by wood cribs consisted of 3 cm × 3 cm × 100 cm sticks covered a 6 m × 29 m area in the 11 m wide, 35 m long and 3 m high compartment. The fuel bed area (6 m × 29 m) had a reported fuel load density of 374 MJ/m^2. However, the fuel load density relating to the entire 11 m × 35 m floor area was actually 169 MJ/m^2.

Survey data on average fuel load density in today's open plan offices is not readily available. The fuel load density of 362 MJ/m^2 used in Test 5 was still within the historical range and would most likely be above today's actual average.

3.2 Instrumentation and Measurement

Thermocouples, heat flux meters, video cameras, disposable cameras and infrared cameras were installed inside and outside the office space for measurements during the test. Char measurements were conducted after the fire test. **Figure 4** shows a layout of the thermocouples and heat flux meters for Test 5.

3.2.1 Thermocouples

- Eighteen (18) thermocouple trees were installed in the open plan office space with 3.05-m spacing (except 4.27-m spacing across the walkway between Bay 3 and Bay 4), symmetric to the floor/ceiling centreline. Each cubicle was equipped with one thermocouple tree. Each thermocouple tree had five (5) thermocouples at 0.5 m, 1.0 m, 2.0 m, 3.0 m and 3.85 m above the floor; the top thermocouple was 0.10-0.18 m below the ceiling and outside the boundary layer (the value varied due to the sloped ceiling in Bay 1 and Bay 4). A total of ninety (90) thermocouples were mounted on the thermocouple trees. The temperatures were measured throughout the space using the thermocouple trees. The top thermocouples on the thermocouple trees, together with the ceiling mounted thermocouples (see next bullet), were also used to monitor flame spread across the ceiling. These thermocouples were type K stainless steel sheathed thermocouples shielded from radiative heat for measuring gas phase temperature;
- Thirty six (36) thermocouples were installed 0.15 m below the ceiling along the centreline and quarter lines in a 2.43-m spacing to measure the temperatures below the ceiling. These ceiling thermocouples, along with the top thermocouples on the thermocouple trees, were used to monitor flame spread across the ceiling. These thermocouples were type K stainless steel sheathed thermocouples shielded from radiative heat for measuring gas phase temperature;
- Six (6) thermocouples were installed in a 2.43-m spacing on the bottom surface of the two beams B202 (346 mm × 546 mm) and B203 (346 mm × 546 mm) in Bay 2 to monitor the flame spread over the beams;
- Thermocouples were embedded in the mass timber ceiling at four locations – the centre of each of the four bays, respectively. At each location, five (5) thermocouples were embedded in the mass timber ceiling at the depths of 25, 50, 75, 100 and 125 mm in the timber, which coincided with one of the ceiling centreline thermocouples mentioned above. All holes drilled to install the thermocouples were sealed to maintain the integrity of the mass timber panels. These thermocouples were used to monitor flame and char progression inside the mass timber ceiling;
- An array of 5 thermocouples was installed on the mass timber shaft surface in the office side at 0.5 m, 1.0 m, 2.0 m, 3.0 m and 3.85 m above the floor.
- Five (5) thermocouples were embedded in the mass timber shaft wall at the depths of 25, 50, 75, 100 and 125 mm in the timber at 2.0 m above the floor, whose height coincided with one of the shaft surface thermocouples. All holes drilled to install the thermocouples were sealed to maintain the integrity of the mass timber panels. These thermocouples were used to monitor flame and char progression inside the mass timber shaft wall;
- Three (3) thermocouples were installed at each selected window opening to measure the temperature of the flame issuing from the opening. The thermocouples were located 0.15 m below the top of the opening on the centreline and at 0.4 m to each edge of the opening. A total of fifteen (15) thermocouples were installed at five selected openings.

- Seven (7) thermocouples were installed on the exterior façade above Bay 3 in its east elevation to measure the fire spread from the window opening to the façade above. The thermocouples were located at 0.75 m, 1.5 m, 2.5 m, 3.5 m and 4.5 m above the top of the window opening along the vertical centreline of the opening. The 3.5-m level had three thermocouples (on the centreline of the opening and at 0.5 m from each side to the centreline of the opening); the other levels had one thermocouple each level. Note that the roof mast had five more thermocouples at 5.5 m, 6.5 m, 7.5 m, 8.5 m and 9.5 m heights above the window opening.
- Seven (7) thermocouples were installed on the exterior façade above Bay 3 in its north elevation to measure the fire spread from the window opening to the façade above. The thermocouples were located at 0.75 m, 1.5 m, 2.5 m, 3.5 m and 4.5 m above the top of the window opening along the vertical centreline of the opening. The 3.5-m level had three thermocouples (on the centreline of the opening and at 0.5 m from each side to the centreline of the opening); the other levels had one thermocouple each level. Note that the roof mast had five more thermocouples at 5.5 m, 6.5 m, 7.5 m, 8.5 m and 9.5 m heights above the window opening.
- Nineteen (19) thermocouples were installed at four connections:
    - beam B204 (263 mm × 494 mm) to column C106 (530 mm × 532 mm) with 5 thermocouples
    - beam B203 (346 mm × 546 mm) to column C106 (530 mm × 532 mm) with 5 thermocouples
    - beam B203 (346 mm × 546 mm) to column C103 (395 mm × 395 mm) with 5 thermocouples
    - column C103 (395 mm × 395 mm) to column C202 (395 mm × 395 mm) with 4 thermocouples

  Figure 4 and **Figure 6** show details of the thermocouples installed at the connections for Test 5. For the beam-column connections, the thermocouples were located 80 mm from the exposed faces of the beams. For the column-column connection, the thermocouples were located 80 mm from the exposed faces of the columns.

Three vertical thermocouple arrays were installed inside the stair shaft as follows, which were operational in all tests.

- A thermocouple array was installed inside the stair shaft in the centre, with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor level of the ground storey.
- Two thermocouple arrays were installed on the mass timber surface in the stair shaft at the quarter lengths, each with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor level of the ground storey.

3.2.2 Heat Flux

- Two (2) HTHFS-01 heat flux sensors (FluxTeq) were installed in Bay 1 to measure radiant heat received by the wall and ceiling. One was installed on the back wall facing Cubicle 3 at 1.5 m high, the other on the ceiling above Cubicle 1 (100 mm by TC 331).
- Nine (9) heat flux meters were located outside the test structure at distances to monitor radiant heat from three selected window openings, providing data on heat exposure to adjacent buildings. For each opening, three heat flux meters were set up: one facing the centre of the opening at 3.0 m away; one aligned to the vertical centreline of the opening and 0.6 m above the opening at 3.0 m away; one facing the centre of the opening at 4.5 m from the face of the structure.

- Six (6) heat flux meters were installed on exterior façade 3.5 m above the top of the window openings in the east and north elevations of Bay 3, each opening with 3 heat flux gauges above aligned with the centreline of the opening and 0.5 m from both sides of the centreline, respectively. Gardon gauges had their probe front surface flush with the exterior façade. These heat flux meters provided data on the fire exposure to the upper storey(s) and exterior cladding from the fire plumes extending from the openings on the fire floor.

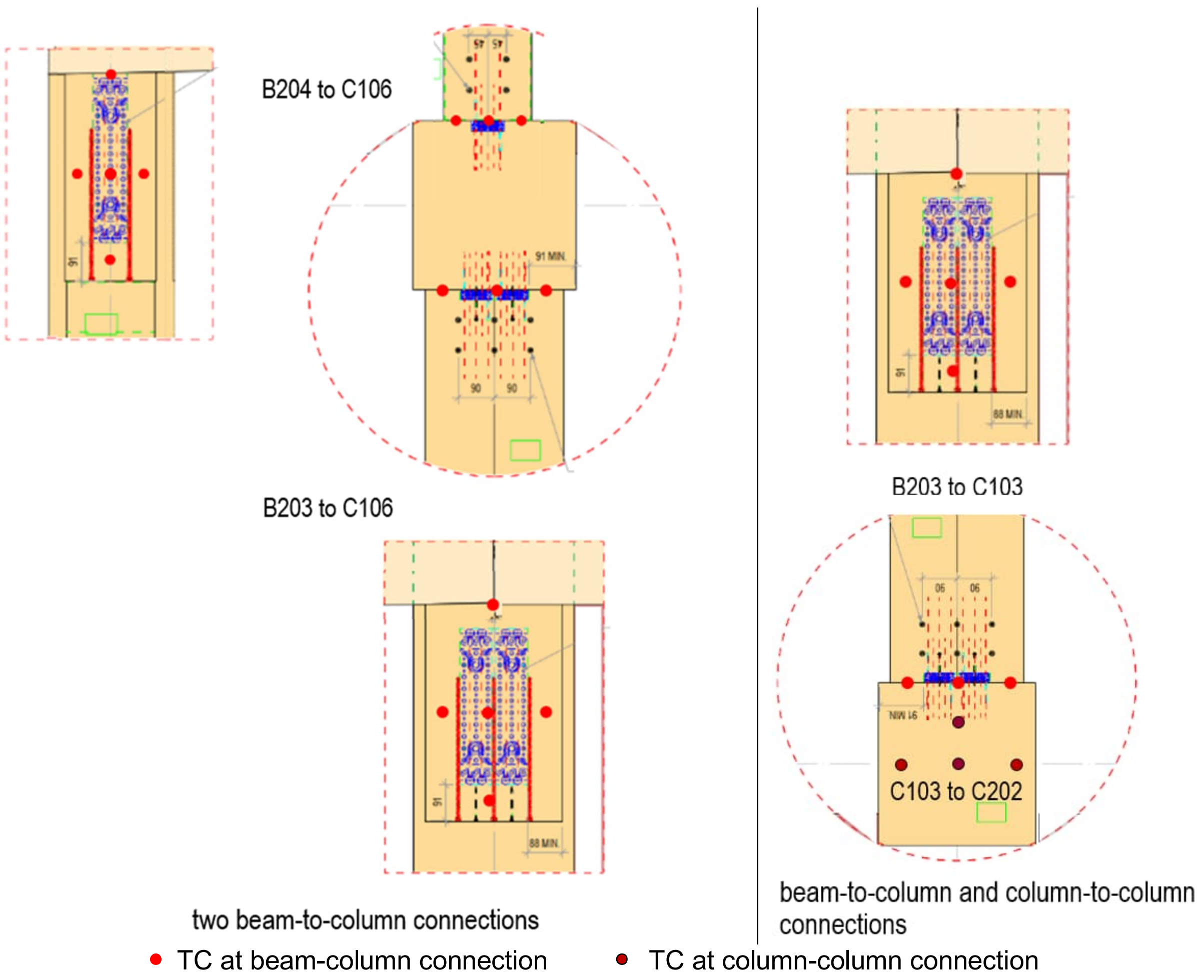


Figure 6. Thermocouples installed at beam-column connection for Test 5.

3.2.3 Camera

- One infrared camera was positioned to look at the exterior façade and through the openings to provide data and visual thermographs on temperature build up.
- One infrared camera was positioned to look at the unexposed side of the ceiling from above Bay 3 in the area of CLT connection with column C106 (above B203) to provide data and visual thermographs on heat transfer to the unexposed side of the ceiling.
- Various video cameras were positioned inside and outside the office space.

3.3 Test 5 Results and Discussions

Test 5 was conducted on June 22, 2022 with the southeast wind of 6 km/hour and ambient temperature of 20.6°C. The moisture content of the mass timber elements was in the range of 8.3-10.4% with an average of 9.3% ± 0.5%. The moisture content of the cubicle fuel load was 7.4-10.9% with an average of 9.1% ± 0.8%. The test started with ignition at 9:45 a.m. and terminated at 1:55 p.m. with data recording for 4 hours 10 minutes. There was neither sprinkler presence during the test nor firefighting intervention until the end of the test. In several respects, Test 5 represented a worst case scenario with intentionally severe testing conditions, including:

- the high fuel load used (likely above the average of typical open plan offices),
- the use of the aggressive ignition package (so that fire plume impinged on the ceiling),
- the use of rough openings instead of real windows (high ventilation and oxygen supply),
- no sprinkler presence, and
- no firefighting intervention during the 4-hour-10-minute test.

The probability that all these conditions coincide in reality would be extremely low. It was under these severe conditions that Test 5 was conducted in order to uninterruptedly demonstrate the fire dynamics and performance of the mas timber structure.

3.3.1 Fire Development

Figure 7 and **Figure 8** and **Figure 9** include photographs showing the ignition and fire development during Test 5. 125 kg wood cribs (2.5 x 50 kg) stacked in Cubicle 3 were the first item ignited with the methanol underneath lighted by a torch. The flame took 3 min to emerge from the top of the cribs. The flame then quickly grew upward and impinged on the ceiling above Cubicle 3 at 3 min 40 s. If the aggressive ignition package had not been used, the flame would have taken longer to impinge on the ceiling.

Figure 7. Ignition of wood crib in Cubicle 3 (adjacent to Cubicle 1) for Test 5.

Figure 8. Fire development during first 3 to 6 minutes of Test 5 (inside cameras destroyed by the 7th minute)**.**

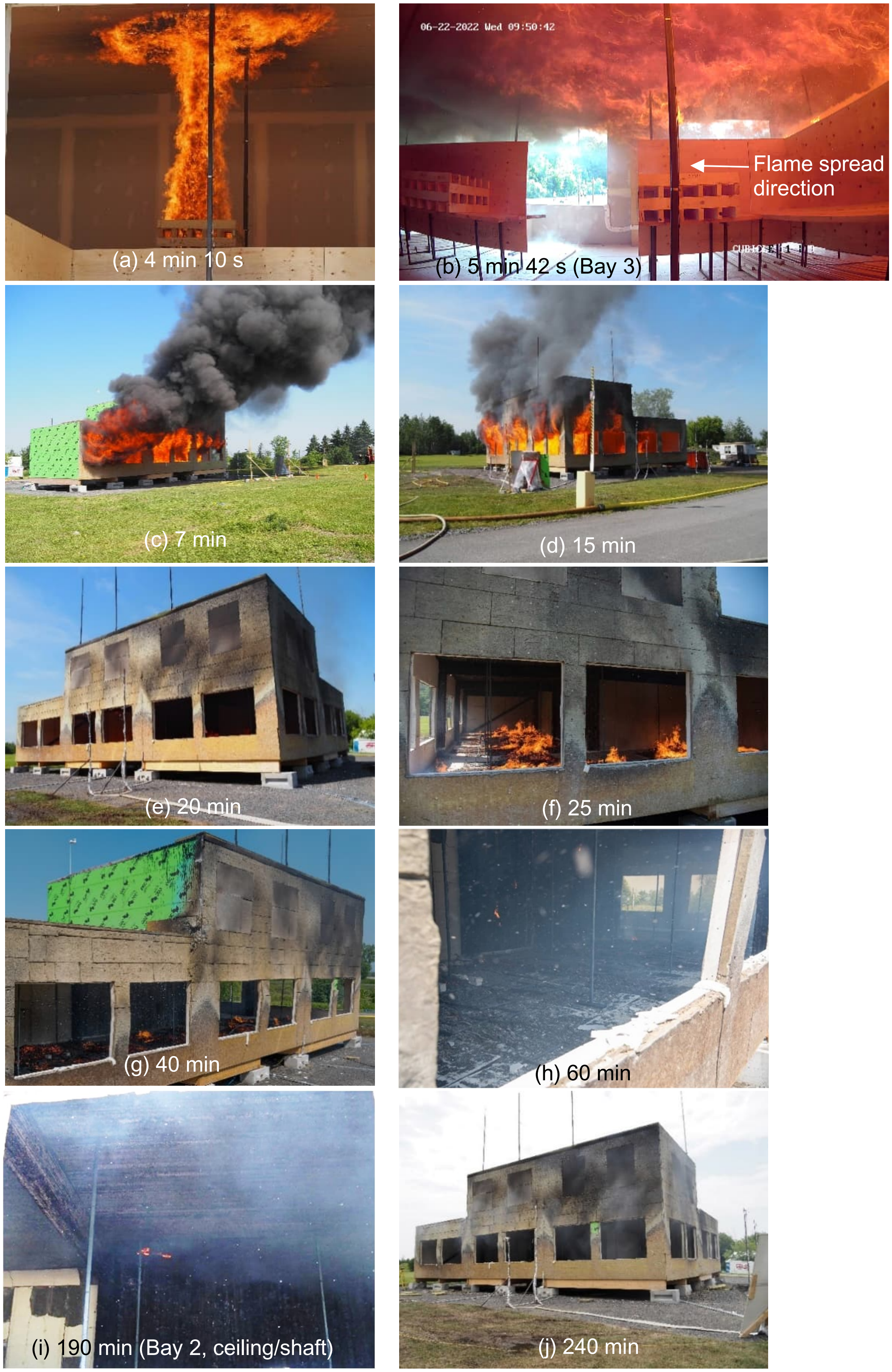


Figure 9. Progression of Test 5.

The flame subsequently spread across the ceiling and across the cubicles on the floor in Test 5. **Figure 10** illustrates the leading edge of the flame front and the trailing edge of the flame where the fuel ceases visible flaming combustion. The leading edge and trailing edge of the flame were determined based on videos and photographs as well as visual observation.

Upon the initial impingement on the ceiling, the fire started to spread over the ceiling in Bay 1 at a steady speed. While the beam (B202) intercepted the ceiling fire spread for a while, the smoke descended and migrated to other bays and exited from the top of all window openings by 5 min. Once passing below the beam B202, the fire spread accelerated and reached the far end of the ceiling by 5 min 43 s. Based on visual observation and video records, the average speed of the fire spread was 140 mm/s across the exposed CLT ceiling.

Large fire plumes issued from all window openings consecutively, starting at 5 min 25 s to 6 min 25 s. The fire plumes issued from the openings were at the maximum height and length at 7 min, extending as high as 7.5 m above and as long as 10 m out of the window openings in Bay 1 and Bay 2.

The radiative heat from the ceiling flame set off the fire spread across the cubicles which were fully involved in the fire consecutively, involving the partition, wood crib, table top and flooring materials inside each cubicle. By 6 min 50 s, all cubicles in the office space including the plywood flooring were fully involved in the fire. The average speed of the fire spread across the cubicles was 100 mm/s (starting from 3 min 40 s). The fire spread across the cubicles on the floor lagged behind the fire spread across the ceiling; for example, when the cubicle flame spread from Bay 1 to Bay 2, the ceiling flame already advanced to Bay 3 (see **Figure 9**(b) and **Figure 10**). The cubicles away from the openings were generally involved quicker in the fire than those cubicles near the openings.

From 6 min 50 s to 18 min, the entire open plan office space was fully involved in the fire from the floor to ceiling height. At 16 min, the fire intensity in Bay 4 area was greatly reduced as Cubicles 15-18 reduced to debris on the floor, the upward flame from the floor level stopped impinging on the ceiling of Bay 4, and the fire plume ceased to issue from the window openings in Bay 4. At 18 min, the ceiling of Bay 4 started to cease flaming combustion and the trailing edge moved towards Bay 3. In the same way, the fire continued to retreat towards Bay 2 and Bay 1 consecutively.

The fire decayed significantly after 18 min in the entire space when all cubicles reduced to debris on the floor, and the flames from the floor level ceased to impinge on the ceiling. By 19 min, fire plumes ceased to issue from all the window openings. By 21 min, there was no more visible flaming combustion on the ceiling, beams, columns and shaft wall; visible flaming combustion was limited to the debris on the floor with the flame heights decreasing. The flaming of the debris was ceased consecutively from Bay 1 at 25 min to Bay 4 at 30 min, after which there was only glowing debris on the floor. The glowing debris was fully ended from Bay 1 at 40 min to Bay 4 at 60 min.

From 60 min to 120 min, intermittent small flames were only observed on the shaft wall. From 120 min to 240 min, visible smoke continued to be produced due to persisted smouldering and intermittent small flames near various mass timber joints (see subsection 3.3.5 for more discussions). After 190 min, the Bay 2 ceiling became smoky, and localized delamination occurred from the ceiling near the shaft. This was confirmed later in the post fire inspection. But this localized delamination did not cause re-ignition nor fire regrowth. The space continued to cool down. The test was terminated at 250 min.

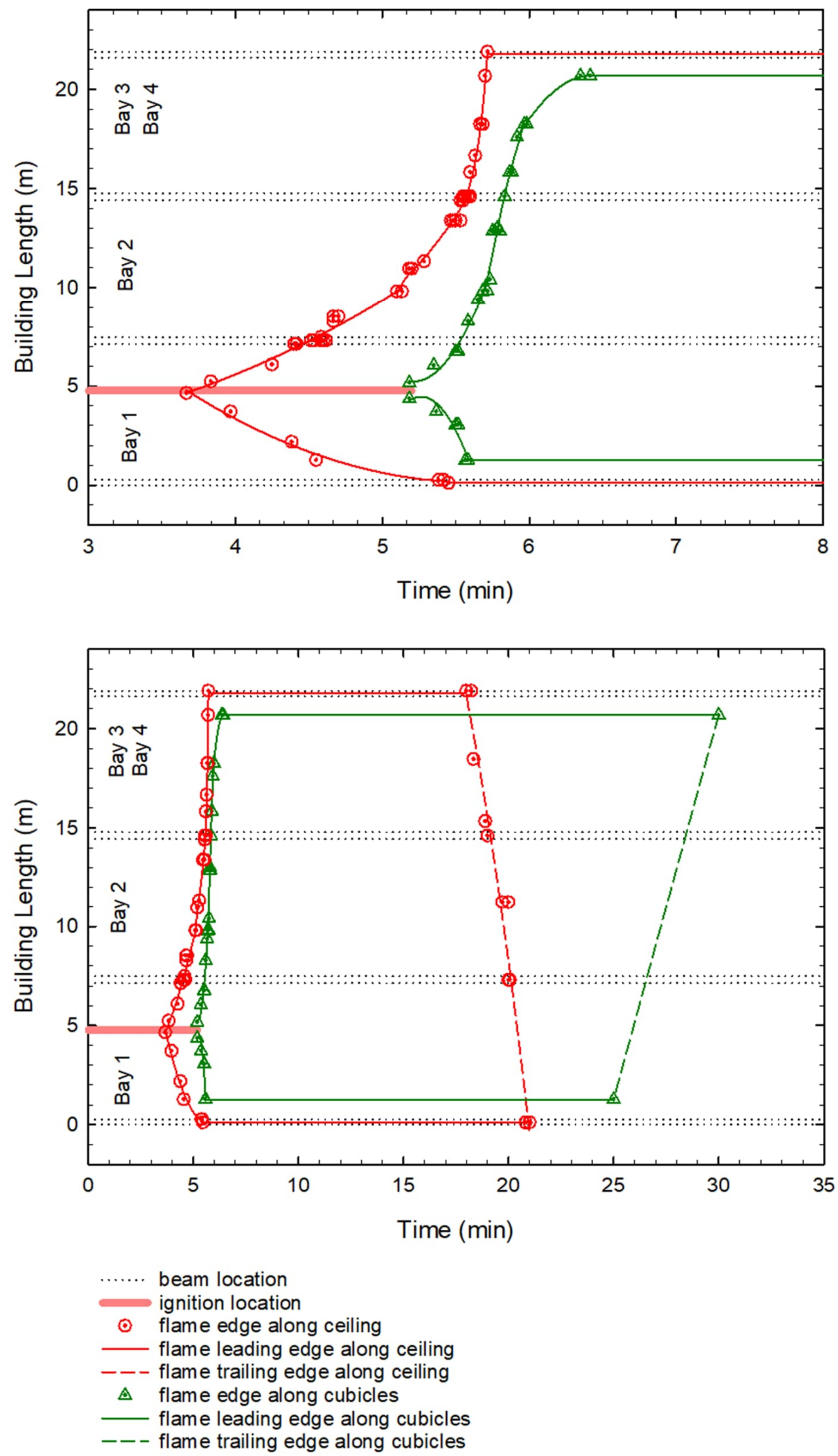


Figure 10. Fire spread across the ceiling and floor cubicles in Test 5.

3.3.1.1 Estimated impact of aggressive ignition package on fire development

Test 5 used the aggressive ignition package in order to ensure the initial flame would impinge on the 4-m high ceiling. The wood cribs were stacked to 1.8 m high for ignition. Upon the initial flame impingement on the ceiling at 3 min 40 s, the fire spread across the exposed CLT ceiling at the speed of 140 mm/s, based on visual observation and video records.

The potential impact of this aggressive ignition package on the fire development was estimated. A comparative analysis of the fire development with other tests in this series indicated that the aggressive ignition package was likely to have impacted the fire development in two ways. Firstly, the initial fire growth from ignition to flame impingement on the ceiling was accelerated. Secondly, once the flame impinged on the ceiling, the speed of fire spread across the ceiling was likely to have accelerated by approximately 50%, relative to unstacked wood cribs. The primary impact would be on the initial fire growth – the timing of when the flame would be impinging on the ceiling. Section 6.3.1.1 has more details of the comparative analysis for the estimation.

3.3.2 Temperature in Open Plan Office Space

Figure 11 to **Figure 14** present the temporal profiles of the temperatures measured in the open plan office space. **Figure 11** shows the temperatures measured using the thermocouples installed 150 mm below the CLT ceiling and on the bottom surface of beams B202 and B203. After the entire open plan office space was fully involved in the fire, the ceiling temperatures reached above 1000 °C in all bays, which continued to increase to higher temperatures. The ceiling temperatures started to decrease continuously after 15 min when most cubicles were reduced to debris on the floor. The ceiling temperatures fell below 300 °C at 80 min and below 100 °C at the end of the test, except for one location near the shaft where the ceiling temperatures was 150 °C at the end of the test.

Figure 12, **Figure 13** and **Figure 14** show the temperatures measured using the thermocouple trees installed in the cubicles, with thermocouples at 0.5, 1.0, 2.0, 3.0 and 3.85 m above the floor. Like the ceiling temperatures after the entire open plan office space fully involved in the fire, the cubicle temperatures increased to above 1000 °C in all bays and started to decrease after 12-15 min as each cubicle was gradually reduced to debris on the floor (Bay 4 starting earlier and Bay 1 started later). Also, all the cubicle temperatures fell below 300 °C by 80 min and below 100 °C by the end of the test. More specifically, the cubicle temperatures in Bay 3 and Bay 4 fell earlier than those in Bay 1 and Bay 2: the cubicle temperatures in Bay 3 and Bay 4 fell below 300 °C at 70 min and below 70 °C at the end of the test.

It was observed that spatial temperature differences were significant in the large open plan office space during the fully-developed burning period, and the hottest burning region was changing and moving. This is illustrated by **Figure 15** with a series of horizontal and vertical contours of the temperatures measured in the office space during the first 80 min of Test 5.

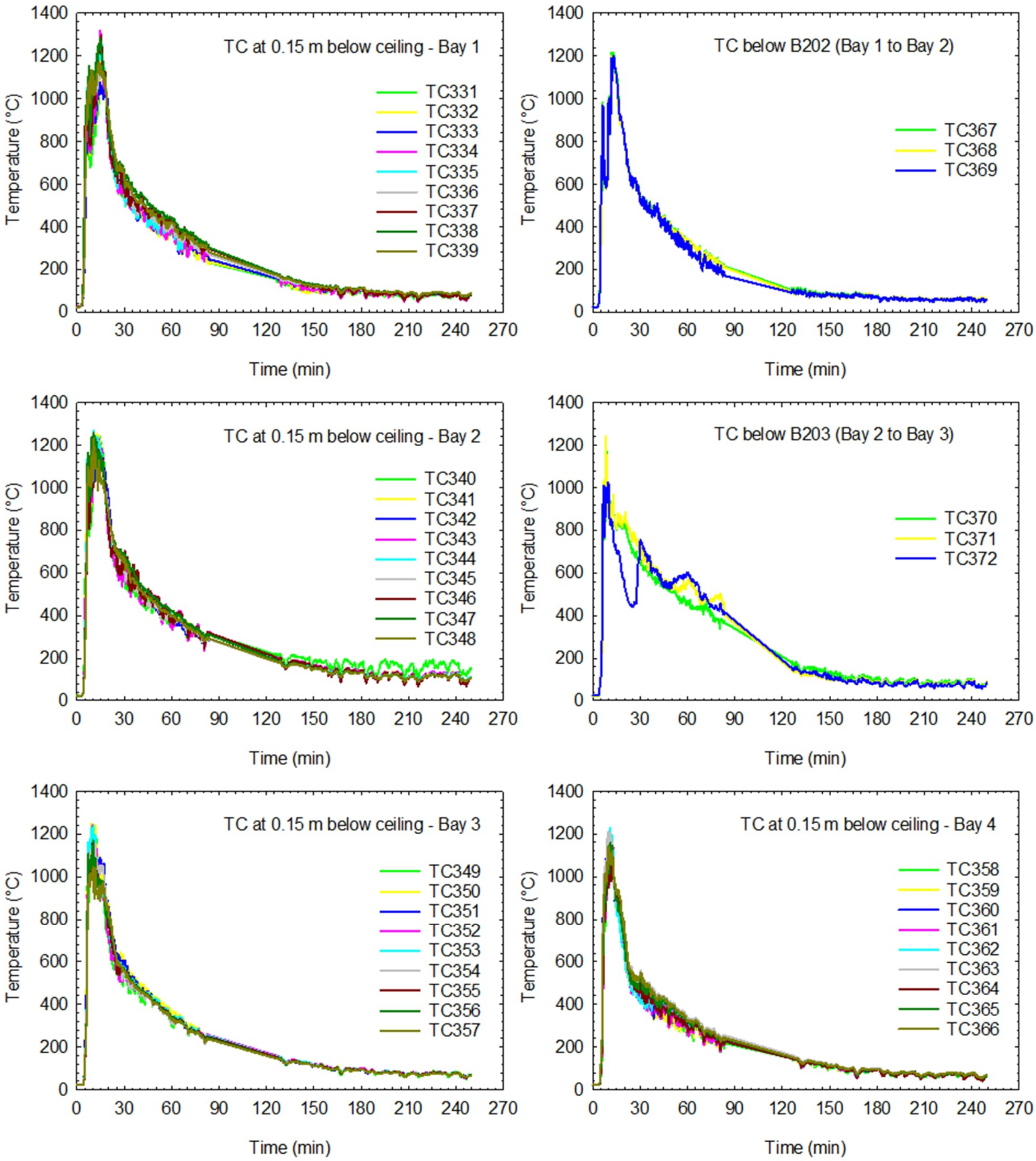


Figure 11. Ceiling temperatures during Test 5.

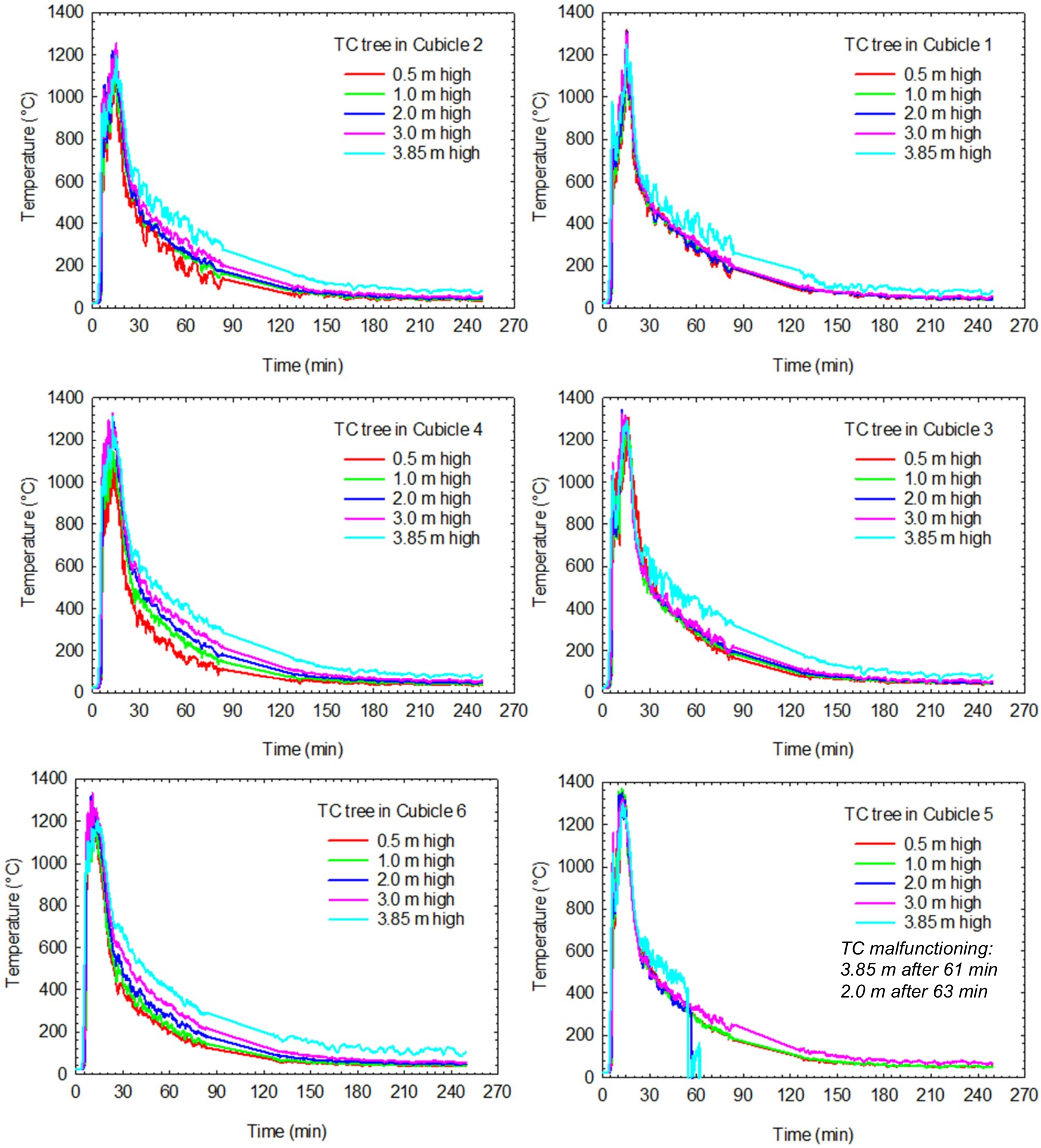


Figure 12. Temperatures in Cubicles 1 to 6 during Test 5.

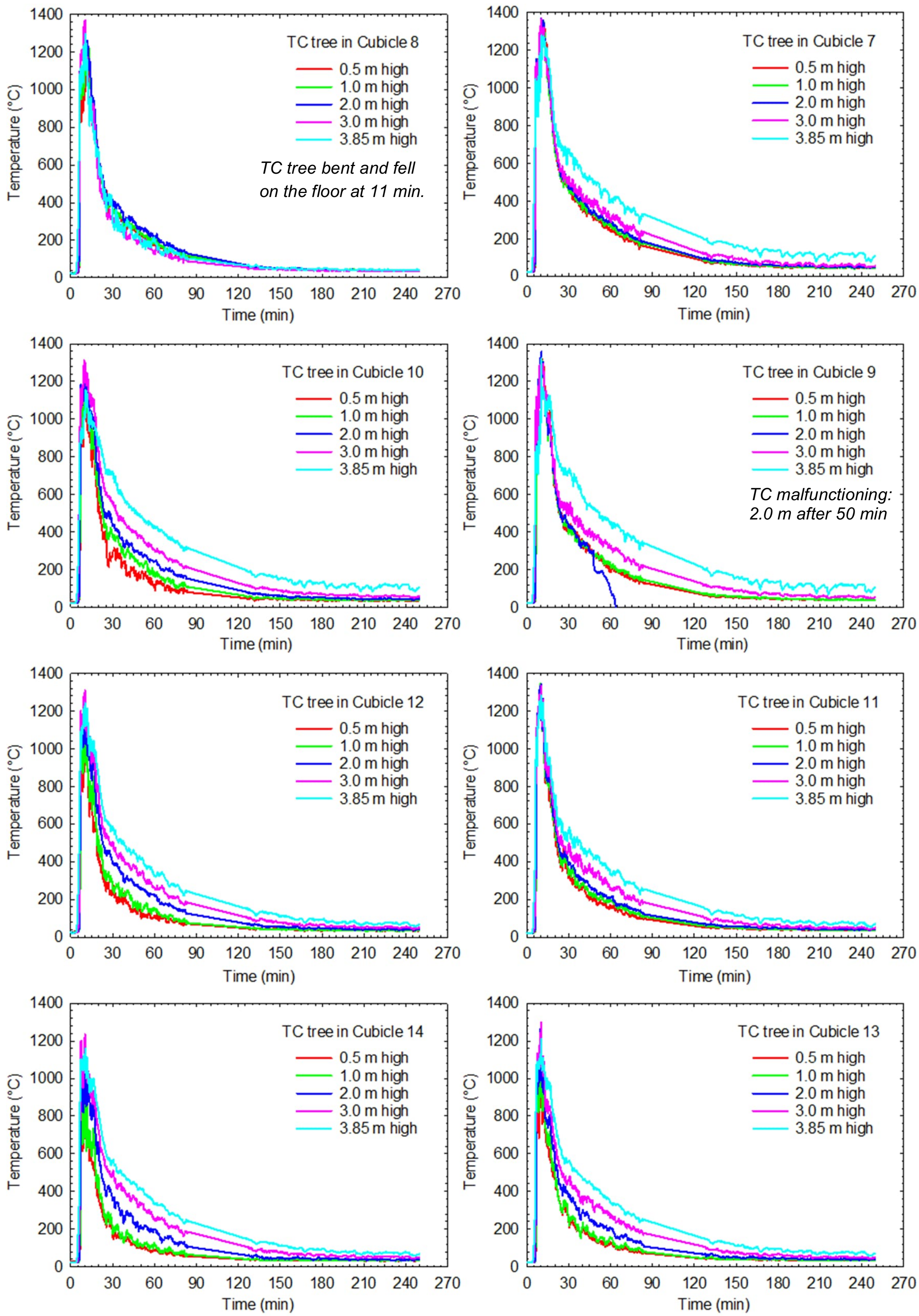


Figure 13. Temperatures in Cubicles 7 to 14 during Test 5.

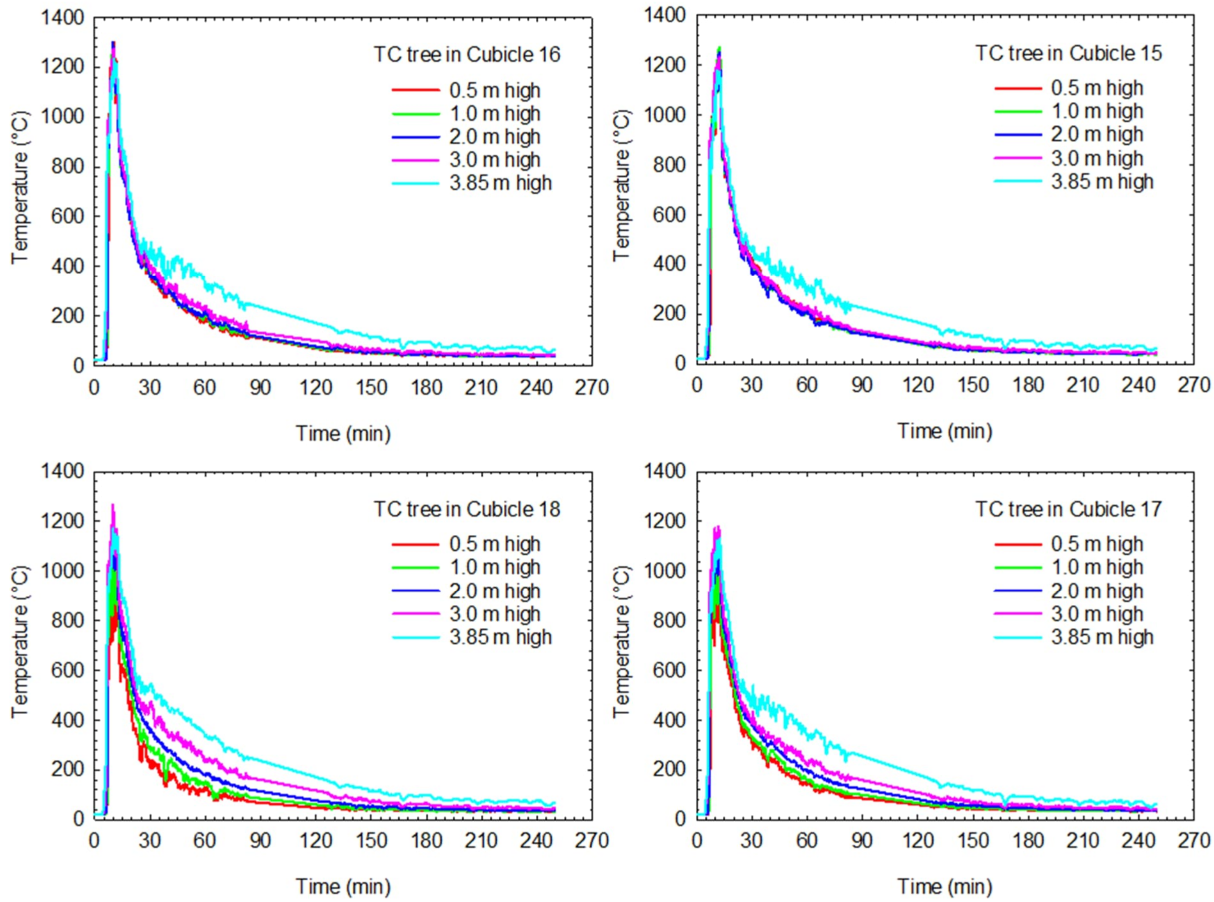


Figure 14. Temperatures in Cubicles 15 to 18 during Test 5.

The contour plots in **Figure 15** show that the flame spread faster across the ceiling than across the cubicles with the flame front at the cubicle level lagging behind the flame front at the ceiling level. This corresponds to the visual observation that at a given location along the building axis, the desktop started to burn approximately 1 min later than the ceiling and the plywood flooring started to burn after another 5-10 s with the radiative heat from the ceiling flame.

The contour plots also show that the fully-developed burning period was from 7 min to 18 min when the entire space was involved. The hottest burning region was moving from Bay 1 towards other bays and also expanding in volume at the same time. At 10 min, the hottest burning region reached its maximum both in volume (50% of the space) and in temperatures (above 1200 °C). Then, the hottest burning region started to retreat back to Bay 2 and Bay 1 consecutively as the fire intensity in Bay 4 and Bay 3 started to weaken with their cubicles gradually falling apart. Large spatial temperature differences existed across the space; e.g., up to 400 °C temperature differences across the upper space. In addition, from 7 min to 15 min, the temperatures at 2.0 m and 3.0 m heights were higher than those at the ceiling height in the hottest burning region; even some of the temperatures at 1.0 m and 0.5 m heights in locations away from the window openings were higher than at the ceiling height.

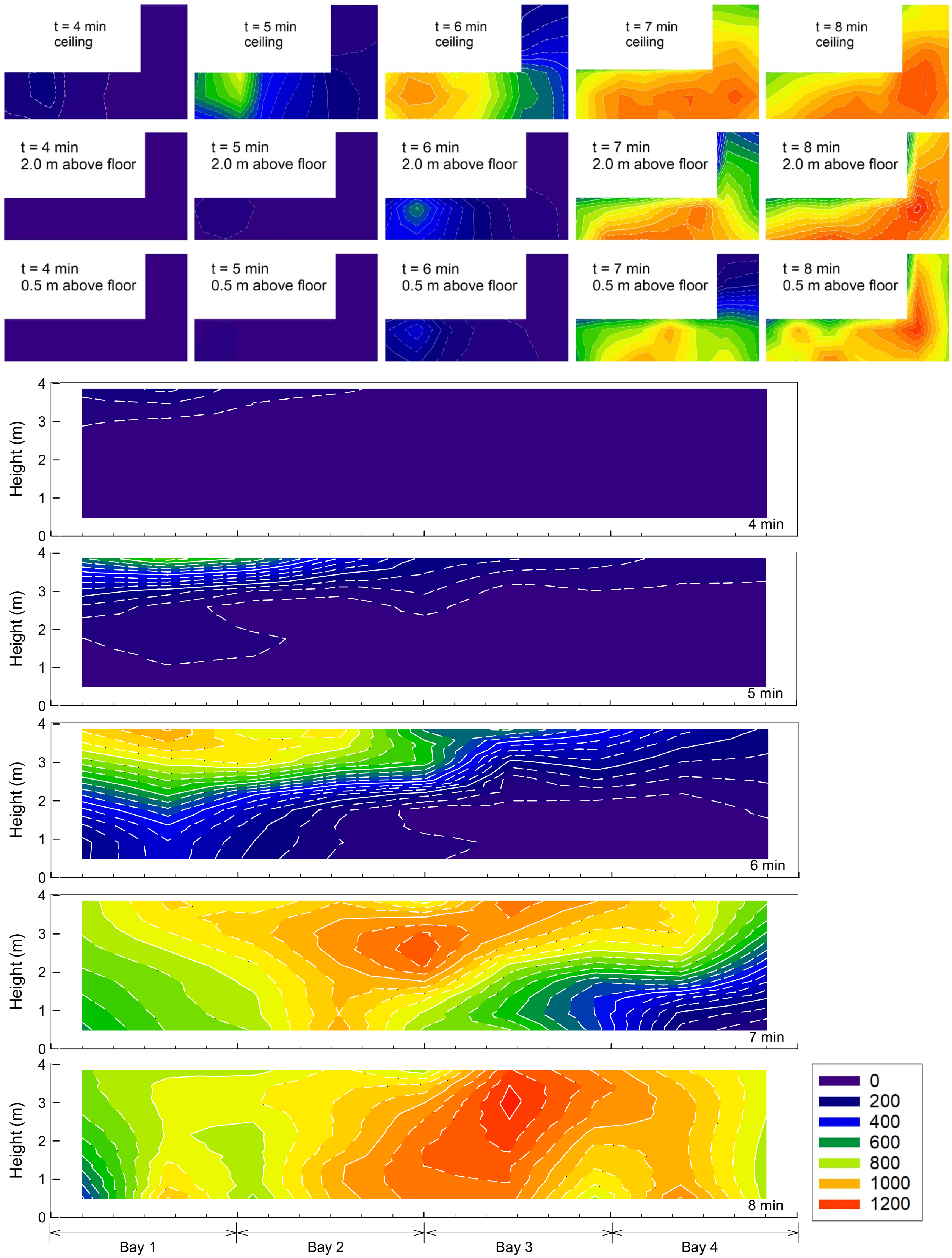


Figure 15. Horizontal and vertical temperature contours in Test 5 (line intervals ΔT=50 °C).

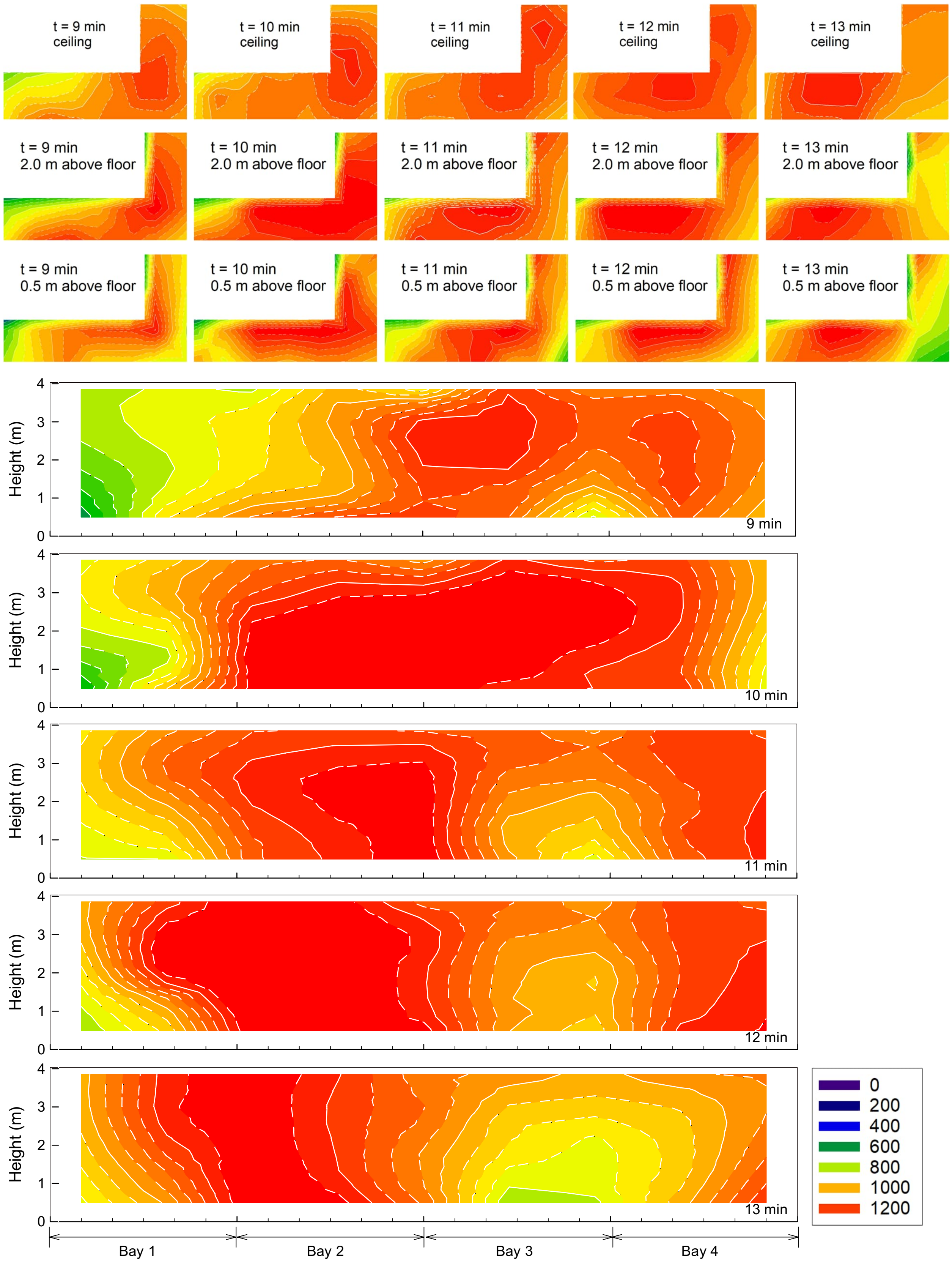


Figure 15. Horizontal and vertical temperature contours in Test 5 (Continued, line intervals ΔT=50 °C).

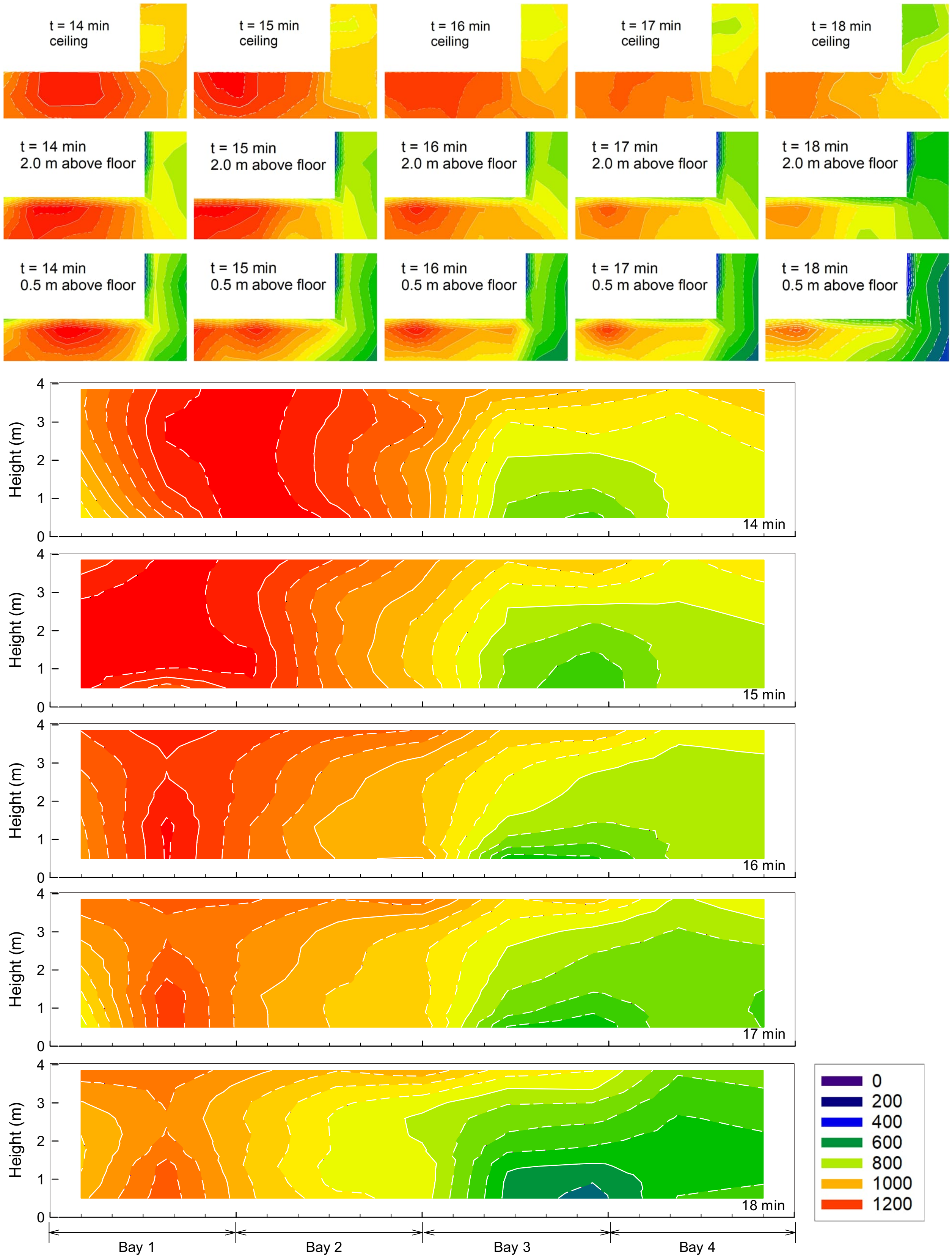


Figure 15. Horizontal and vertical temperature contours in Test 5 (Continued, line intervals ΔT=50 °C).

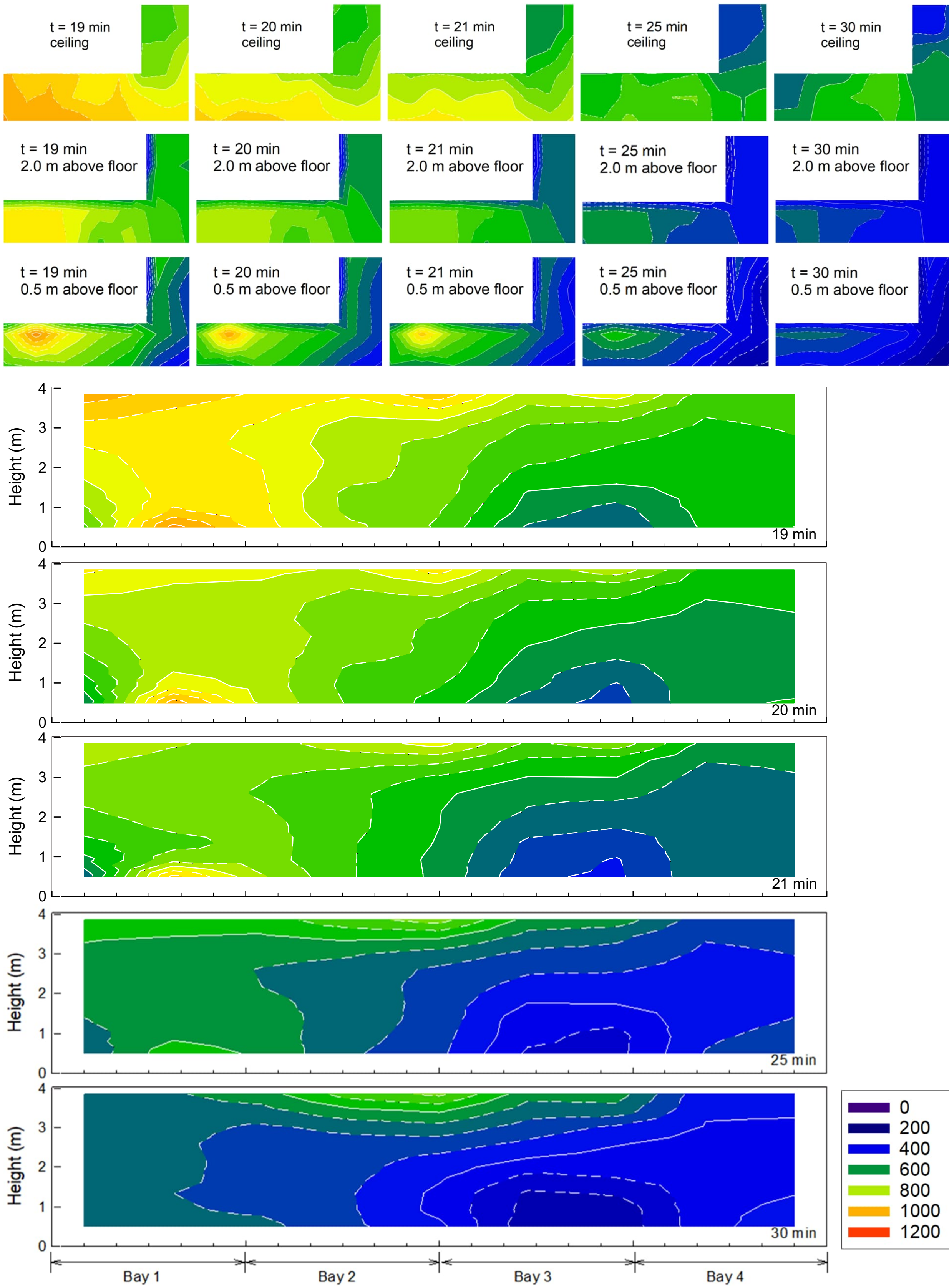


Figure 15. Horizontal and vertical temperature contours in Test 5 (Continued, line intervals ΔT=50 °C).

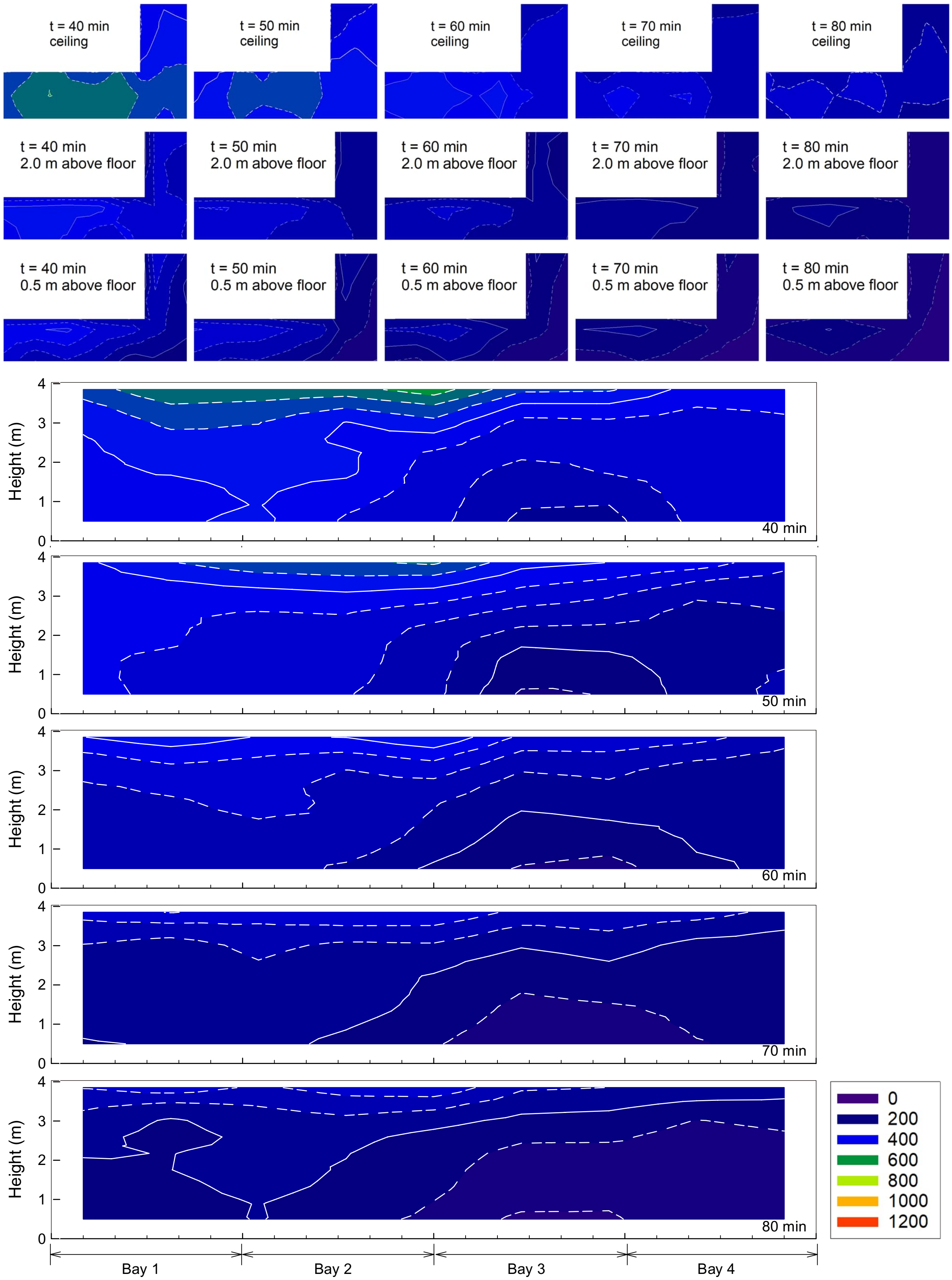


Figure 15. Horizontal and vertical temperature contours in Test 5 (Continued, line intervals ∆T=50 °C)**.**

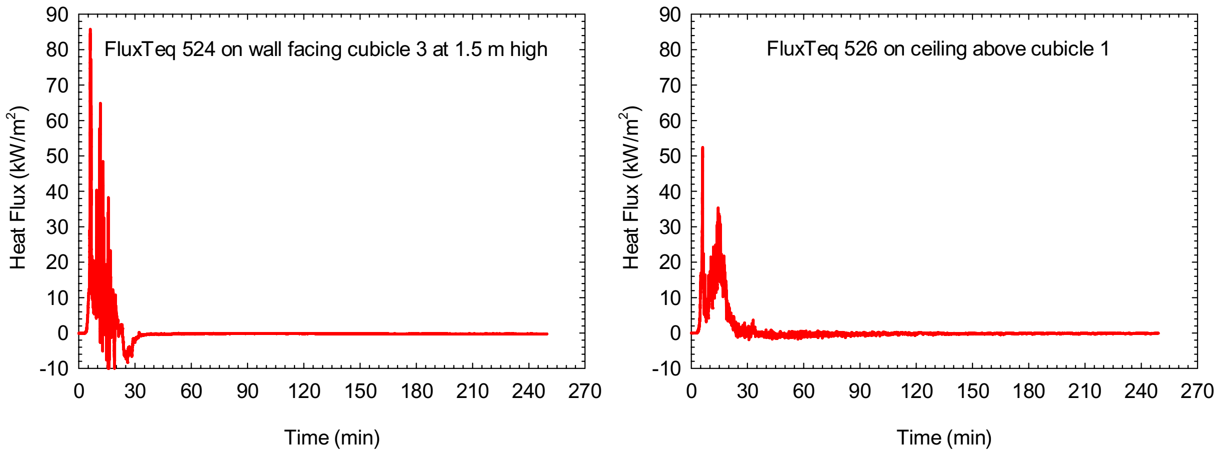


Figure 16. Heat fluxes to wall by Cubicle 3 and ceiling above Cubicle 1 during Test 5.

Heat fluxes received by the wall and ceiling in Bay 1 are shown in **Figure 16**. For the sensor installed on the ceiling above Cubicle 1 (which was just located at the left edge of the contour plots), there are two distinct peaks of 52 kW/m^2 at 6 min and 35 kW/m^2 at 15 min. Similarly for the sensor installed on the wall facing Cubicle 3 (at 1.5 m high), two distinct peaks are 86 kW/m^2 at 6 min and 65 kW/m^2 at 12 min. These separate peaks correspond to the movement of the hottest burning region away from and back to Bay 1 successively.

3.3.3 Temperature inside Structural Elements

Figure 17 shows the temperatures measured using embedded thermocouples in the mass timber ceiling and shaft. The maximum temperatures measured at 25 mm depth were 225 °C in Bay 1, 235 °C in Bay 2, 120 °C in Bay 3 and 150 °C in Bay 4, well below the typical charring temperature of 300 °C. The maximum temperatures measured at other depths were even lower. The temperatures at 25 mm depth reached the maximum values at around 60 min and then started to decrease, dropping to about 100 °C at the end of the test. Compared to the timing when the flaming combustion ceased on the ceiling, beams, columns and shaft wall by 21 min, thermal lags were present inside the mass timber panels. The measurements from the embedded thermocouples implied that the char depths in the ceiling and shaft panels at the measurement locations should be less than 25 mm, which appeared to be undervalued as the post-test char measurements determined the char depths being greater than 25 mm (see section 3.3.5). Literatures indicated that thermocouples perpendicularly implanted from the back into the timber plane tended to underrate the temperatures inside the timber because of thermal conduction through the metal wires [26, 27].

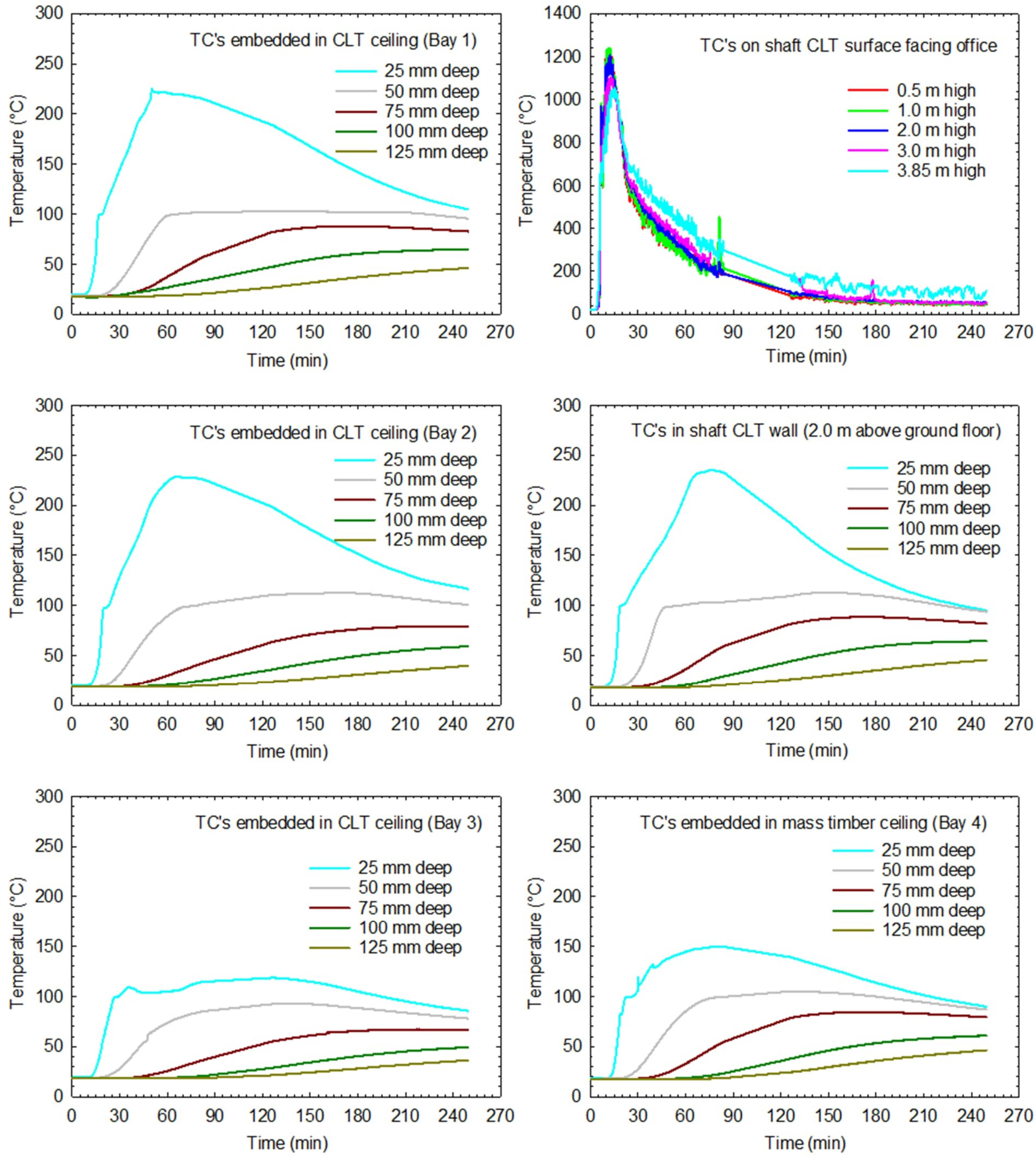


Figure 17. Temperatures in CLT ceiling and shaft during Test 5.

Figure 18 shows the temperatures measured using embedded thermocouples in the mass timber connections (see **Figure 6** for installation details at connections). In general, the temperatures at the connections followed an ascending trend during the test.

In the C103-C202 column to column connection, the measured temperatures were all below 90 °C. For the B203-C106 beam to column connection, the measured temperatures were all below 200 °C with the left thermocouple giving the highest reading of 200 °C while all others were well below 100 °C. This was because that left thermocouple was just adjacent to the mass timber shaft, subjecting to more heat exposure than the others. For the B204-C106 beam to column connection, the measured temperatures were all below 250 °C with the right thermocouple giving the highest reading of 250 °C while all others were well below 100 °C. This was because that right thermocouple was closest to the interior in Bay 4, subjecting to more heat exposure than the others.

For the B203-C103 beam to column connection, three of the five thermocouples measured the temperatures of over 300 °C at the top, left and right positions with the top thermocouple reaching 630 °C at the end of the test. This connection continued smouldering during and after the test, requiring considerable efforts in the post fire operation to fully extinguish the hidden hot spots in the ceiling-beam-column junction. Possible causes for this are discussed in Section 3.3.5.

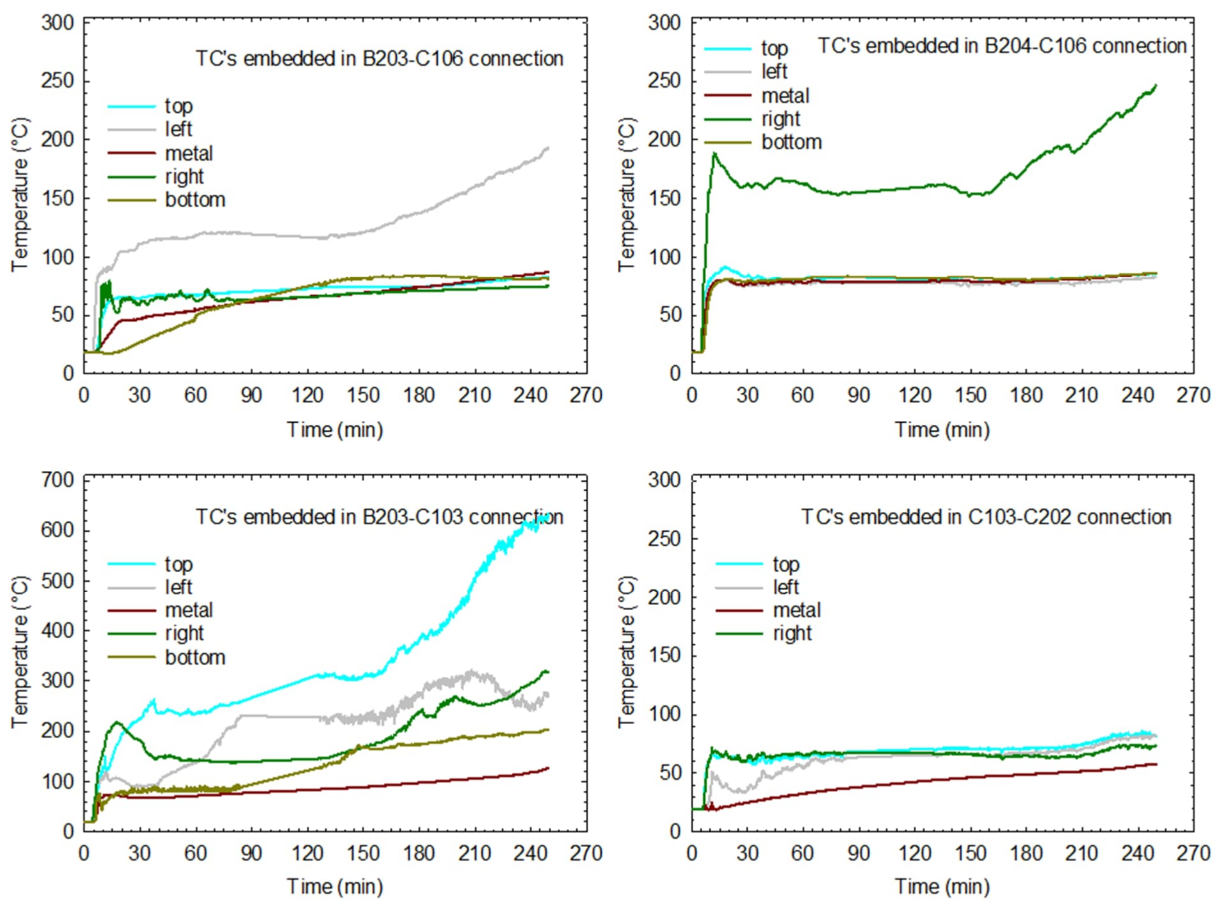


Figure 18. Temperatures in mass timber connections during Test 5.

3.3.4 Temperature and Heat Flux outside Office Space

All temperatures measured inside the stairwell were below 36 °C, including those on the CLT surface. Maximum temperatures measured inside the suites on the second storey were 30-65 °C depending on locations.

The temperatures measured at the window openings had the similar trend to those shown in **Figure 11** to **Figure 14**. The initial temporal profiles of the temperatures measured at the top of window openings are presented in **Figure 19**, showing that fire spread within 2 min.

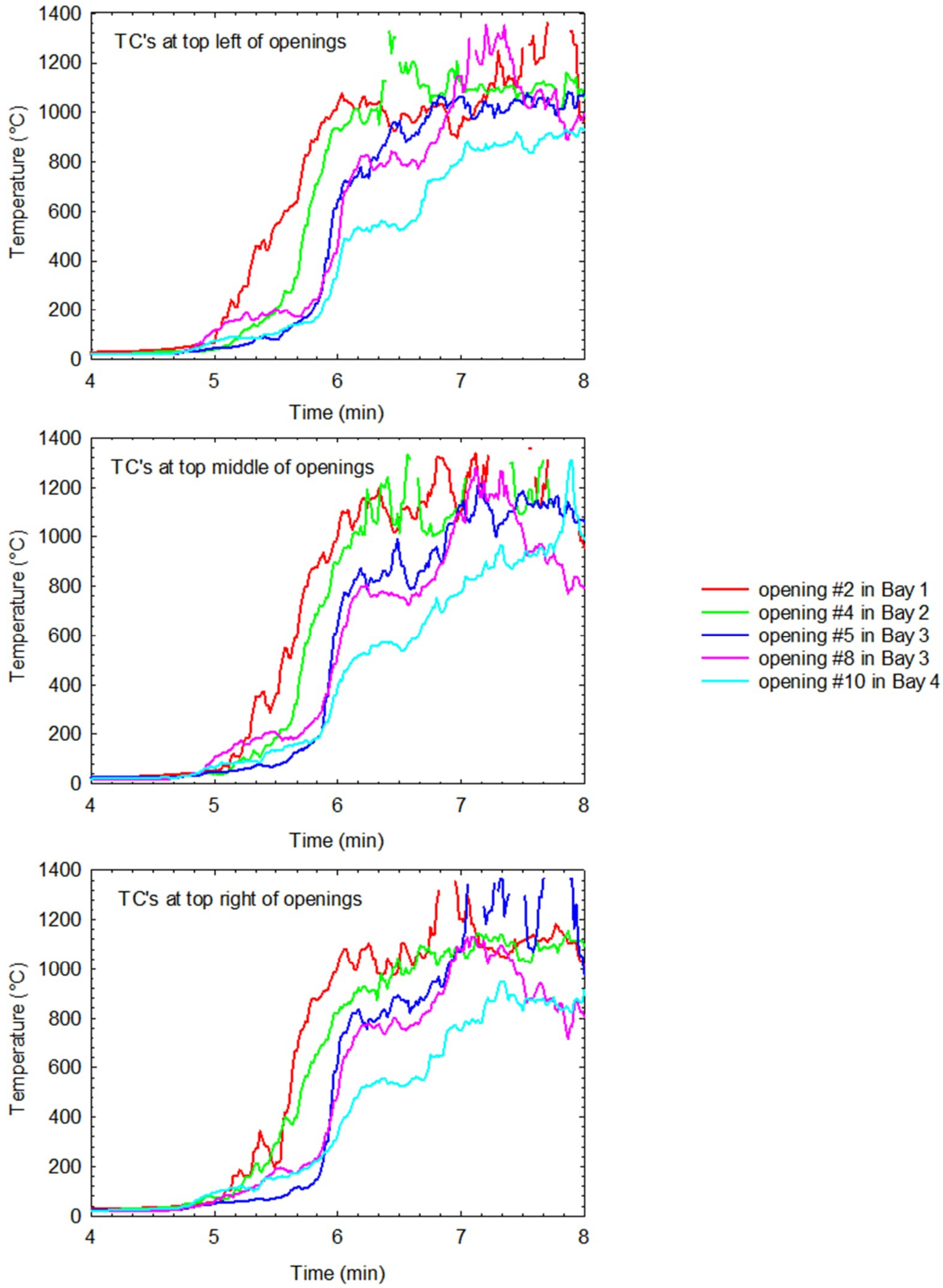


Figure 19. Temperatures at top of openings during first 4 to 8 minutes of Test 5.

Figure 20 shows temperatures measured on the exterior facades and tall masts above the window openings. Exterior infrared images of the test structure are provided in **Figure 21**. The peak temperatures at different heights are tabulated in **Table 2**.These temperature measurements indicated that the fire plumes were extended beyond 5.5 m high above the openings in Bay 2, consistent with visual observation, videos and photographs that the fire plumes reached as high as 7.5 m above the openings. The temperatures rises were mainly caused by radiation since the fire plumes were projecting away from the building.

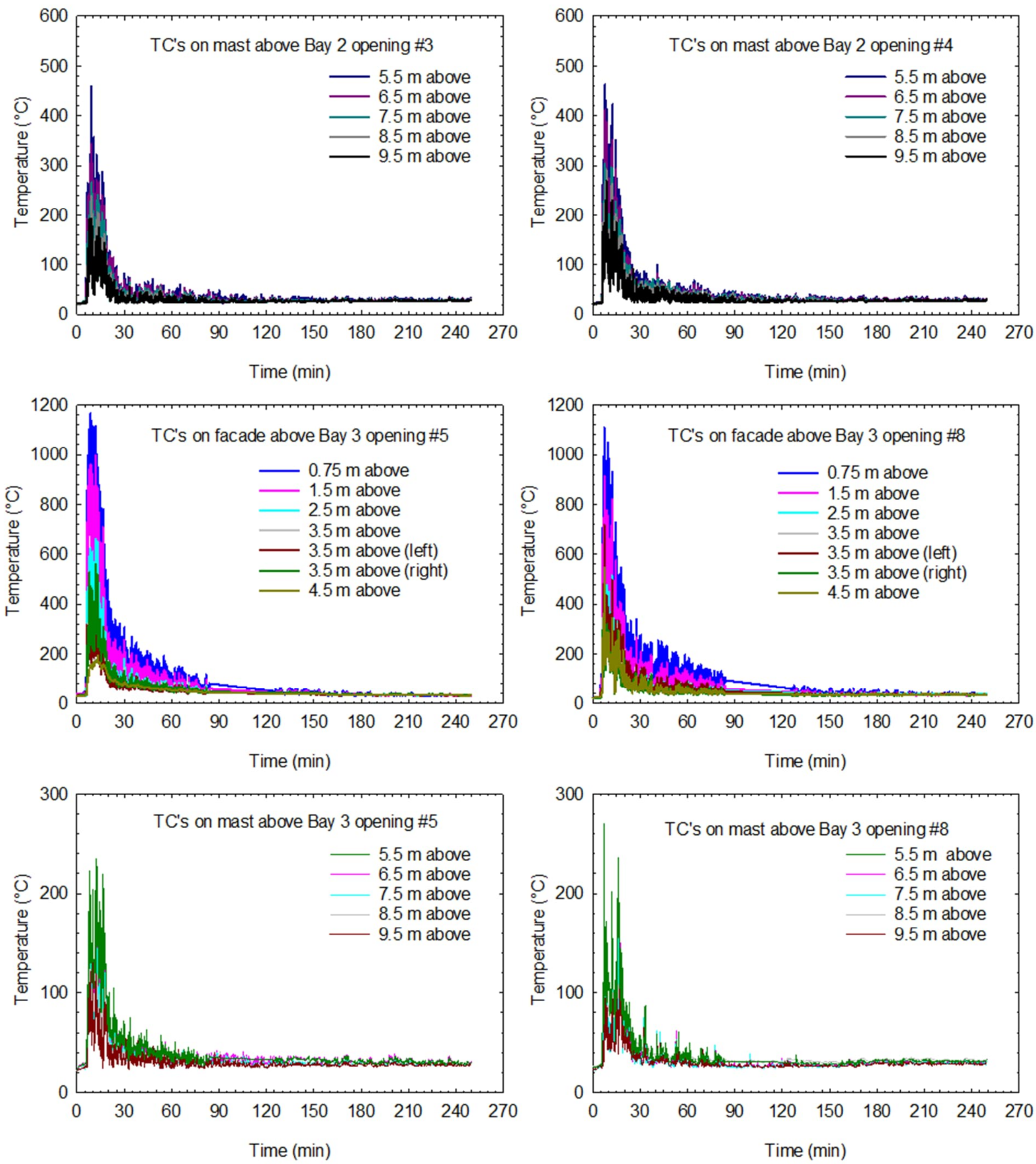


Figure 20. Temperatures measured on exterior façade above openings during Test 5.

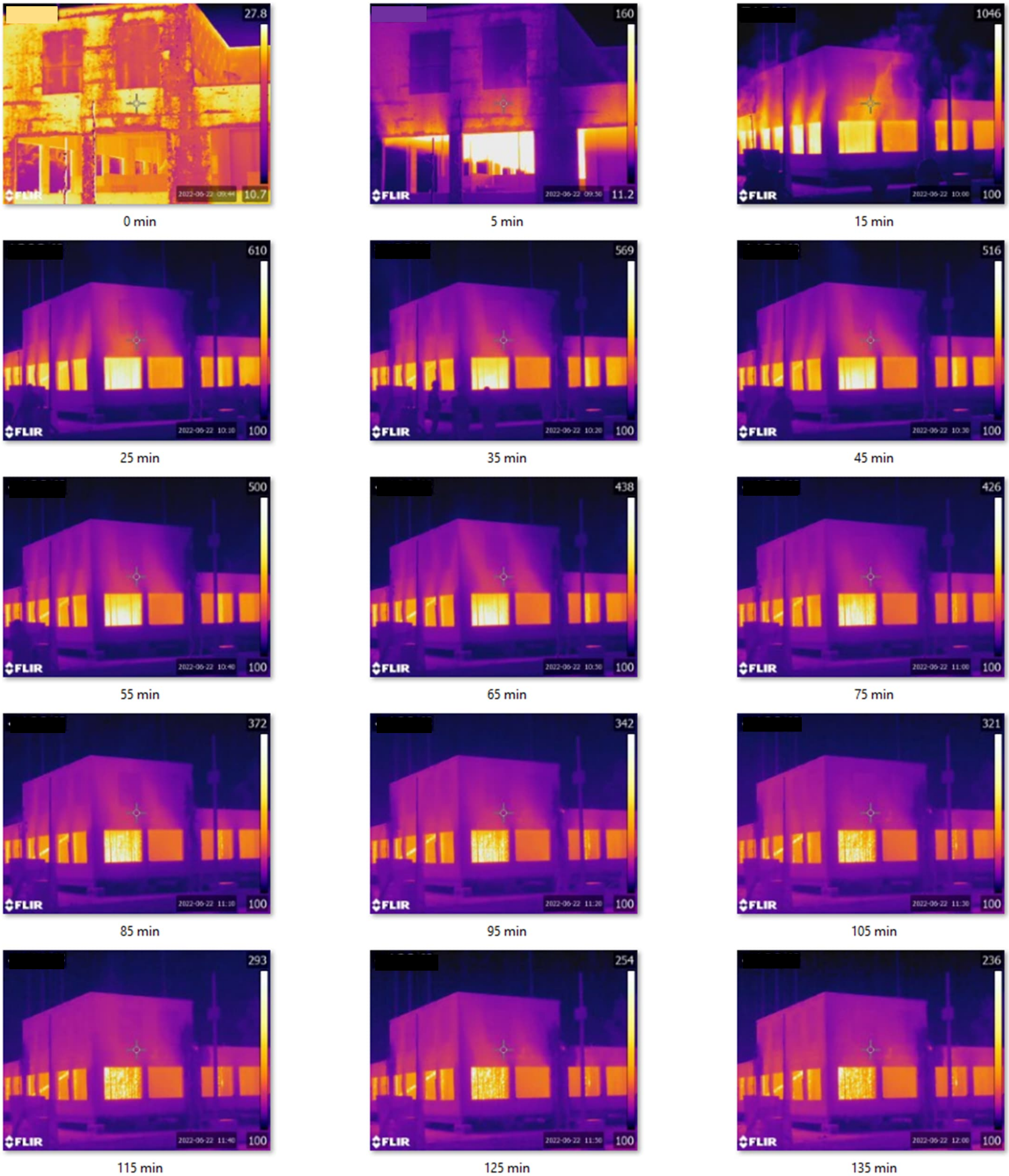


Figure 21. Infrared images from distance during Test 5.

Table 2. Peak temperatures on facades and tall masts above the window openings.

Height (m) above opening	Opening #3 (°C)	Opening #4 (°C)	Opening #5 (°C)	Opening #8 (°C)
9.5	192	268	147	128
8.5	240	291	159	115
7.5	266	305	160	163
6.5	344	413	203	177
5.5	460	463	235	270
4.5	-	-	192*	547
3.5 (centre)	-	-	510	607
2.5	-	-	661	625
1.5	-	-	997	913
0.75	-	-	1167	1109
0.0	-	1300	1300	1300

** This thermocouple was at 4.5 m above the opening and very close to the top of the roof which was at 4.6 m above the opening. To prevent the roof waterproofing membrane (which draped around at the top edge of the exterior façade) from being involved in the fire, 100-mm wide gypsum board strips were used to cover the top edge of the façade. The gypsum strips might have obstructed this thermocouple.*

- No thermocouple was installed at this location (see **Figure 4***)*

Figure 22 shows heat fluxes measured on the exterior facades above the window openings. With 1-min running average, the peak heat fluxes at 3.5 m height reached 37 kW/m^2 above opening #5 and 50 kW/m^2 above opening #8.

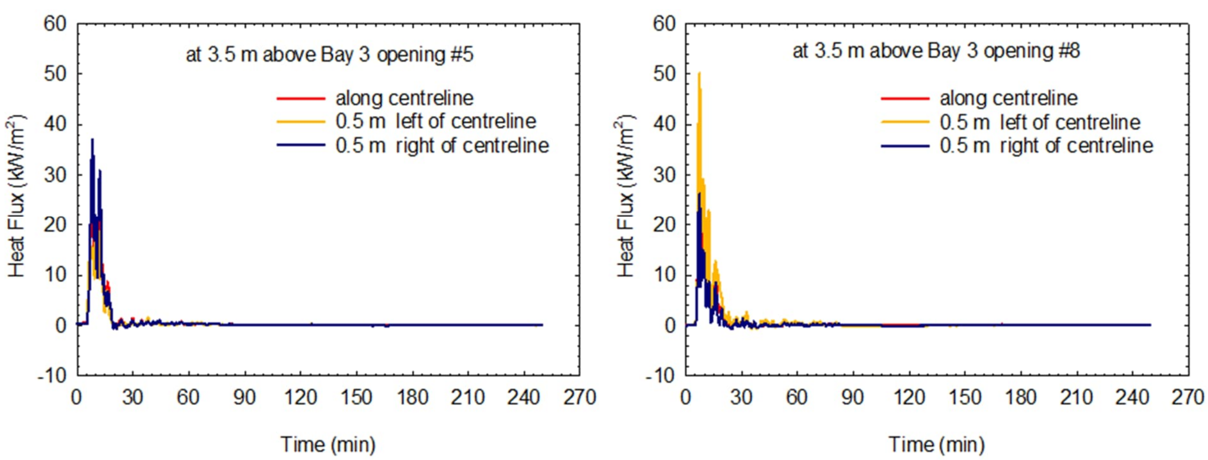
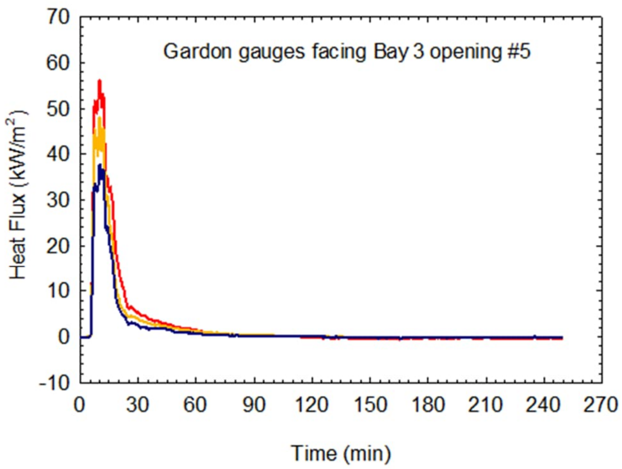
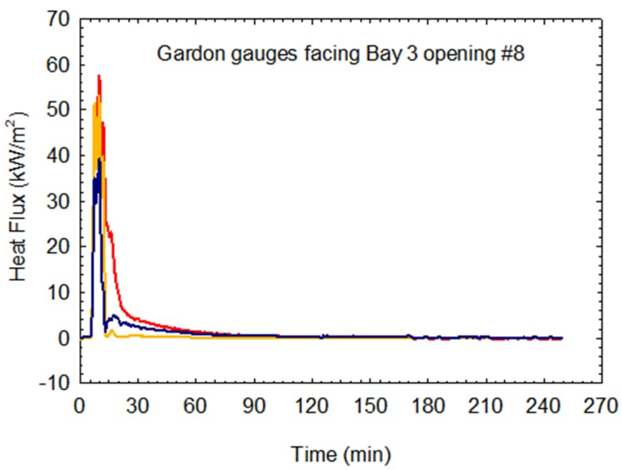


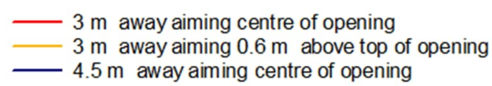
Figure 22. Heat fluxes measured on exterior façade above openings during Test 5.

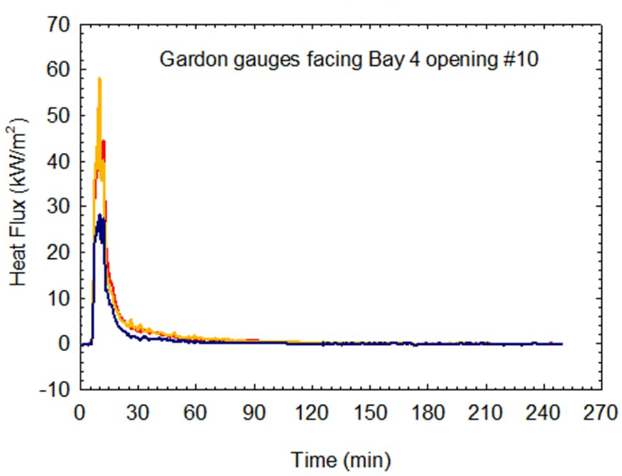
Strong thermal radiation from the fire was measured and felt at distance during the initial fully-developed burning period. **Figure 23** shows heat fluxes at distances to the structure during the test, smoothed by 1-min running average. The peak heat fluxes reached 58 kW/m^2 at 3 m away from window openings #5, #8 and #10; 39 kW/m^2 at 4.5 m away from window openings #5 and #8; and 28 kW/m^2 at 4.5 m away from window opening #10.



Damaged plastic safety cones (from left to right) which were placed at 11, 14, 17, 21 and 24 m away.







Deformed plastic casing of display screens which were placed at 30 m away.

Figure 23. Heat fluxes at distance to structure's openings during Test 5.

The heat fluxes measured at distances were consistent with visual observation, videos and photographs pertinent to heat exposure of the surrounding objects. **Figure 23** includes photographs of damaged plastic safety cones (collected after the test) and deformed plastic casing of large display screens. These safety cones were placed at 11, 14, 17, 21 and 24 m away from the structure during the test. They melted or deformed during the first 18 min of the test. The grass within 20 m to the window openings started to burn at 9-13 min (water had to be sprayed to cool down the grass). Two cameras installed at 11 m away from the test structure started melting at 12 min (lost function at 30 min). Plastic casing of two large display screens placed at 30 m away also deformed noticeably.

3.3.5 Post Fire Operations and Char Measurements

After the termination of the fire test, smouldering persisted at several spots, particularly in joints. The Ottawa Fire Services were deployed to tackle the remaining hot spots and to cool down the space. Char measurements were conducted afterwards.

An electronically controlled drilling device – Resistograph – was used to drive a long thin drill bit through the timber and record the drilling resistance thus to determine the remaining timber depth. The char depth is then calculated by subtracting the remaining timber depth from the original timber dimension. **Figure 24** shows actual char depths measured using Resistograph in the ceiling and shaft panels, selective beams and columns. In this figure, the char depth values appear schematically at the locations where they were measured with 2.4 m spacing for ceiling and beam measurements, 1.0 m vertical spacing for column and shaft measurements, and quarter point horizontal spacing for shaft measurements. For the beam and column measurements, each location involved two drillings perpendicular to each other to determine the char depths for three exposed sides; **Figure 24** shows the char depth per exposed side. As mentioned in section 3.3.3, most actual char depths in the ceiling and shaft panels are greater than the values implied by the embedded thermocouples which were perpendicularly implanted.

The mass timber structural elements used in this test structure met the 2-hour fire-resistance rating, which were designed according to CSA O86-19 to allow charring from each exposed side. The Resistograph measurement results shown in **Figure 24** reflect an overall picture of the general char depths in Test 5, which are well within the design allowance. The vertical mass timber elements (shaft panels and columns) had greater char depths than the horizontal elements (ceiling panels and beams). Beams and columns generally had deeper charring at their two ends. The averaged char depths are 24 mm for the ceiling panels, 29 mm for the beams, 39 mm for the columns and 42 mm for the shaft panels.

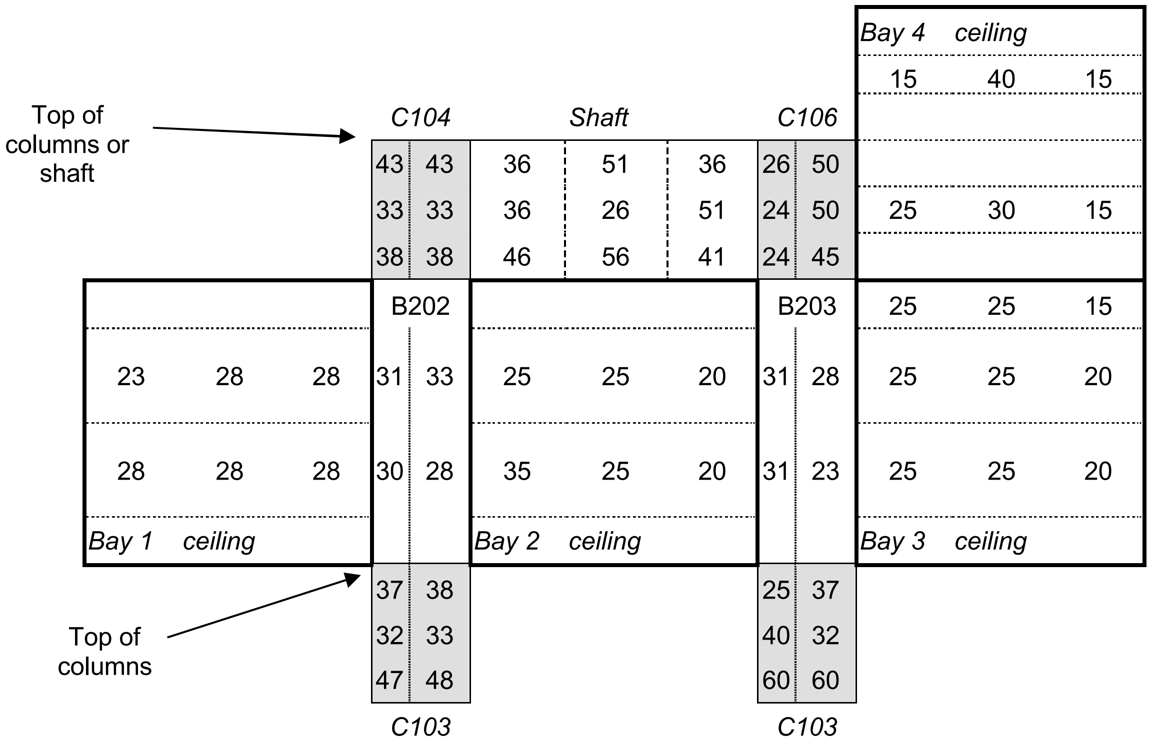


Figure 24. Char depths (mm per exposed side) **in ceiling, shaft, beams and columns in Test 5.**

Some photographs taken near the end of the test and during the post test operations are included in **Figure 25**, **Figure 26** and **Figure 27**.

The CLT ceiling near the shaft in Bay 2 had some localized delamination after 190 min during the test. Several delaminated pieces could be seen hanging below Bay 2 ceiling near the shaft towards the end of the test. More delaminated pieces fell down from the ceiling later while the space was cooling down further. **Figure 25** (c) shows delamination at 3 hours 40 min during the fire test while **Figure 25** (d) and (f) show delamination during intervention of the fire department. It should be noted that the localized delamination did not cause re-ignition nor fire regrowth during the fire test, and that no heat delamination was observed from the CLT ceiling in other bays nor from the glulam beams, columns or GLT decking.

The protected CLT floor generally had no charring, except for a few spots near the shaft and under the large wood cribs in Cubicle 3 where the floor had up to 16 mm char depth, as shown in **Figure 25** (h).

Several locations, especially joints and connections, were observed to have greater char depths than the values shown in **Figure 24**. There was a concentration of severe charring that caused a hole at the bottom of the CLT shaft beside the column C104, as shown in **Figure 25** (e) and (g).


(a) Bay 1 – after test
(b) Bay 1 – ceiling-pipe penetration after test
(c) Bay 2 – at 3 hours 40 min during test
(d) Bay 2 – at 12 min after end of test
(e) burnt hole through CLT shaft beside C104
(f) Bays 2~4 – during post test operations
(g) closer view of burnt hole through CLT shaft
(h) floor after gypsum cover removed

Figure 25. Photographs of Bay 1, Bay 2 and Bay 3 near or after the end of Test 5.

In the junction of the beam-to-column connection B203-C103-C202 and CLT ceiling panel butt joint between Bay 2 and Bay 3, smouldering continued for nearly three hours after the test. After several attempts to extinguish it with hose stream from below, this beam-column-ceiling junction still persisted smouldering. In the end, the smouldering had to be extinguished from the top on the second floor by removing the fire caulking from the floor butt joints and pouring a bucket of water into the junction. **Figure 26** (a) shows that the CLT butt joint was still hot (> 160 °C) nearly three hours after the end of the test on the unexposed side while **Figure 26** (b) shows the CLT butt joint (unexposed side of the ceiling) after the full extinguishment of the smouldering in the junction.

The main reason for deep charring in some joints and connections such as described above was believed to be that the firestop installation was compromised by the rainy weather during the construction – some firestop caulking was washed away by the rain during installation, compounded by the absence of normally used concrete toping on the floor/ceiling assemblies. The manually installed connection hardware and various mass timber products from different manufacturers/suppliers could not achieve the fit as good as those typically produced using the CNC technology with high precision. These negatively impacted the fire separation continuity of the floor/ceiling assemblies. Also, the perimeter walls of the test structure were not built as airtightly as normal buildings. Although steps were taken to remedy the issues after the construction, physical obstruction by the finished building elements prevented some joints from getting a complete seal. These incomplete seals would likely have allowed hot fire gases to move through and caused continuous smouldering at the joints, in addition to the absence of firefighting intervention during the four-hour long test. However, the issues were unique to the test structure only. For normal buildings, the CNC technology would be used in the production of the mass timber structural elements and the installation of connection hardware to provide tight fits, concrete topping would be poured on the floor assemblies and their building envelope would be airtight to limit air leakage and thermal transfer in order to meet the NECB.

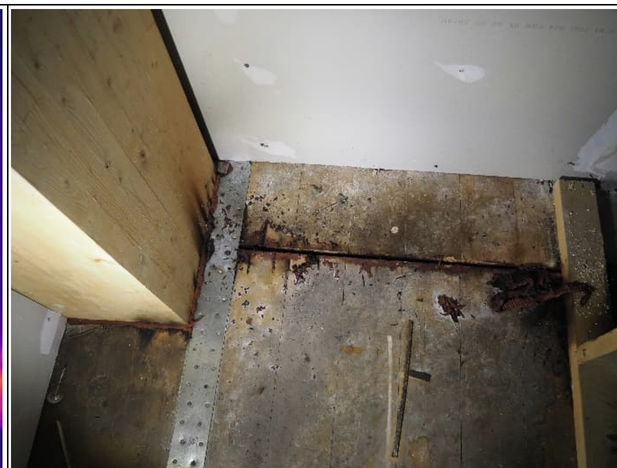
In the other junction of the beam-to-column connection B203-C106 and CLT ceiling panel butt joint as shown in **Figure 26** (c) and (d), the unexposed side on the second floor was only 40 °C at 50 min during the test and had only minor smoke deposition mark after the test.

On the protected CLT shear walls in Bay 4, the face layer gypsum board deformed but remained in place; the base layer gypsum board was not impacted by the fire and stayed well in place on the CLT panels. The CLT shear walls showed no fire damages after the gypsum board was removed as shown in **Figure 27** (a) and (b).

Several burnt pockets were developed at the junctions of the CLT ceiling panel butt joints and beam B203 in Bay 3 (see **Figure 27** (c) and (d)). Burnt holes were also produced at the junctions of the GLT ceiling panel butt joints and beams B204 and B206 in Bay 4 (see **Figure 27** (e) and (f)). The standard edge profile of GLT panel products created small triangle space in the butt joints, as illustrated in **Figure 28**. The ends of the GLT joints were not sealed during the construction but firestop caulking was added from the exterior side after the construction, which was far from an ideal seal; this was likely the main cause for the burnt pockets. Again, this issue was unique to the test structure only and would be unlikely to happen in the normal buildings where firestop would be applied to meet the NBC and the building envelope would be airtight to limit air leakage and thermal transfer in order to meet the NECB.

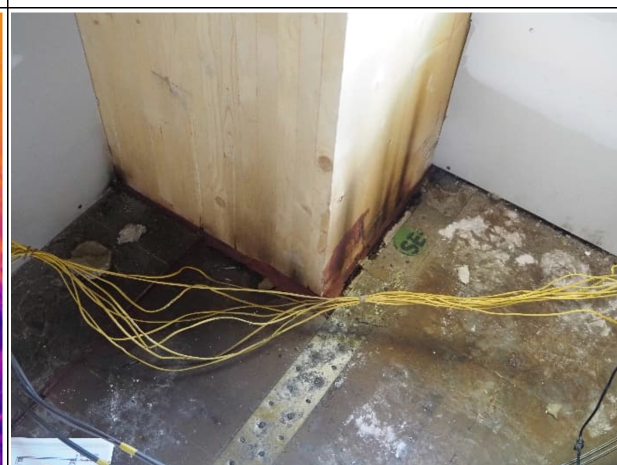
For the two pipe penetrations through the ceiling in Bay 1 and Bay 4, firestop sealant around the cast iron pipes had no visual changes on the unexposed (roof) side as shown in **Figure 27** (g) and (h) as well as **Figure 25** (b).

(a) hot spots at CLT butt joint sitting above B203 and connecting C103 and C202 (unexposed side of the ceiling panels) at 2 hours 50 minutes after the test



(b) CLT butt joint sitting above B203 and connecting C103 and C202 (unexposed side of the ceiling panels) after full extinguishment by manually removing the caulking and pouring water into the butt joint at 3 hours after the test

(c) hot spots at CLT butt joint sitting above B203 and connecting C106 at 50 min during the test (unexposed side of the ceiling panels)



(d) CLT butt joint sitting above B203 and connecting C106 after the test and post fire operation (unexposed side of the ceiling panels)

Figure 26. CLT-CLT butt joint and connection with columns on non-fire side in Test 5.

Figure 27. Photographs of Bay 3 and Bay 4 after Test 5.

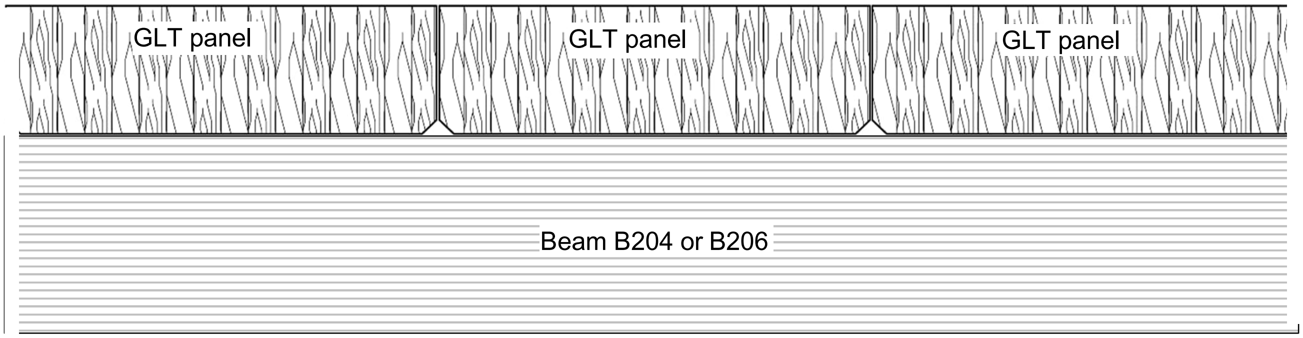


Figure 28. Butt joints of GLT panels with profiled edge supported on beams.

3.4 Test 5 Summary

Test 5 was conducted in a fully furnished open plan office space of 204 m^2 floor area with a total of 291 m^2 exposed mass timber surfaces of the columns, beams, ceiling and stair shaft wall. The office space was furnished with 18 working cubicles as the movable contents with the fuel load density of 362 MJ/m^2, which is believed to be above the average of today's fuel load density in the open plan offices.

By design, Test 5 represented a worst case scenario combining several severe testing conditions including the high fuel load, the aggressive ignition package, the rough openings with high ventilation and oxygen supply (instead of real windows), the absence of sprinklers, and the absence of firefighting intervention during the long test. The probability that all these conditions coincide would be extremely low in reality. It was under these severe conditions that Test 5 was conducted in order to uninterruptedly demonstrate the fire dynamics and performance of the mass timber structure.

The initial fire growth, from ignition to flame impingement on the ceiling, took 3 min 40 s, which was greatly accelerated by the aid of the aggressive ignition package and the high ventilation openings. If a less aggressive ignition conditions had been used, the initial fire growth would have taken a longer time for the flame to build up the height to reach the ceiling.

Once the flame impinged on the ceiling above the ignition location, the fire spread across the exposed mass timber ceiling within 2 min at the average speed of 140 mm/s. Then, the radiative heat from the ceiling flame set off the fire across the cubicles consecutively at the average speed of 100 mm/s. The use of the aggressive ignition package likely accelerated the speed of fire spread across the ceiling by 50%. Also, if real windows had been used, it would have taken some time for heat to build up to break the window glass in order to obtain enough oxygen for combustion.

The entire open plan office (floor to ceiling) was fully involved in the fire from 7 to 18 min. Fire dynamics in this large open plan office space exhibited the highly heterogeneous temperature distribution. The spatial temperature differences were significant with up to 400 °C temperature differences across the upper layer and with the temperatures at the mid heights greater than the ceiling.

Large fire plumes were issued out of the window openings, extending as high as 7.5 m and as long as 10 m. The peak heat fluxes reached up to 50 kW/m^2 at 3.5 m above the window openings on the exterior facades, up to 58 kW/m^2 at 3 m away and 39 kW/m^2 at 4.5 m away from the window openings.

The fire started to decay after 18 min. The flaming combustion was ceased by 21 min on the ceiling, beams, columns and shaft wall and by 30 min in the cubicles with only glowing debris on the floor. The glowing debris was completed consumed by 60 min.

During the subsequent three hours, the office space was continuously cooled down but smouldering persisted in several mass timber joints and the temperatures in the mass timber connections followed an ascending trend due to the thermal lags in the mass timber elements. The CLT ceiling panels near the shaft experienced localized delamination after 190 min, which did not cause re-ignition nor fire regrowth. The test was terminated at 250 min.

The general char depths in the mass timber members were well within the design allowance for the structural members of 2-hour fire-resistance rating designed according to CSA O86-19. The averaged char depths were 24 mm for the ceiling panels, 29 mm for the beams, 39 mm for the columns and 42 mm for the stair shaft panels, with the vertical mass timber members charred more than the horizontal members.

However, deeper charring due to smouldering was observed at several locations, especially at joints and connections. There were also deep burnt pockets at several junctions of the ceiling panel butt joints on top of the beams and at the bottom of the CLT shaft beside the column. It was believed that the firestop installation was compromised by the rainy weather during the construction – some firestop caulking was washed away by the rain during installation, compounded by the absence of normally used concrete toping on the floor/ceiling assemblies. The manually installed connection hardware and various mass timber products from different manufacturers/suppliers could not achieve the fit as good as those typically produced using the CNC technology with high precision. These negatively impacted the fire separation continuity of the floor/ceiling assemblies. Also, the perimeter walls of the test structure were not built as airtightly as normal buildings. Although steps were taken to remedy the issues after the construction, physical obstruction by the finished building elements prevented some joints from getting a complete seal. These incomplete seals would likely have allowed hot fire gases to move through and caused continuous smouldering at the joints, in addition to the absence of firefighting intervention during the four-hour test. However, the issues were unique to the test structure only. For normal buildings, the CNC technology would be used in the production of the mass timber structural elements and the installation of connection hardware to provide tight fits, concrete topping would be poured on the floor assemblies and their building envelope would be airtight to limit air leakage and thermal transfer in order to meet the NECB.

The test structure was very stable and solid after enduring more than four hours of severe fire testing. The post test operations were devoted to tackle hidden hot spots in some mass timber joints and connections by the Ottawa Fire Services and NRC staff. These hot spots were fully extinguished by the post test operations. Subsequent fire watches observed no more hot spots or smouldering.

4 COMPARATIVE RESIDENTIAL ROOM TESTS

One of the MTDFTP tasks was to compare the fire performance of a mass timber residential suite consisted of some exposed mass timber elements with a building of noncombustible construction including combustible interior finishes as permitted by the NBC. One of the 7.3 m × 7.3 m bays on the second storey was divided into two studio residential suites (A and B), each studio suite with interior floor dimensions of 3.2 m × 7.0 m.

Lightweight steel studs along with mineral wool insulation and 15.9 mm Type X gypsum board were used to construct a non-loadbearing wall between Suite A and Suite B (see **Figure 29**). Since this suite separation wall would be exposed to severe fire exposure twice (one from each side), it was constructed using two S2a walls listed in NBC 2020 Division B Table A-9.10.3.1.A. This double-wall suite separation (two S2a walls attached together as one assembly) provided a combined 2-hour fire-resistance rating.

4.1 Test 1: Baseline – Building of Noncombustible Construction (Residential)

Test 1 involved a fire in a fully furnished residential suite as a baseline scenario representing an acceptable solution of the NBC 2020 (e.g., a code-prescribed solution of noncombustible construction). The purpose of this test was to provide results for comparison to a similar fire (Test 2) within a residential suite of mass timber construction that includes both exposed and protected mass timber elements.

Test 1 was conducted in Suite B. All mass timber structural elements (CLT ceiling, floor and stair shaft wall) inside Suite B were protected with two layers of 15.9 mm Type X gypsum board to prevent their involvement in the fire, simulating a baseline scenario for a building of noncombustible construction including combustible interior finishes as permitted by the NBC 2020 for the comparison purpose.

This baseline test involved the use of combustible interior linings on the ceiling and three interior walls over the gypsum board (except the exterior wall with the opening). One layer of 25 mm thick plywood was used as the combustible lining on the walls, and two layers of 12.7 mm thick fire retardant treated plywood (flame-spread rating ≤ 25) on the ceiling. The combustible finishes were 22.2 m^2 on the ceiling and 49.5 m^2 over the walls for a total of 71.7 m^2 surface area in Residential Suite B.

4.2 Test 2: Exposed Mass Timber Construction (Residential)

Test 2 involved a fire in a fully furnished residential suite (Suite A) of mass timber construction which included exposed mass timber columns, beam and ceiling. The purpose of this test was to provide results for comparison to a similar fire (Test 1) within a residential suite constructed to be representative of noncombustible construction, and to demonstrate the fire performance of exposed mass timber in a realistic occupied residential scenario as well as to showcase the outcome of using greater exposed surfaces of mass timber elements than allowed by the NBC 2020 Division B, Article 3.1.6.4.

The exposed mass timber surfaces involved 22.6 m^2 on the ceiling, 3.1 m^2 over the columns, and 4.2 m^2 over the beam for a total of 30.0 m^2 exposed mass timber surfaces. The mass timber ceiling surface was entirely exposed (100% of the total ceiling area) in the suite. The aggregate surface area of the exposed mass timber beam and columns was equal to 12% of the total wall area of the perimeter of the suite.

The mass timber shaft wall was encapsulated (protected) in the suite side with two layers of 15.9 mm Type X gypsum board. The mass timber floor was encapsulated (protected) by two layers of 15.9 mm Type X gypsum board, instead of normally used concrete toping.

Figure 29 and **Figure 30** show the two residential suites along with the arrangement and location of the furnishings used in Test 1 and Test 2.

4.3 Fuel Load and Ignition

Test 1 and Test 2 used an identical movable fuel load. The movable fuel load represented residential contents in a studio apartment with sleeping, living and kitchen areas. The furnishings included a queen size bed with “mattress” and wooden bedframe and large storage drawers underneath, night table, dresser, bookcase, “upholstered sofa”, coffee table, multipurpose table and chairs, and kitchen counters and cabinets. The “upholstered sofa” and coffee table were simulated with two 50-kg wood cribs as described in the following paragraph. The “mattress” was replaced by thin wood sticks with equivalent calorific value; a cotton flat sheet was used to cover the bed. All other items were real consumer furniture. Plywood sheets were laid on a portion of the floor on top of the gypsum board to simulate an engineered wood flooring. The movable fuel contents had a fuel load density (FLD) of 613 MJ/m^2 in the studio suite.

Each of the two 50-kg wood cribs simulating the “upholstered sofa” and coffee table consisted of 38 mm × 89 mm × 800 mm SPF lumber pieces in rows of six stacked to 712 mm high (8 layers high) [21]. One of the wood cribs was ignited from underneath with 1000 mL of methanol in shallow metal pans (the heat output of this methanol ignition source was 40 kW approximately). A method was developed to ignite the crib remotely. Three small model rocket engines (small propulsion packs) were inserted in the wood crib. Once remotely activated, the rocket engines sent torch flames onto the pans below to ignite the methanol, which in turn ignited the wood crib. (Note: a propane torch was used in Test 2 for manual ignition due to malfunction of the small rocket engines.)

The fuel load consisted of essentially the same furniture package as used in NRC’s CLT compartment fire studies conducted for NFPA’s Fire Protection Research Foundation [28]. The same sets of the furniture were also subsequently used in the US and Sweden’s studies [29, 30]. The FLD used in Test 1 and Test 2 is 10% higher than these three previous mass timber studies (i.e., 10 % higher than the average residential FLD).

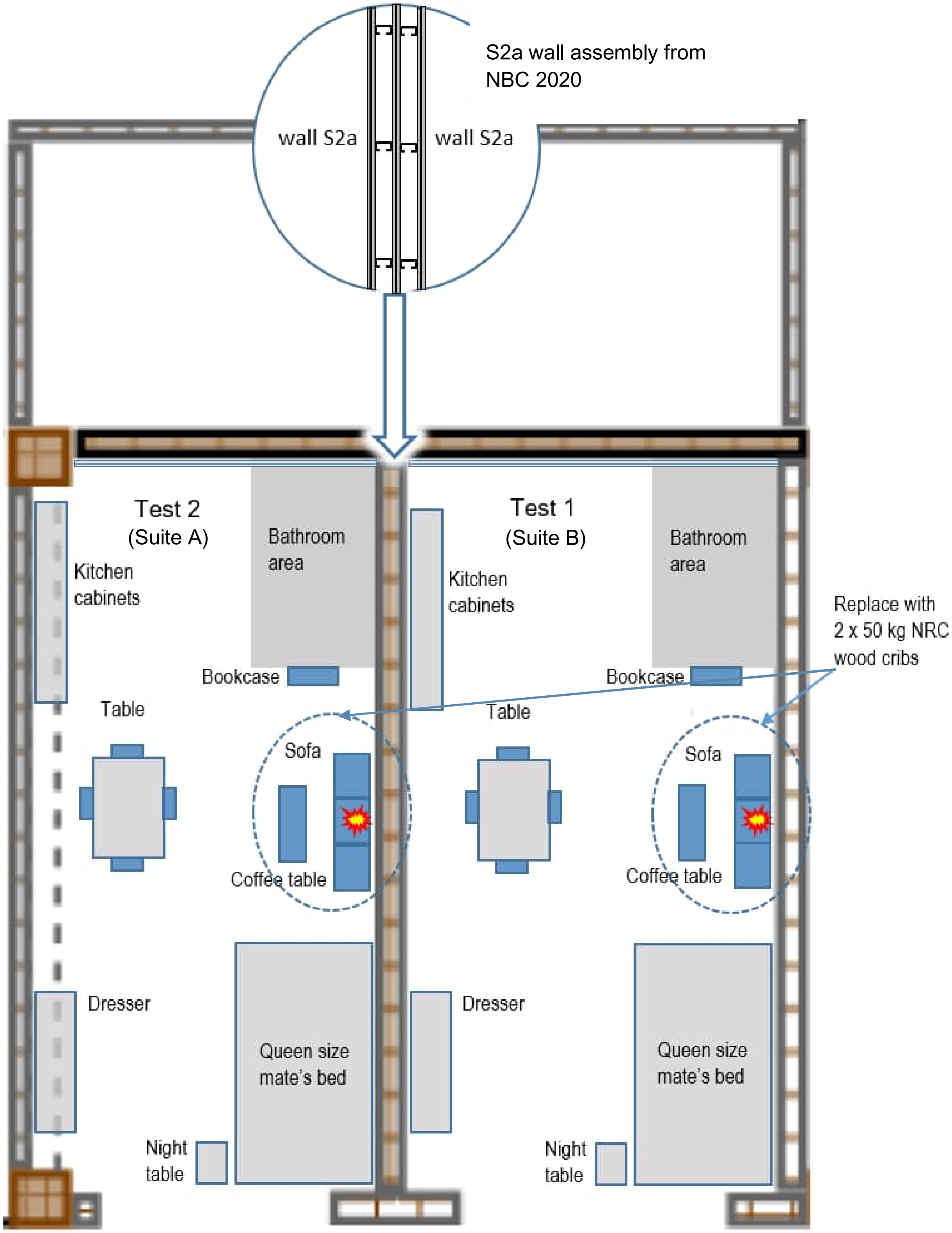


Figure 29. Studio suites and fuel load for Test 1 and Test 2.

Mass Timber Room for Test 2 with exposed ceiliing, beam and columns	Baseline Room for Test 1 with plywood lining on ceiling and walls

Figure 30. Furnished studio suites for Test 1 and Test 2.

4.4 Instrumentation and Measurement

Thermocouples, heat flux meters, video cameras, disposable cameras and infrared cameras were installed inside and outside each studio suite for measurements. **Figure 31** and **Figure 32** show a layout of the thermocouples and heat flux meters for Test 1 and Test 2.

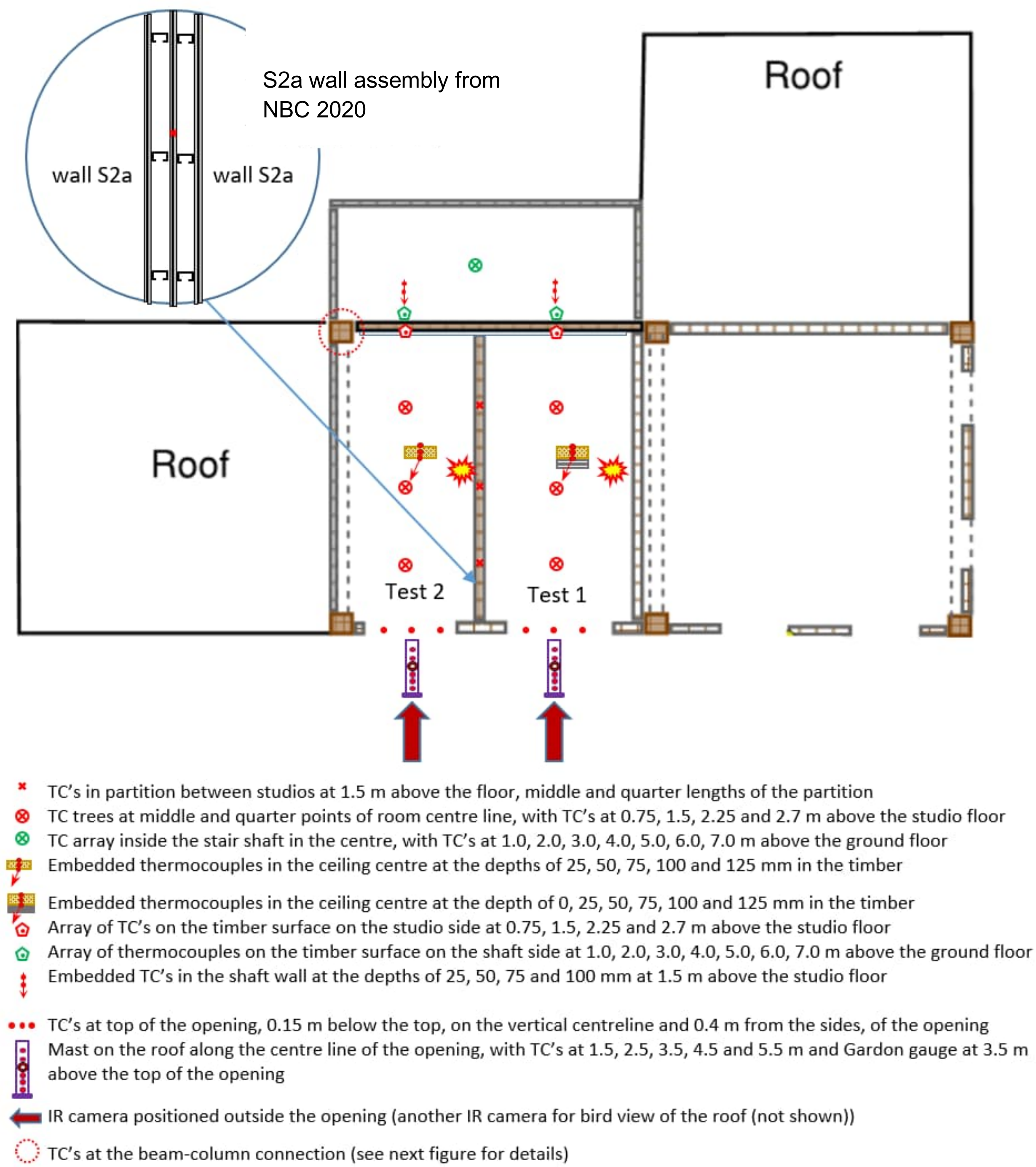


Figure 31. Instrumentation for Test 1 and Test 2.

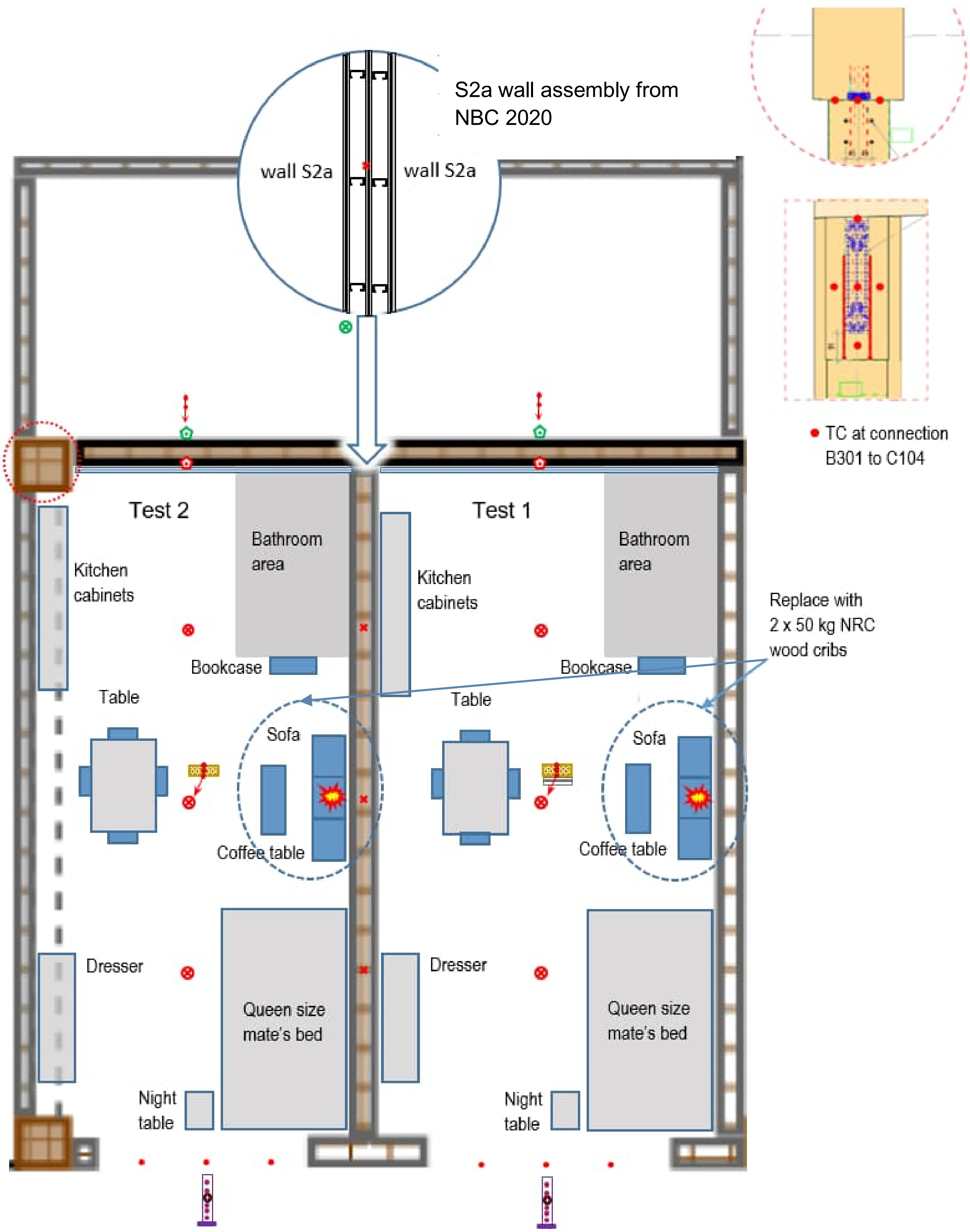


Figure 32. Instrumentation and fuel load for Test 1 and Test 2.

- Three (3) thermocouples were installed in the wall separating the studio suites on the contacting surface of the two S2a walls at 1.5 m above the studio suite floor at the middle and quarter lengths of the suite separation wall.
- Three (3) thermocouple trees were installed at the middle and quarter points of the studio suite centreline to measure compartment temperatures. Each thermocouple tree had four (4) thermocouples at 0.75 m, 1.5 m, 2.25 m and 2.7 m above the floor. These thermocouples were type K stainless steel sheathed thermocouples shielded from radiative heat for measuring gas phase temperature.
- Five (5) thermocouples were embedded in the centre of the ceiling at the depths of 25, 50, 75, 100 and 125 mm in the mass timber, which coincided with the middle thermocouple tree. All holes drilled to install the thermocouples were sealed to maintain the integrity of the mass timber panels. These thermocouples were used to monitor the ceiling assembly. (For Test 1 only, one additional thermocouple was embedded at the interface between the mass timber and gypsum board.)
- An array of four (4) thermocouples were installed at the interface between the base layer gypsum board and mass timber shaft wall at 0.75 m, 1.5 m, 2.25 m and 2.7 m above the floor to monitor the interface. All holes drilled to install the thermocouples were sealed to maintain the integrity of the mass timber panels.
- Four (4) thermocouples were embedded in the mass timber shaft wall at the depths of 25, 50, 75 and 100 mm in the timber at 1.5 m above floor, whose height coincided with or was in close proximity to the two of the surface thermocouples on both sides of the mass timber shaft wall. All holes drilled to install the thermocouples were sealed to maintain the integrity of the mass timber panels.
- Three (3) thermocouples were installed at the window opening to measure the temperature of the flame issuing from the opening. The thermocouples were located 0.15 m below the top of the opening on the vertical centreline and at 0.4 m from each side of the opening.
- A mast with five (5) thermocouples and one Gardon gauge was placed on the roof along the vertical centreline of the window opening to measure the exterior upward fire spread. The thermocouples were located at 1.5 m, 2.5 m, 3.5 m, 4.5 m and 5.5 m, and the Gardon gauge was located at 3.5 m, above the top of the opening.
- One infrared camera was positioned to look through the window opening to provide data and visual thermographs on temperature build up and stratification from ceiling to floor.
- Various video cameras were positioned inside and outside the suite to capture images of the test.
- For Test 2 only, five (5) thermocouples were installed at the connection where beam B301 (265 mm × 494 mm) met column C104 (406 mm × 413 mm). **Figure 32** shows the installation details of the thermocouples at the connection for Test 2, which were located 80 mm from the exposed faces of the beam.

The tests also made the use of the three vertical thermocouple arrays that had already installed inside the stair shaft, including:

- A thermocouple array was installed inside the stair shaft in the centre, with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor level of the ground storey.

- Two thermocouple arrays were installed on the mass timber surface in the exit stair at the quarter lengths, each with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor level of the ground storey.

4.5 Results and Comparison of Test 1 and Test 2

Test 1 was conducted on July 7, 2022 with the southeast wind of 3 km/hour and ambient temperature of 21.6°C. The test started with ignition at 9:28 a.m. and terminated at 1:32 p.m. with data recording for 4 hours 4 minutes.

Test 2 was conducted on July 14, 2022 with the northwest wind of 5 km/hour and ambient temperature of 17.2°C. The moisture content of the mass timber structural elements was in the range of 8.5-10.2% with an average of 9.5% ± 0.5%. The test started with ignition at 9:14 a.m. and terminated at 1:23 p.m. with data recording for 4 hours 9 minutes.

There was neither sprinkler presence during the test nor firefighting intervention until the end of the two tests.

4.5.1 Fire Development

The fire development was very similar between Test 1 and Test 2. **Figure 33** shows some pictures of the ignition and initial fire development during Test 1 and Test 2. One of the wood cribs simulating the sofa was the first item ignited from underneath. In each test, the flame took over 2 min to emerge from the crib. After that, the flame quickly grew upward and then impinged on the ceiling above the crib. The ceiling was ignited at 3 min 45 s and 3 min 30 s in Test 1 and Test 2, respectively. Flames exited from the top of the window openings shortly after 4 min. Flashover occurred at 4 min 48 s in Test 1, and at 4 min 44 s in Test 2, respectively, involving all room contents and plywood lining or exposed mass timber.

Large fire plumes issued from the window opening after the flashover. **Figure 34** and **Figure 35** are the exterior view of the fire development during Test 1 and Test 2, respectively. Test 1 had larger fire plumes than Test 2 especially in the period of 20 min to 27 min, and the size of the plumes decreased much earlier in Test 2 (at 20 min) than in Test 1 (at 26 min) because the plywood interior lining in Test 1 (representing the code-prescribed noncombustible construction scenario) was more than double the exposed mass timber surface in Test 2. The fire plumes ceased to issue to the outside after 28 min and 27 min in Test 1 and Test 2, respectively. By these times, the fire had decayed significantly and all room contents had been reduced to debris on the floor.

Figure 36 shows some pictures during the decay stage of the fire during Test 1 and Test 2. At 30 min, the debris on the floor was still burning in both tests; Test 2 had less vigorous flames of the debris but some small flames still on the exposed mass timber ceiling, beam and columns. By 45 min, there was no more visible flaming on the mass timber in Test 2; afterwards small flickers occurred intermittently at the back left corner on the ceiling and beam, partly due to the flaming of the remaining debris below on the floor at that corner. The debris of the two tall kitchen cabinets at the back left corner in the room kept burning for a long time in both tests. Test 1 certainly had much more glowing embers on the floor because of a large quantity of debris from the plywood interior lining, which persisted until the end of the 4-hour test. Towards the end of Test 2, there was almost no glowing embers on the floor but the ceiling at the back left corner had frequent small flames. There was also visible intermittent smoke from the exterior front corner during the decay stage in Test 2.

Figure 33. Comparing Test 2 with Test 1 – Initial fire development.

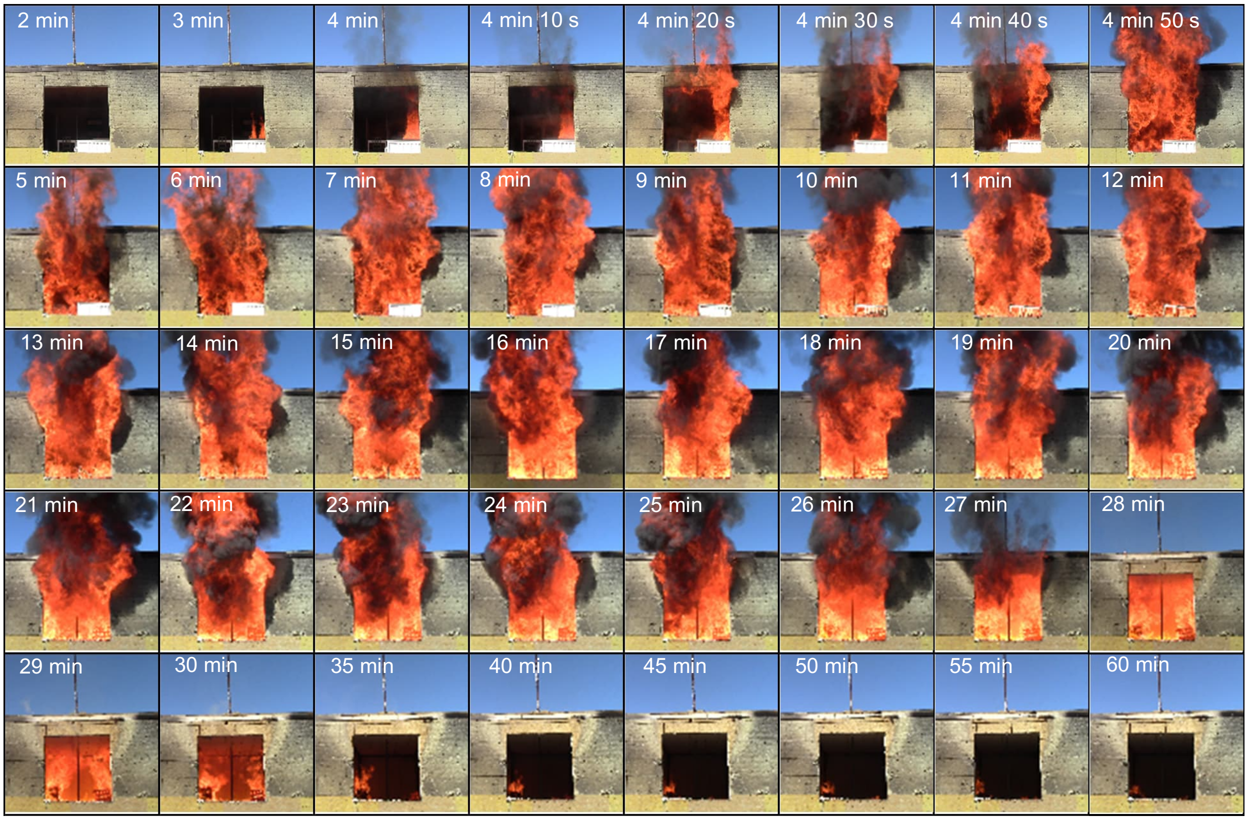


Figure 34. Exterior view of fire development during baseline Test 1.

Figure 35. Exterior view of fire development during mass timber Test 2.

Figure 36. Comparing Test 2 with Test 1 – Decay stage of the fire.

The room temperatures measured using the thermocouple trees are presented in **Figure 37**. Related to the flashover time, the hot layer temperatures at the 2.25 m height reached 600 °C at 4 min 29 s on the front tree and 4 min 53 s on the back tree in Test 1, and at 4 min 20 s on the front tree and 4 min 52 s on the back tree in Test 2, which are consistent with the observed flashover times when the entire room involved in the fire. During the fully developed fire stage, the room reached the peak temperatures of 1200 °C in both tests. The vertical temperature differences on each thermocouple tree were relatively small while the lateral temperature differences across the room were larger during the fully developed fire stage in both tests. As shown in **Figure 37**, the back tree reached the peak temperatures up to 10-15 min later than the front and middle trees, indicating that in both tests the fuel contents in the front area of the room dominated the combustion first while the back area dominated later. This was due to the ventilation-controlled conditions, i.e. the availability of oxygen supply controls the combustion process. The fire started to decay earlier and quicker in Test 2 (at 25 min) than in Test 1 (at 30 min), with the compartment temperatures decreased continuously to below 200° C by the end of these two tests.

Given that both tests had the ventilation-controlled fire in the fully developed stage, the heat release rate was estimated by assuming 70% combustion efficiency and using the approximation: $HRR = 0.7 \times 1.56 \times A_o \times \sqrt{H_o}$, where A_o is the area (m^2) and H_o the height (m) of the opening [31]. The estimated heat release rate was at least 8 MW in both tests with the window opening of 2.2 m × 2.2 m. The actual heat release rates would likely be greater since there was extensive exterior burning. Test 1 would likely have a greater heat release rate than Test 2 since the combustible interior lining was more than double the exposed mass timber surface, causing Test 1 to be more under-ventilated inside with more vigorous exterior combustion.

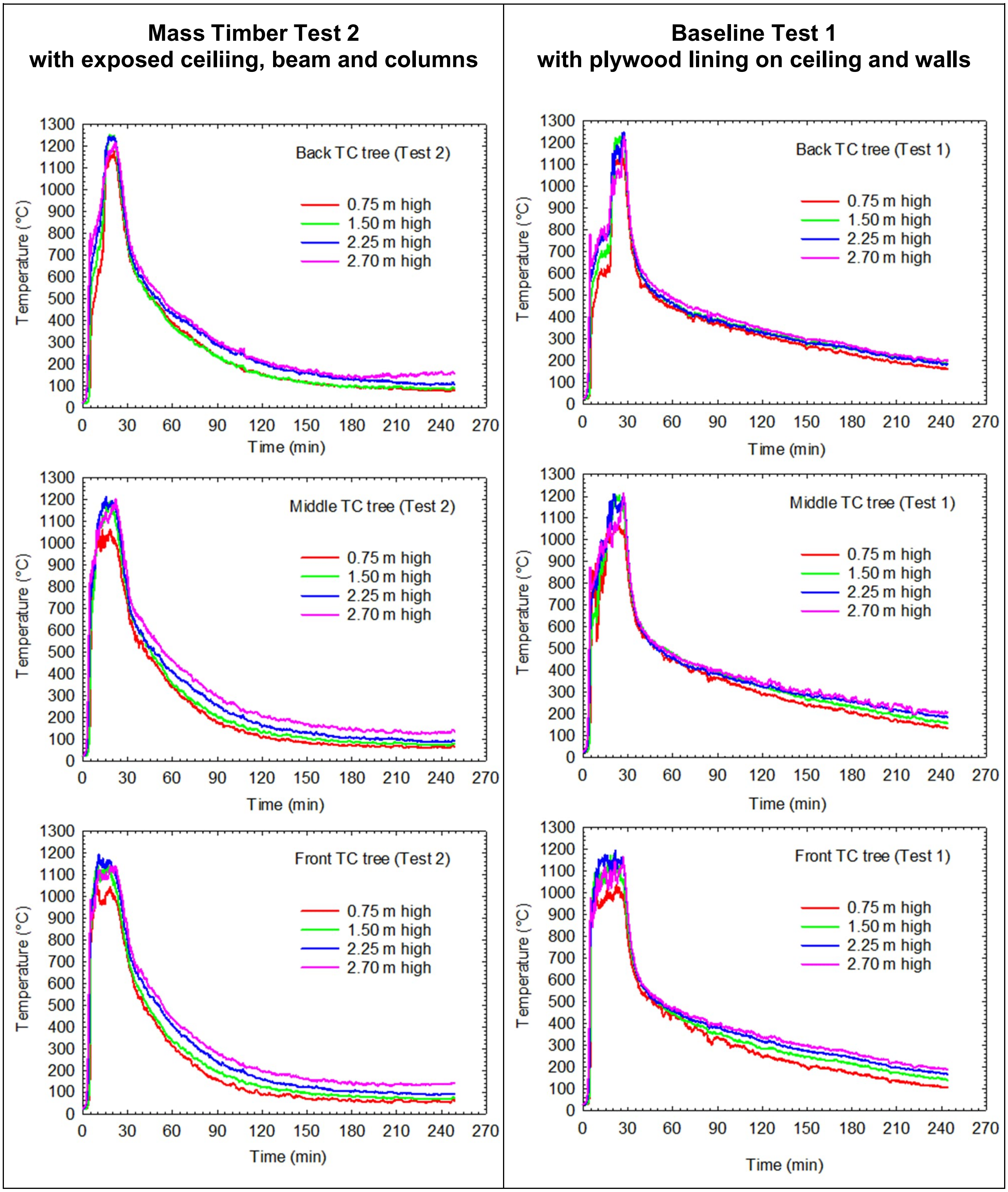


Figure 37. Comparing Test 2 with Test 1 – Room temperatures.

4.5.2 Fire Impact on Structural Elements

4.5.2.1 Protected structural elements

As shown in **Figure 36**, two layers of gypsum board remained in place on the protected walls and ceiling in Test 1, probably because the plywood lining over the gypsum took on most of the heat exposure. While the base layer gypsum board stayed on the protected walls in Test 2, the face layer gypsum board was disintegrated with a section falling off during the test.

After the tests, the remaining gypsum board was removed from the protected structural elements. **Figure 38** and **Figure 39** reveal the state of the protected structural elements.

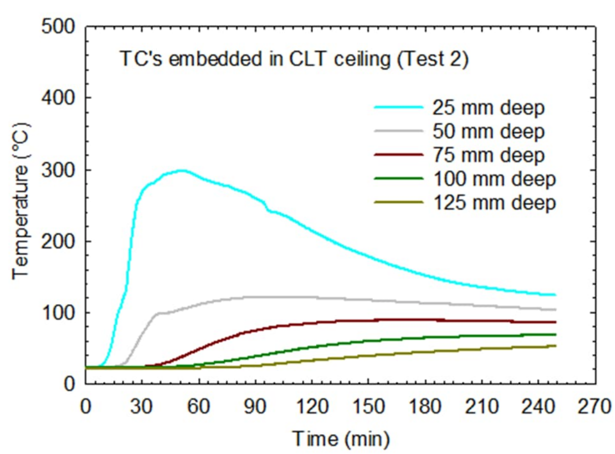
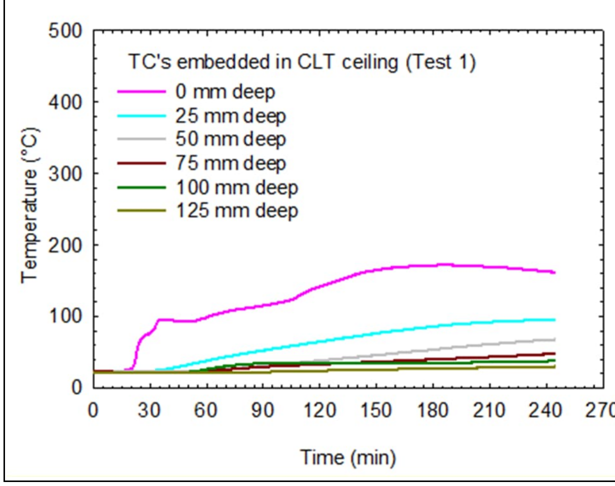
Mass Timber Test 2	Baseline Test 1
	
gypsum board removed after Test 2 from the protected CLT wall	gypsum board removed after Test 1 from the protected ceiling and walls
	

Figure 38. Comparing Test 2 with Test 1 – Charring on mass timber elements and temperatures in CLT ceiling.

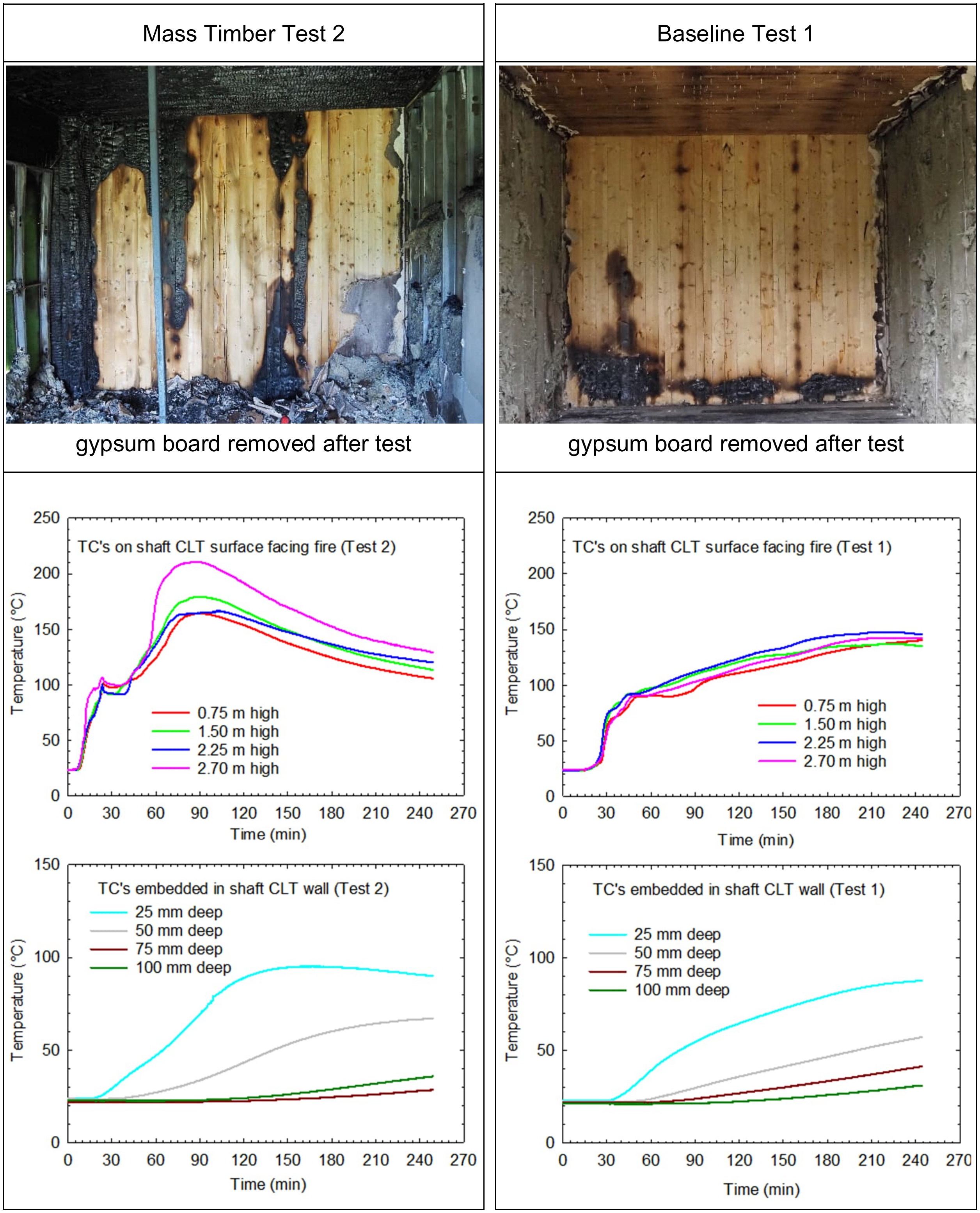


Figure 39. Comparing Test 2 with Test 1 – Temperatures in CLT shaft panels and charring behind gypsum board.

In the Test 1 room, the CLT ceiling and most part of the CLT shaft wall had a few slightly darken marks along the gypsum seams and screw spots. The temperatures measured at the CLT-gypsum interfaces were below 170 °C and the temperatures inside the CLT were even lower. There was some surface charring (up to 4 mm) at the bottom of the CLT shaft wall due to the persisted glowing embers on the floor at the back of the room. This minor charring should have negligible effect on the fire dynamics of this baseline test, which was intended to represent a fire scenario in a building of noncombustible construction.

In Test 2, the temperatures measured at the shaft CLT-gypsum interfaces were up to 210 °C and the temperatures inside the CLT were much lower. However, the protected CLT shaft wall charred more along the gypsum seams and screw spots than in Test 1. There was also some charring at the top left corner on the CLT shaft wall near the ceiling and column C104 due to the frequent small flames on the ceiling at the back left corner.

The CLT floor assembly endured the fire exposures from both sides in multiple fire tests. The preceding Test 5 already created deeper charred pockets along the junction of the CLT floor/ceiling assembly with the shaft wall from the underside. During Test 2, a hole was completely burnt through the CLT junction from above as the result of the combined fire exposures from Test 2 and Test 5, as shown in **Figure 40**.

(a) hole in CLT floor-shaft junction (gypsum board removed from the shaft wall and floor)

(b) zoom into the junction

(c) hole in CLT floor-shaft junction (underside)

(d) zoom into the junction (underside)

Figure 40. Effect of 2-side exposures after both Tests 2 and 5 on CLT floor and shaft junction.

In addition to the two-sided fire exposures and the absence of firefighting intervention during the two long tests (Test 2 and Test 5), the rainy weather during the construction likely compromised the integrity of the firestop installation which was compounded by the absence of normally used concrete toping on the floor/ceiling assembly. The incomplete seal allowed hot fire gases to move through and caused the hole at the floor-wall joint. However, the issue was unique to the test structure only. For normal buildings, firestop would be applied in compliance with the NBC requirement, and concrete topping would be poured on the floor assemblies to limit the hot gas movement and convection heat transfer through the joint.

4.5.2.2 Exposed mass timber elements

During Test 2, the peak temperatures measured inside the exposed CLT ceiling were 300 °C at 25 mm deep, 120 °C at 50 mm deep and below 90 °C at 75-125 mm deep (see data plots for Test 2 in **Figure 38**), which implies 25 mm < the ceiling char depth < 50 mm. The maximum temperatures at 25 mm deep were reached at around 50 min and then started to decrease, dropping to about 130 °C at the end of the test.

The char measurements using Resistograph were conducted on the ceiling, beam B301, columns C104 and C201 after Test 2. The char depths were measured with a spacing of 1.8 m across the ceiling and along the beam on the two exposed sides, and at 0.75 m, 1.5 m and 2.25 m high along each column on the two exposed sides. **Figure 41** shows schematically the char depths. For the beam and columns, each location involved two drillings perpendicular to each other to determine the char depths on the two exposed sides. The char depths in the ceiling are consistent with the embedded thermocouple measurements inside the CLT.

Most of the measured char depths are well within the design allowance for 2-hour rated structural elements according to CSA O86-19. Only the bottom side of beam B301 and the room-facing side of column C201 developed 90-95 mm char depth near the design limit at a few locations. The averaged char depths were 40 mm for the ceiling panels, 70 mm on each exposed side for the beam, 57 mm and 67 mm on each exposed side for columns C104 and C201, respectively.

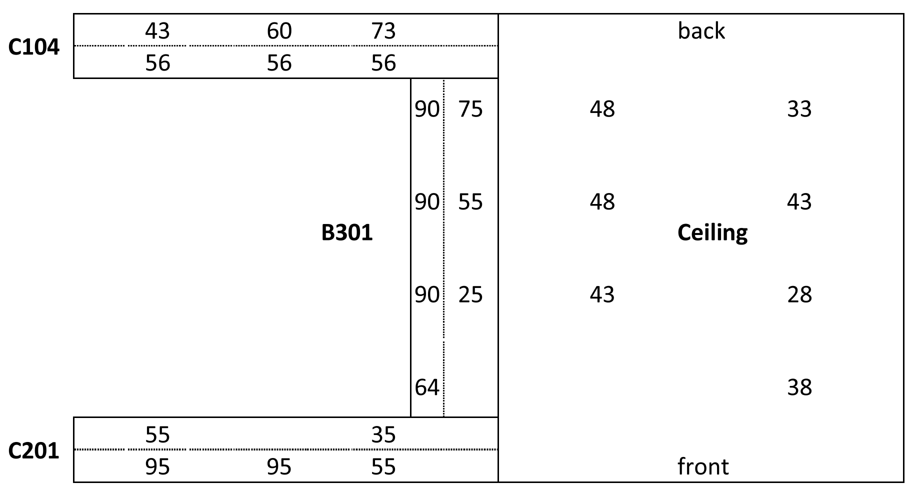


Figure 41. Char depths (mm per exposed side) **on ceiling, beam and columns in Test 2.**

Deeper charring occurred at several locations. **Figure 42** shows the B301-C201 beam-column-ceiling connection in/on the front left corner from Test 2. This joint/connection continued smouldering during the test. The CLT ceiling panel in this corner charred away 143 mm with only 70 mm of wood remaining. The fire burnt through between the beam and column connection, leaving a large hole in-between, and the metal connector was visible from both interior and exterior. The cross section of the top portion of the column was reduced from 395 mm × 395 mm to 300 mm × 275 mm (charred away 95 mm and 120 mm respectively). The column also lost 160 mm in height, leaving a 300 mm gap between the column and the charred ceiling in the corner. This continuous smouldering was likely related to the compromised firestop installation in the construction phase. A single bead of firestop caulking had been applied in the joint between the CLT ceiling panel and the top of the column, which seemed inadequate for this corner geometry along with the negative impact of rain on the firestopping. A 5-mm gap had been spotted in the beam-to-column connection after the construction. The manually installed connection hardware and various mass timber products from different manufacturers/suppliers could not achieve the fit as good as those typically produced using the CNC technology with high precision. Although firestop calking was applied to fill the gap, it could not completely seal the connection due to the obstruction by the exterior wall. Also, the lightweight steel exterior wall assemblies were not built as airtightly as normal buildings (not well sealed in the joints with the mass timber beam, column and ceiling), providing passages for hot gases to move through and smouldering to continue during the 4-hour fire test and 1-hour post test operations. However, the issues were unique to the test structure only. Normal buildings would have the structural elements and connections tightly fitted using the CNC technology, and their envelope would be more airtight to limit air leakage and convection heat in order to meet the NECB.

Figure 42. Charring near the B301-C201 beam-column-ceiling junction from Test 2.

Figure 43 shows the temperatures measured using embedded thermocouples in the B301-C104 beam-column-ceiling connection (see **Figure 32** for details of embedded thermocouples) in the back left corner during Test 2 and a photograph after the test. For the most part of the test, the temperatures measured inside the B301-C104 connection were only up to 100 °C. Towards the end of the test, the bottom thermocouple embedded in the connection detected a quick temperature rise from 100 °C to 400 °C; this thermocouple was installed at 80 mm away from the bottom side of the beam B301, indicating heat being transferred deeper to the connection. The bottom side of the beam charred away 125 mm from the interior portion as determined by measuring the exposed lengths of the screws which were used to reinforce the beam for the installation of the metal connector. This again was mainly because the exterior lightweight steel stud wall assembly did not have airtight joints with the beam and column, allowing the hot gases to pass through and smouldering to continue. However, normal buildings would be more airtight to limit the leakage and flame paths.

Minor localized delamination from the CLT ceiling was observed during Test 2 as shown in **Figure 44**. The delamination nevertheless did not lead to re-ignition nor fire regrowth.

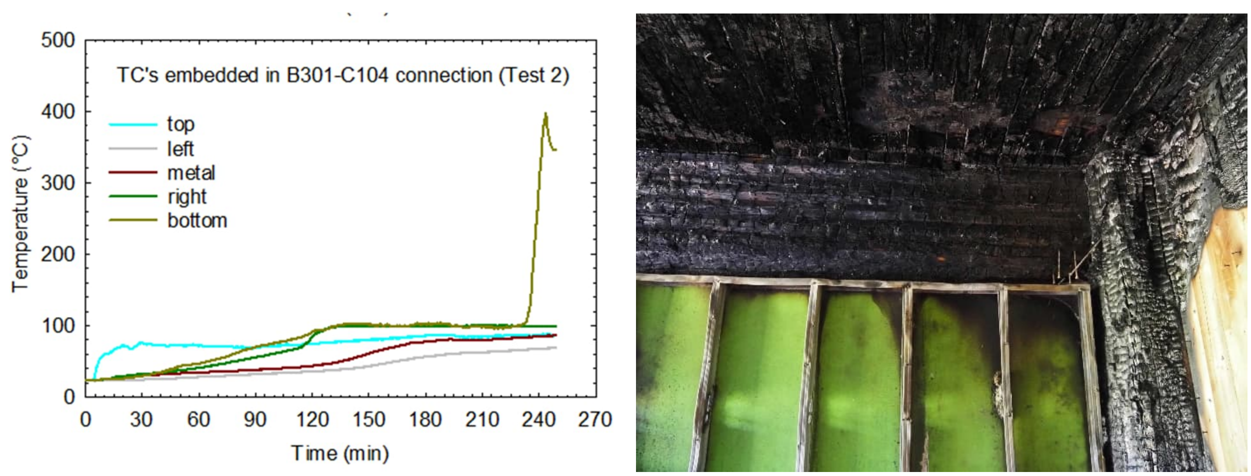


Figure 43. Charring and temperatures in ceiling-beam-column connection in Test 2.


Figure 44. Some delamination from CLT ceiling in Test 2.

4.5.3 Fire Exposure outside Fire Compartments

After the flashover during Test 1 and Test 2, large fire plumes were issued from the window opening. **Figure 45** compares the fire plumes between the baseline Test 1 (representing the code-prescribed noncombustible construction scenario) and the mass timber Test 2. The fire plumes were over 6 m high at around 8 min in both tests.

Figure 45. Comparing Test 2 with Test 1 – Fire plumes issued from openings.

The temperatures and heat fluxes measured at and above the openings are presented in **Figure 46**. The peak temperatures at the top edges of the openings were essentially the same between Test 1 and Test 2. However, Test 1 stayed at the peak temperatures longer than Test 2 since the plywood interior lining in Test 1 was more than double the exposed mass timber surface in Test 2.

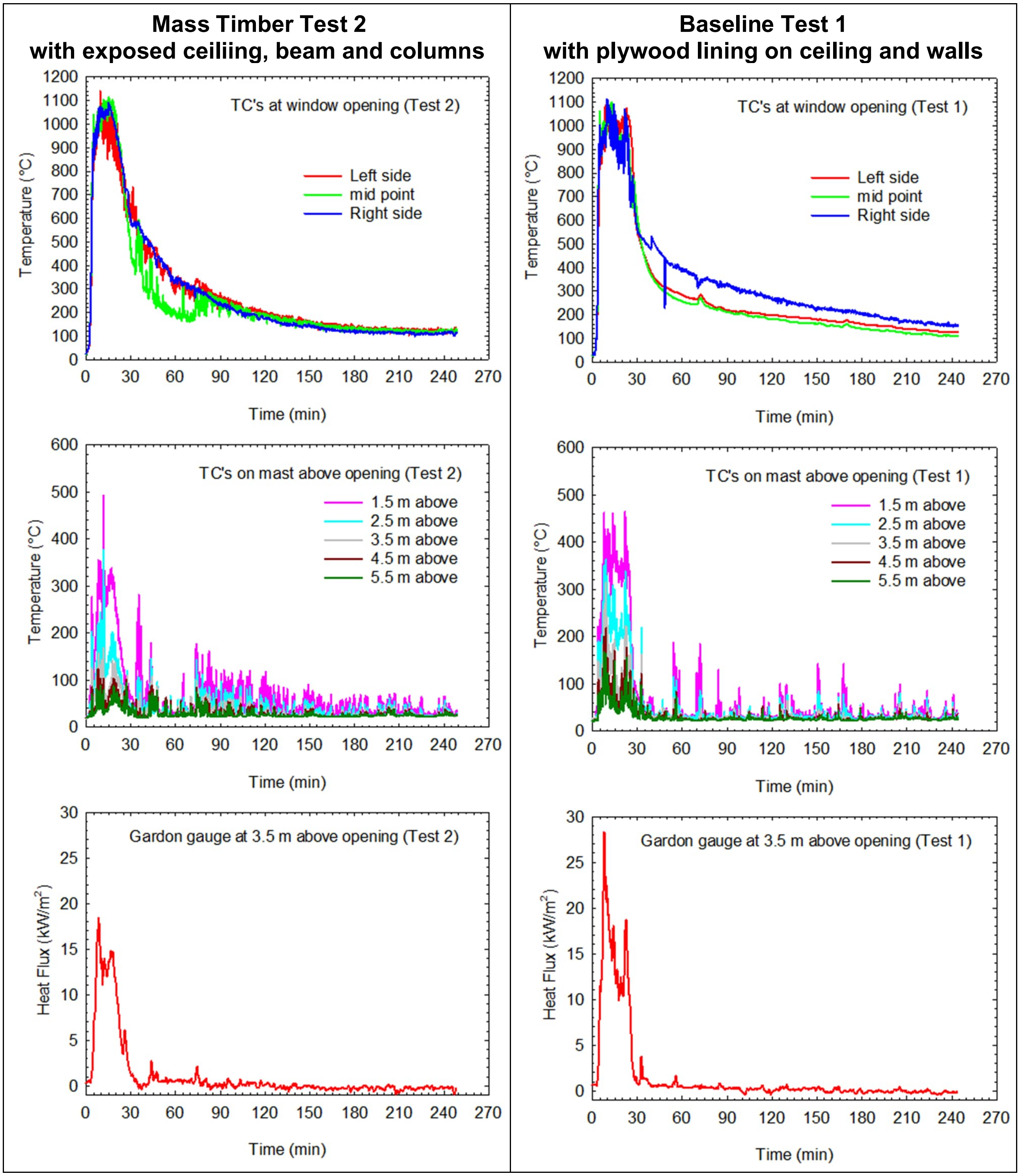


Figure 46. Comparing Test 2 with Test 1 – Temperatures and heat fluxes above openings.

Shortly after the flashover, the roof mast pole bowed back away from the plumes in both tests, which may have caused lower heat exposure being registered by the thermocouples and heat flux meters on the roof masts in both tests. In addition, due to the northwest wind in Test 2, the fire plumes were driven further away from the roof mast, resulting in less heat being received by the roof mast in Test 2 than in Test 1. The peak heat flux was 28.5 kW/m^2 in Test 1 and 18.5 kW/m^2 in Test 2.

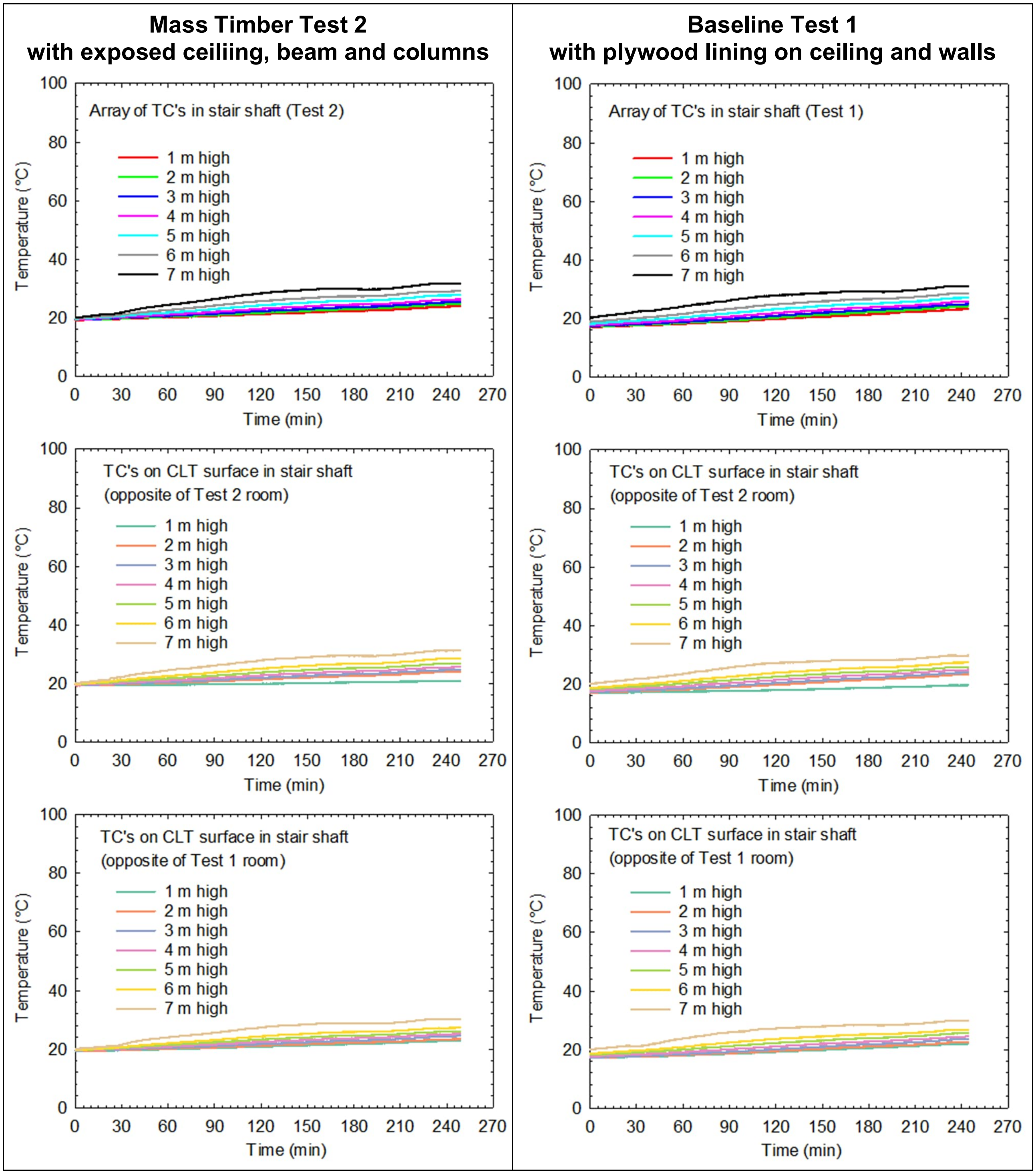


Figure 47. Comparing Test 2 with Test 1 – Temperatures in stairwell.

The temperatures in the stairwell are shown in **Figure 47** for both tests. All temperatures including the CLT surface in the stairwell were below 32 °C. The fires did not affect the conditions in the adjacent stairwell in both tests.

4.5.4 Post Fire Operations

After more than four hours of fire testing, both tests left hidden hot spots in the connections and/or junctions. The Ottawa Fire Services were deployed to tackle the remaining hot spots and to cool down the space after Test 1 and Test 2, involving interior and exterior operations (including the adjacent suites and the rooftop). These hot spots were fully extinguished by the post test operations. Subsequent fire watches observed no more hot spots or smouldering.

4.6 Test 1 and Test 2 Summary

Test 1 and Test 2 were conducted to compare the fire performance of the mass timber residential suite consisted of exposed mass timber columns, beam and ceiling with the noncombustible baseline and to showcase the outcome of using greater exposed surfaces of mass timber elements than allowed by the NBC 2020. Each test used a fully furnished residential suite of 22.4 m^2 floor area with the same room contents at the fuel load density of 613 MJ/m^2, which is slightly above the average fuel load density in modern residential suites. Test 1 simulated a code-prescribed noncombustible construction baseline room with combustible interior linings (25 mm thick plywood) on the three interior walls and two layers of 12.7 mm thick fire-retardant treated plywood on the ceiling, and the total combustible linings were 72.2 m^2. Test 2 involved exposed mass timber columns, beam and ceiling and the total exposed mass timber surfaces were 29.7 m^2.

In general, the fire development was very similar between Test 1 and Test 2. In both tests, flashover occurred at similar times (4 min 48 s in Test 1; 4 min 44 s in Test 2), and large fire plumes were issued from the window opening (over 6 m high) after the flashover. During the fully developed fire stage, the room reached the peak temperatures of 1200 °C in both tests. The vertical temperature differences at each location were relatively small, and the front part of the room dominated the combustion first while the back part of the room dominated later during the fully developed fire stage in both tests. The fire started to decay earlier and quicker in Test 2 (at 25 min) than in Test 1 (at 30 min). The compartment temperatures decreased continuously to below 200° C by the end of both tests. The estimated heat release rate was at least 8 MW for both tests. The actual heat release rates would likely be greater, should the extensive exterior burning have been accounted for. Test 1 was more under-ventilated inside with more vigorous exterior combustion due to the large amount of combustible interior lining and therefore would likely have a greater heat release rate than Test 2.

Both tests had small fires lingering in the decay stage until the end of the 4-hour tests. The debris continued to burn on the floor with glowing embers until the end of Test 1 due to the large quantity of combustible interior linings used. Test 2 had no sustained flaming on the mass timber elements after 45 min but small flickers kept occurring intermittently on the ceiling and beam. Localized delamination from the CLT ceiling was observed during Test 2, which nevertheless did not cause re-ignition nor fire regrowth.

The averaged char depths in Test 2 were 40 mm for the ceiling panels, 70 mm on each exposed side for the beam, 57 mm and 67 mm on each exposed side for the two columns. Deeper charring occurred near the connections and junctions. The test structure was not built as airtightly as normal buildings and also lacked sufficient firestopping, which allowed smouldering to continue in the joints and connections during the test. Firefighting operations were required after Test 1 and Test 2, respectively, in order to ensure that the hot spots were fully extinguished.

5 TEST 4: CONSTRUCTION SITE FIRE SCENARIO

Test 4 was designed to represent a construction site fire scenario with exposed mass timber floor, ceiling, beams and columns (beams and columns exposed on 2 or 3 sides). The purpose of Test 4 was to demonstrate the performance of exposed mass timber in a severe construction site fire scenario. As shown in **Figure 48**, Test 4 was conducted in the corner bay (Suite C) on the second storey involving an open space of 7.1 m × 7.5 m × 3.0 m high and representing a portion of a building under construction.

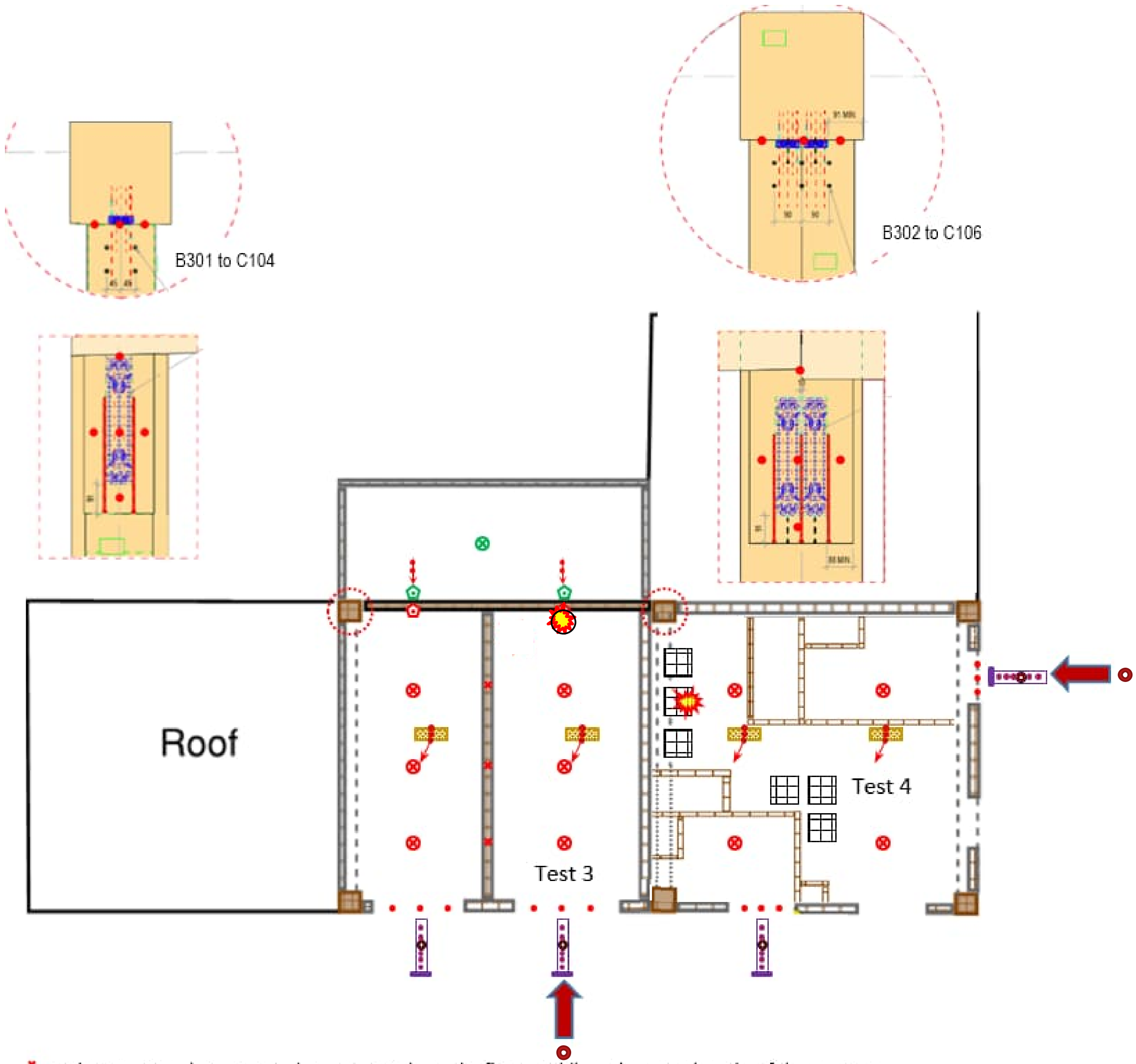
The exposed mass timber surfaces were 50.2 m^2 on the DLT ceiling, 52.5 m^2 over the CLT floor, 8.8 m^2 over the Glulam columns and 13.1 m^2 over the Glulam beams for a total of 124.6 m^2. The mass timber ceiling and floor surfaces were completely exposed (100% of the total area). The aggregate exposed surface area of the mass timber beams and columns was 25% of the total wall area of the perimeter of the suite.

The suite separation wall between Residential Suite B (Test 1) and Suite C (Test 4) was a single steel stud wall assembly with two layers of 15.9 mm Type X gypsum board on each side and mineral wool insulation in the stud cavity, providing a 2-hour fire-resistance rating in accordance with cUL Design No. U419.

5.1 Fuel Load and Ignition

To simulate a realistic scenario during construction of a residential unit, the fuel load included exposed 2×4 wood framing for interior walls (no gypsum board) and six large wood cribs (50 kg each). The wood cribs simulated combustibles building materials in the mass timber construction sites. Each wood crib consisted of 38 mm × 89 mm × 800 mm SPF lumber pieces in rows of six stacked to 712 mm high (8 layers high) [21]. The 2×4 wood framing was constructed using 300 kg of 38 mm × 89 mm SPF. The wood cribs and the exposed wood framing provided a fuel load density of 224 MJ/m^2 in addition to the exposed mass timber elements. **Figure 48** and **Figure 49** show the layout of the fuel load and the ignition location in the residential unit under construction. One of the wood cribs was ignited from underneath with 1000 mL of methanol in shallow metal pans.

Today's mass timber construction projects are dominated by prefabrication and do not have much other combustible products on site. Test 4 used a higher fuel load density than those typically found on the mass timber construction sites.



TC's in partition between studios at 1.5 m above the floor, middle and quarter lengths of the partition
TC trees at middle and quarter points of space, with TC's at 0.75, 1.5, 2.25 and 2.7 m above the 2nd storey floor
TC array inside the stair shaft, with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the ground floor
Embedded thermocouples in the ceiling at the depths of 25, 50, 75, 100 and 125 mm in the timber
Array of TC's on the mass timber shaft surface (exposed side) at 0.75, 1.5, 2.25 and 2.7 m above the 2nd storey floor
Array of TC's on the mass timber shaft surface (unexposed side) at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the ground floor
Embedded TC's in the shaft wall at the depths of 25, 50, 75 and 100 mm at 1.5 m above the 2nd storey floor

TC's at top of the opening, 0.15 m below the top, on the vertical centreline and 0.4 m from the sides, of the opening
Mast on the roof along the centre line of the opening, with TC's at 1.5, 2.5, 3.5, 4.5 and 5.5 m and Gardon gauge at 3.5 m above the top of the opening

IR camera positioned outside the opening (another IR camera for bird view of the roof (not shown))

TC's at the beam-column connection TC at connection

Gardon gauge at 4.5 m away from the opening

Figure 48. Fuel load and instrumentation for Test 3 and Test 4.

interior view

exterior view

interior view

view through two northern openings

Figure 49. Under-construction suite for Test 4 (before testing).

5.2 Instrumentation and Measurement

The following thermocouples and heat flux meters were installed in the corner bay, as shown in **Figure 48**. Char measurements were conducted after the fire test.

- Four (4) thermocouple trees were installed at the quarter points in the corner bay. Each thermocouple tree had four (4) thermocouples at 0.75 m, 1.5 m, 2.25 m and 2.7 m above the floor. These thermocouples were type K stainless steel sheathed thermocouples shielded from radiative heat for measuring gas phase temperature.
- Thermocouples were embedded in the mass timber ceiling at two locations – the left centre and right centre of the corner bay, respectively. At each location, five (5) thermocouples were embedded in the mass timber ceiling at the depths of 25, 50, 75, 100 and 125 mm in the timber. All holes drilled to install the thermocouples were sealed to maintain the integrity of the mass timber panels. These thermocouples were used to monitor flame and char progression inside the mass timber ceiling.
- Three (3) thermocouples were installed at each of the two selected window openings in the corner bay to measure the temperature of the flame issuing from each opening. The

thermocouples were located 0.15 m below the top of the opening on the vertical centreline and at 0.4 m from each side of the opening.

- A mast with five (5) thermocouples and one Gardon gauge was placed on the roof along the vertical centreline of two window openings in the corner bay to measure the exterior fire spread upward. The thermocouples were located at 1.5 m, 2.5 m, 3.5 m, 4.5 m and 5.5 m, and the Gardon gauge was located at 3.5 m, above the top of the opening.
- A heat flux meter was installed to align with the centre of one of the openings at 4.5 m from the structure.
- One infrared camera was positioned to look through the window opening to provide data and visual thermographs on temperature build up and stratification from ceiling to floor.
- One infrared camera was positioned to look at the roof from above to provide data and visual thermographs on heat transfer to the unexposed side of the ceiling.
- Various video cameras were positioned inside and outside the suite to capture images of the test.
- Five (5) thermocouples were installed at the connection where beam B302 (346 mm × 546 mm) met column C106 (530 mm × 532 mm). **Figure 48** shows the installation details of the thermocouples at the connection for Test 4, which were located 80 mm from the exposed faces of the beam.

The test also made the use of the three vertical thermocouple arrays that had already installed inside the stair shaft, including:

- A thermocouple array was installed inside the stair shaft in the centre, with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor level of the ground storey.
- Two thermocouple arrays were installed on the mass timber surface in the exit stair at the quarter lengths, each with TC's at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 m above the floor level of the ground storey.

5.3 Test 4 Results and Discussions

Test 4 was conducted on September 15, 2022 with the northwest wind of 16 km/hour and ambient temperature of 9.8°C. The moisture content of the mass timber structural elements was in the range of 8.7-11.3% with an average of 9.5% ± 0.8%.

Test 4 represented a worst case scenario with intentionally severe testing conditions, including:

- a higher fuel load than those typically found on the mass timber construction sites, and
- no firefighting intervention during the test.

It was under these conditions that Test 4 was conducted in order to uninterruptedly demonstrate the fire dynamics in, and the fire performance of, the mas timber test structure. In reality, the probability of fire services not responding to fires for two and half hours is almost zero.

The test started with ignition at 9:41 am and terminated at 12:08 pm with data recording for 2 hours 28 minutes. The test was terminated earlier than planned due to smoke migrating toward the occupied buildings on the campus (air quality concerns for building occupants). There was no firefighting intervention until the end of the test.

5.3.1 Fire Development

Figure 50 and **Figure 51** show the ignition and fire development during Test 4. One of the wood cribs under the beam B302 was the first item ignited from underneath. The flame took 4 min 30 s to emerge from the crib. The flame then grew, reached the beam at 6 min, and ignited the DLT ceiling above the crib at 6 min 20 s. The ceiling jet flame started to spread on the DLT ceiling and also ignited the top of the light wood framing at 7 min. The flame spread over the entire ceiling at 7 min 40 s with large fire plumes exiting from the window openings. The compartment was fully involved in the fire at 7 min 45 s, involving all the wood cribs, light wood framing and mass timber elements (floor, ceiling, beams and columns).

There was a 10-min period of fully-developed burning (the fully developed fire stage) during which the light wood framing and most wood cribs were either consumed or fell onto the floor. After this, the flaming combustion was quickly reduced on the mass timber elements by 19 min, and at the same time the fire plumes ceased to issue from the openings, regaining a clear view of the compartment interior. As the fire continued to decay, visible flaming on the mass timber elements mostly ceased after 30 min, except that the fallen debris of the wood cribs and light wood framing remained glowing on the floor and the mass timber elements exhibited small flickering intermittently especially in joints and junctions. All the fallen debris (from the wood cribs and light wood framing) were completely consumed by 60 min.

The temperatures measured inside the compartment using the thermocouple trees are presented in **Figure 52**. After the compartment was fully involved in the fire, the vertical temperature differences on each thermocouple tree were relatively small while the lateral temperature differences across the room were relatively large during the fully developed fire stage. The peak temperatures were above 1100 °C in four different quadrants. The temperature profiles clearly indicate that the fire started to decay at 18 min once the light wood framing and most wood cribs were fallen onto the floor. Except the front right quadrant at upper heights, the compartment temperatures decreased to a minimum of 300-400 °C at 60 min and then slowly ascended.

The front right quadrant experienced raising or higher temperatures at the 2.25 m and 2.7 m heights during 50 min to 100 min. There was no wood crib nor light wood framing initially installed in this quadrant. Although not much fallen debris was accumulated on this part of the floor, it was observed that the CLT floor panels developed more and more visible flickers and smoke while the CLT floor in other three quadrants had less and less glowing debris. The front right quadrant dominated the flickering and smouldering of the CLT floor in this timeframe, resulting in the higher temperatures.

During the entire test duration, the exposed CLT floor was visibly glowing, and intermittent flickers kept occurring in the DLT ceiling perimeter and mass timber joints and junctions. An increased amount of dense smoke was also produced due to persistent smouldering. The strong wind further exacerbated the smouldering and glowing. After 120 min, there were more frequent flickers and brighter glowing.

Although the fire reached decay stage, it did not go all the way to the full extinguishment and the compartment stayed at relatively high temperatures. By the end of the test, the compartment temperatures at the ceiling levels were still up to 600 °C. This is also evident in the infrared images shown in **Figure 53**. Due to the smoke being blown towards the occupied buildings on the campus, the test had to be terminated at 148 min.

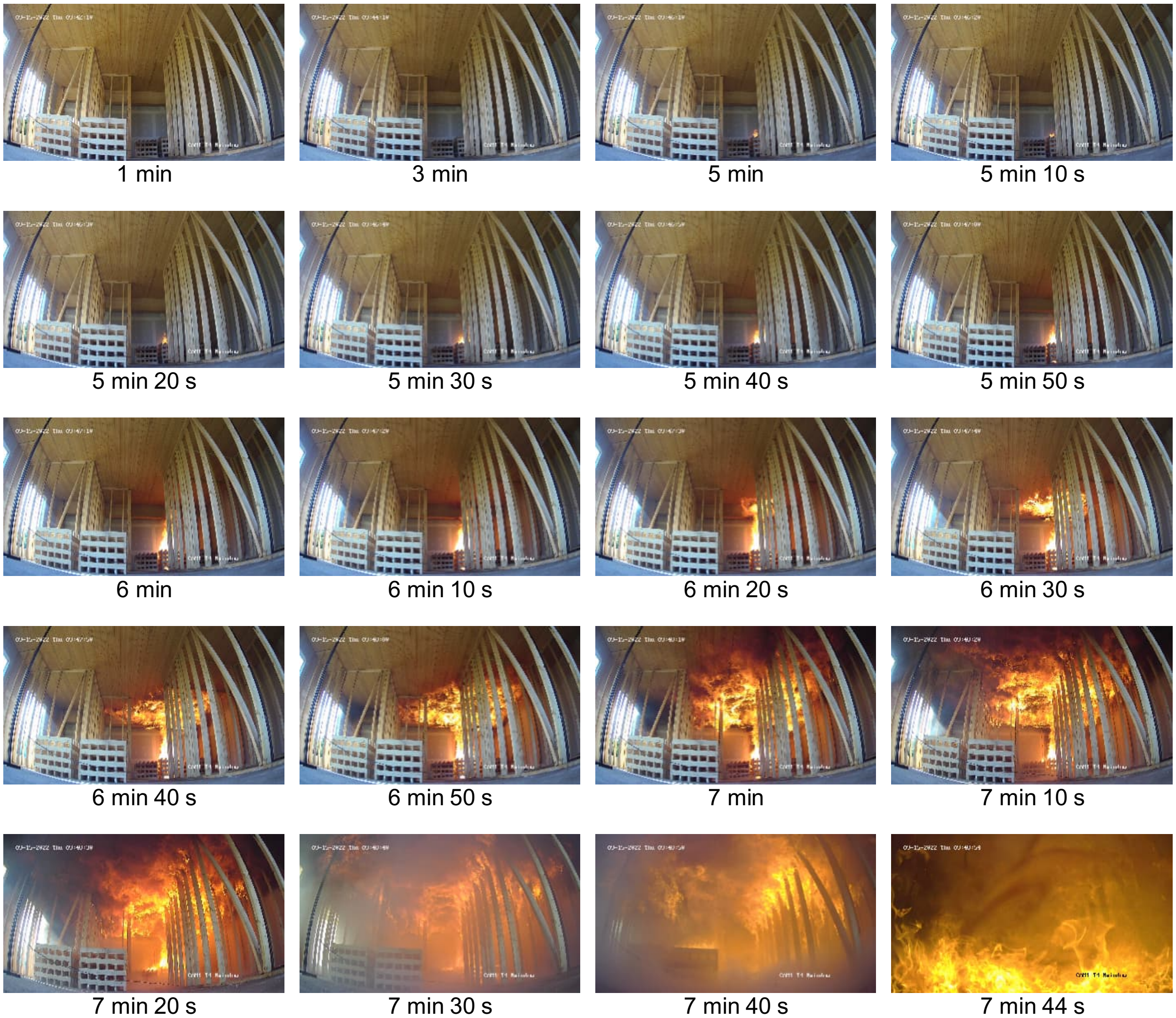


Figure 50. Initial fire development in Test 4.

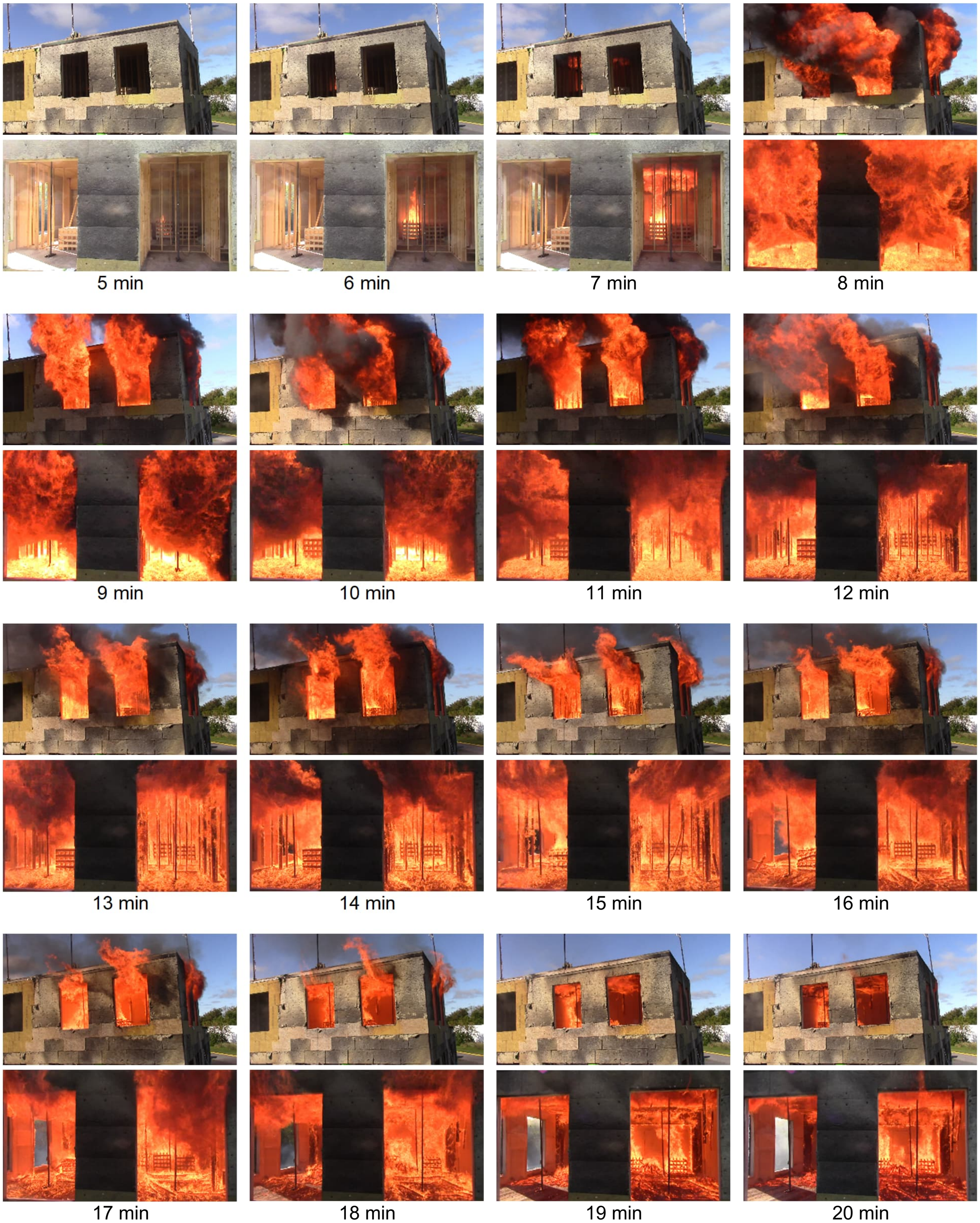


Figure 51. Views from exterior and through two northern openings in Test 4.
(Continued to next page)

Figure 51. Views from exterior and through two northern openings in Test 4.
(Continued from previous page)

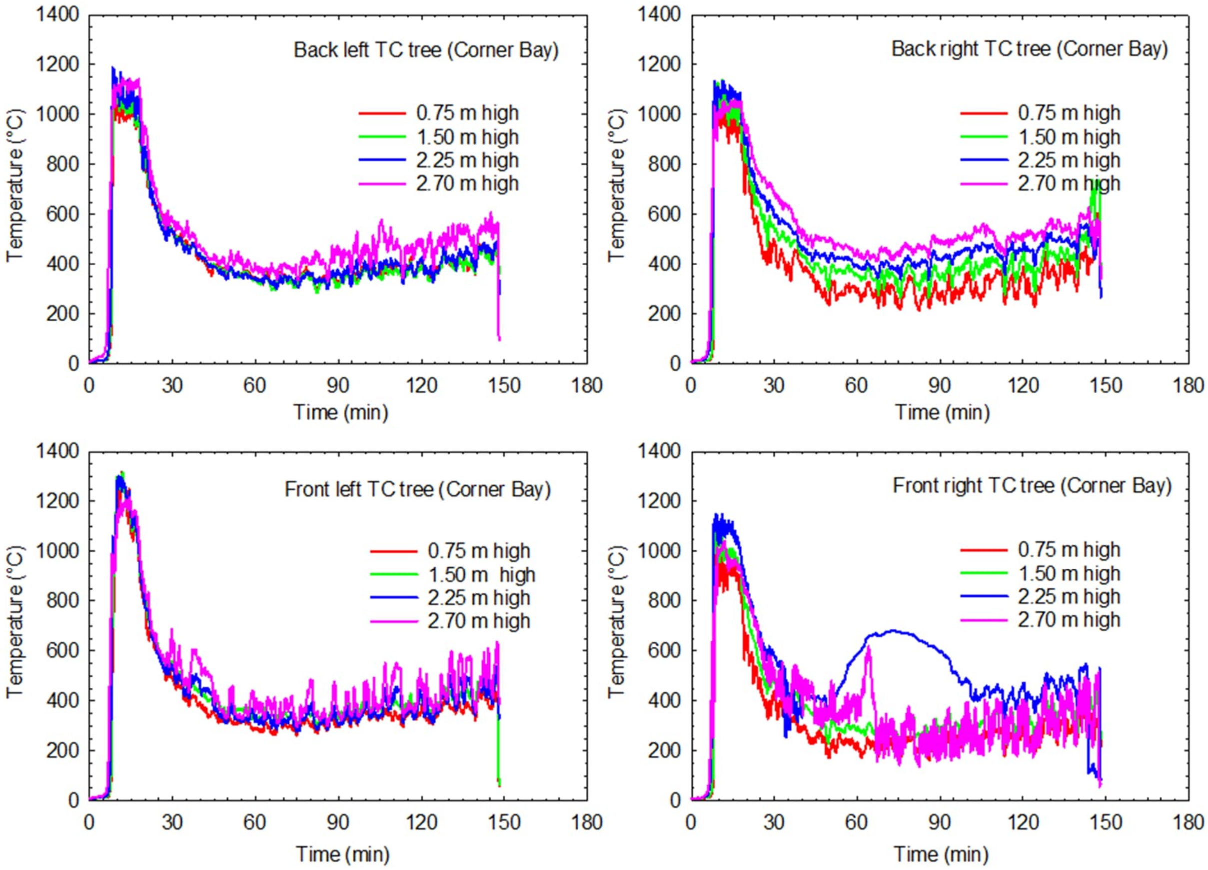


Figure 52. Room temperatures during Test 4.

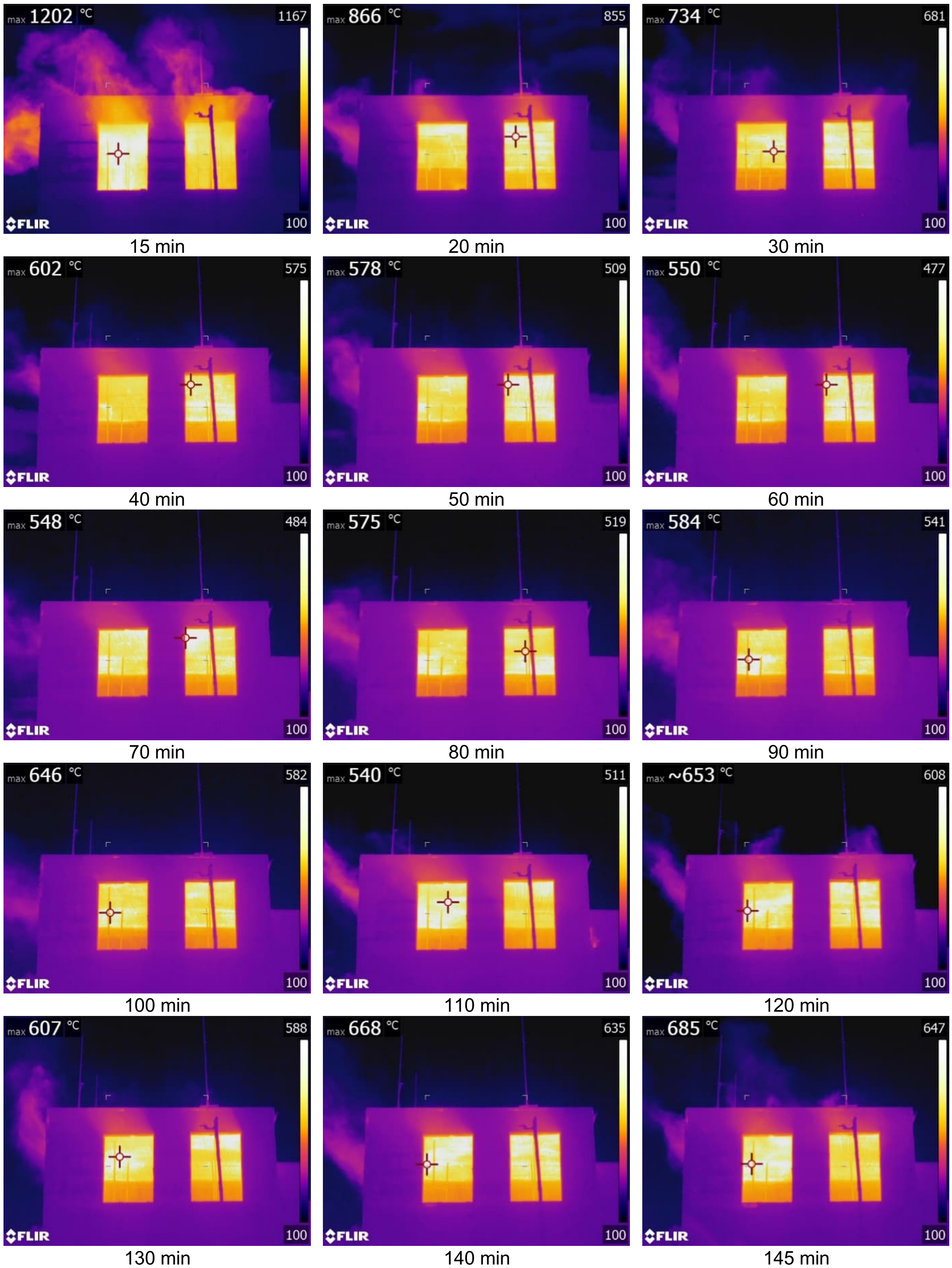


Figure 53. Infrared thermal images during fire decay stage in Test 4.

5.3.2 Fire Impact on Structural Elements

During Test 4, the structure endured approximately 20-min flaming combustion and 120 min smouldering combustion. **Figure 54** shows that at the end of the test, the CLT floor remained glowing red, the DLT ceiling had lingering flickers around its perimeter, the beams and columns still endured some small flames. In particular, flames came out from behind the beam B302 and column C202 due to gaps from the adjacent suite separation wall (67 mm between the wall and C202; 92 mm between the wall and B302) which made beam B302 and column C202 exposed to the fire on three sides.

Figure 55 and **Figure 56** show some photographs of the mass timber structure after the test, along with the temperature profiles measured inside the exposed DLT ceiling. The temperatures certainly exhibited an ascending trend inside the DLT ceiling. One of the thermocouples inserted in the 125-mm depth produced several large temperature spikes which might had been inserted in-between the lamellas or into the finger joints of lumber boards where tiny gaps might had existed for hot pyrolysis gases to pass through. In spite of this, the general temperature profiles suggest the char depths in the DLT panels being over 75 mm at the measurement locations (where the temperatures reached above 300 °C).

Char measurements were conducted after Test 4. The char depths were measured with 1.8 m spacing across the ceiling and along each beam, 2.4 m spacing across the floor, and at 0.75 m, 1.5 m and 2.25 m high along each column. For the beams and columns, each measurement involved two drillings perpendicular to each other to determine the char depths on all exposed sides (B302 and C202 being exposed from three sides; B303, C105, C108 and C106 being exposed from two sides). **Figure 57** shows schematically the measured char depth per exposed side.

Except for one measurement location, all measured char depths are well within the design allowance for the 2-hour rated structural elements according to CSA O86-19. The room-facing side of column C202 charred 135 mm (i.e., 44 mm more than the design allowance) at the 0.75 m height.

Greater char depths than average occurred at several locations. **Figure 58** shows the B303 beam-column-ceiling connections after the test. The DLT ceiling panel charred away 125 mm on this exterior corner. Beam B303 even charred away 28 mm from the exterior side (behind gypsum sheathing) near the connection to column C105 with the edge of the metal connector (RICON XL 390x80) visible.

Figure 59 shows the beam B302 beam-column-ceiling connections after the test. At the ceiling-B302-C202 connection, the top portion of column C202 reduced from the 395 mm × 395 mm cross section to 225 mm × 325 mm (charred away 70 mm from the room-facing side, 85 mm from each of the other two exposed sides). This connection experienced the severest heat penetration from three exposed sides of B302 and C202.

Figure 59 also shows the temperature profiles inside the ceiling-B302-C106 connection during the test. All temperatures within the connection exhibited an ascending trend (see **Figure 48** for details of embedded thermocouples). The right thermocouple in the connection detected 300 °C at 70 min, 600 °C at 120 min and 750 °C at 140 min while the top thermocouple detected 300 °C at 90 min, 600 °C at 120 min and 650 °C at 140 min. Among all four beam-column-ceiling connections, this connection experienced the least heat penetration, which means that the other three connections would have endured at least similar thermal conditions.

CLT floor and C202

DLT ceiling and B302

DLT ceiling, B302 and C202

DLT ceiling, B302 and C106

CLT floor and C202

CLT floor

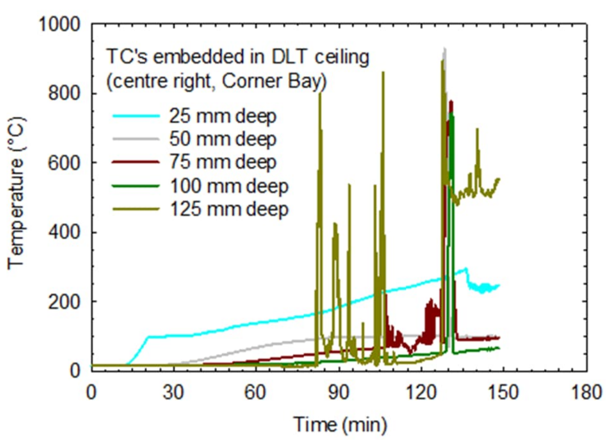
Figure 54. Structural elements at the end of Test 4.

DLT ceiling, C105-B303-C108

DLT ceiling, C202-B302-C106

DLT ceiling, B303

DLT ceiling, B302



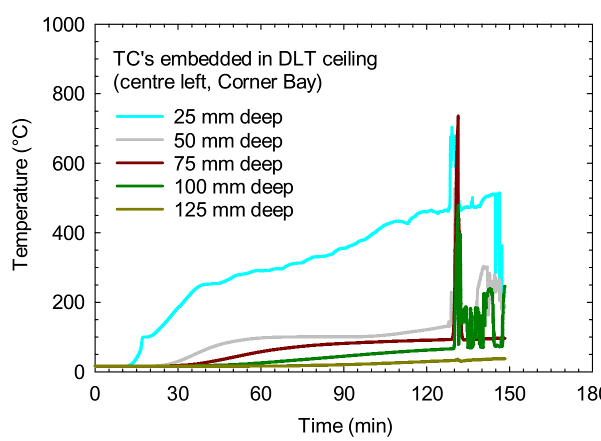


Figure 55. Charring on mass timber elements and temperatures in DLT ceiling (Test 4).

Figure 56. Charring on CLT floor (Test 4).

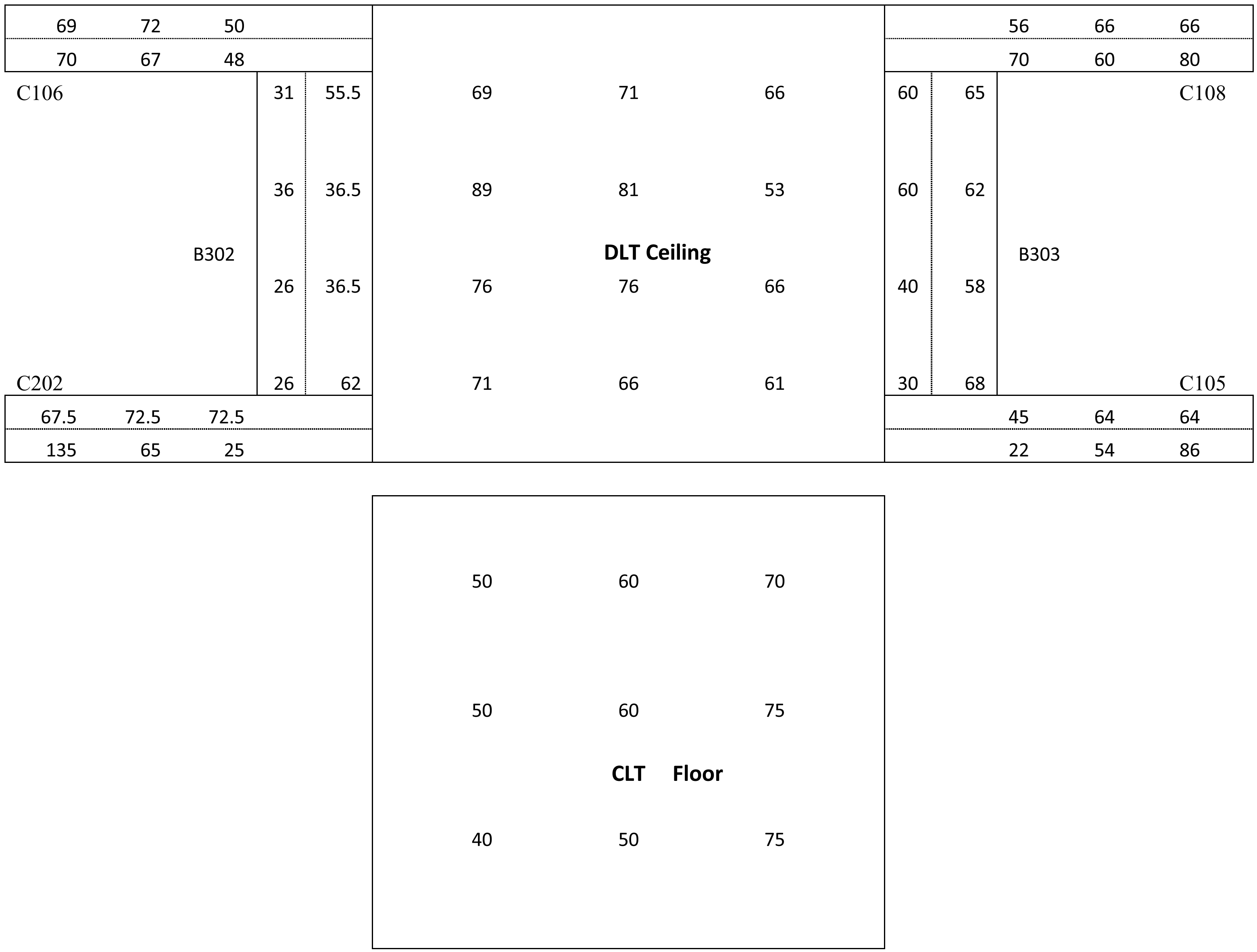


Figure 57. Char depths (mm per exposed side) **on ceiling, beam and columns in Test 4.**

ceiling-B303-C105 connection (north view)

ceiling-C105 connection (east view)

ceiling-B303-C105 connection (north zoom in)

ceiling-C105 connection (east zoom in)

ceiling-B303-C105 connection (interior view)

ceiling-B303-C108 connection (SW view)

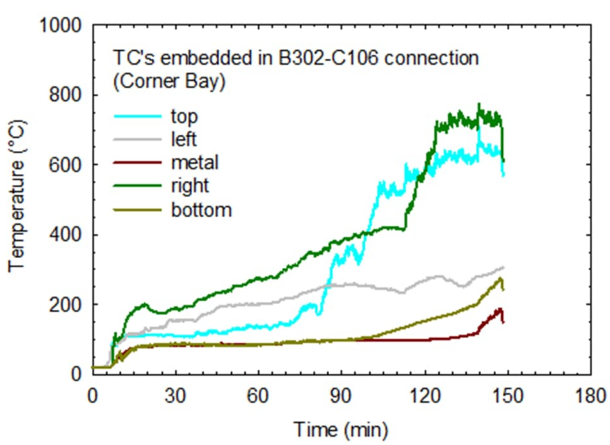
Figure 58. Charring on structural elements connected to beam B303 (Test 4).

ceiling-B302-C106 connection

ceiling-C202 connection

B302-C106 connection

B302-C202 connection



Temperatures in ceiling-B302-C106 connection

ceiling-B302-C202 connection

Figure 59. Charring on beam B302 and connected elements and connection temperatures (Test 4). (Zoom in and zoom out to the corner from interior and exterior)

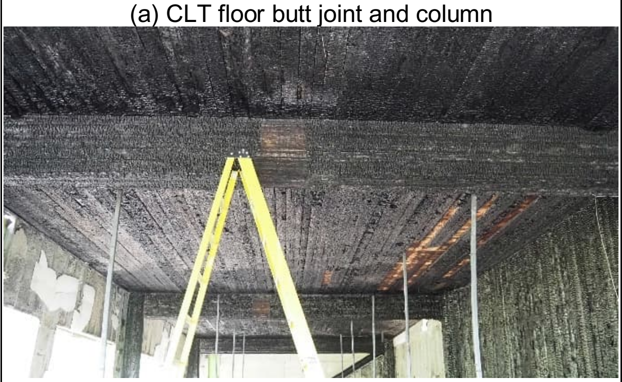
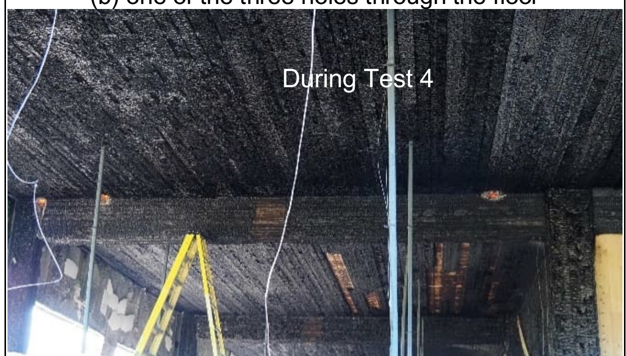
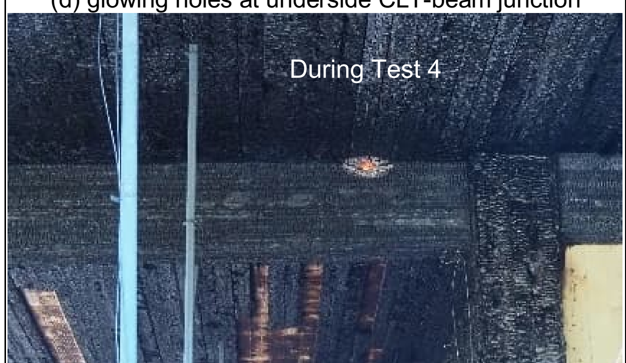
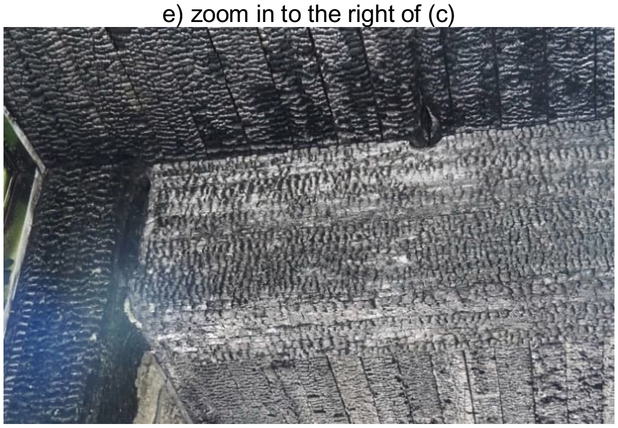
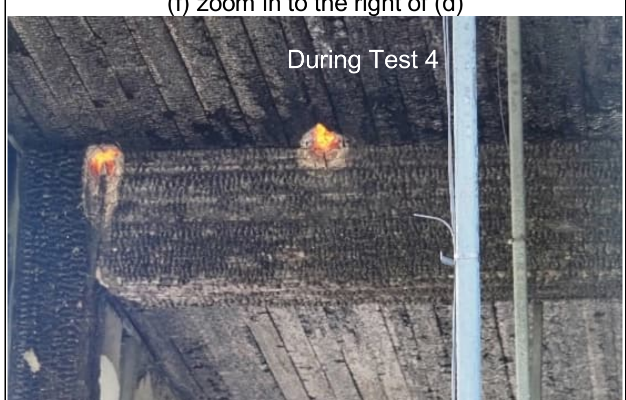
Before Test 4	During or After Test 4
	
(a) CLT floor butt joint and column	(b) one of the three holes through the floor
	
(c) underside of CLT floor on beam B203	(d) glowing holes at underside CLT-beam junction
	
e) zoom in to the right of (c)	(f) zoom in to the right of (d)
	
(g) zoom in to the left of (c)	zoom in to the left of (d)

Figure 60. Effect of 2-side exposures after both Tests 4 and 5 on CLT floor and beam junction.

The CLT floor assembly (i.e., the first storey's ceiling assembly) endured the fire exposures on both sides in Test 4 and Test 5, respectively. The preceding Test 5 already created deeper charred pockets along the junction of the CLT floor/ceiling assembly with the beam B203 from the underside as well as along the CLT floor butt joint. During Test 4, three holes were completely burnt through the joint and junction from above as the result of the combined fire exposures from Test 4 and Test 5, as shown in **Figure 60**.

5.3.3 Fire Exposure outside Fire Compartment

As already mentioned, large fire plumes exited the openings during the fully developed fire stage. **Figure 61** shows the fire plumes that were over 6 m high at around 8 min. **Figure 62** shows the temperatures and heat fluxes measured above the openings and at distance. Due to the predominant north wind (16 km/hour), the fire plumes were driven away from the roof masts above the fire compartment and the distant mast facing the north openings. This lowered the temperatures and heat fluxes being registered by the thermocouples and heat flux meters on the masts, especially by the north masts above and away from the north opening. Nevertheless, the east roof mast still registered the heat flux of 33 kW/m^2 at 3.5 m above the east opening and the distant mast still registered the heat flux of 15 kW/m^2 at 4.5 m away from the north opening.

In the stairwell, all temperatures including those on the CLT surface in the stairwell were below 22 °C. The fire did not affect the conditions in the adjacent stairwell during the test.

5.3.4 Post Fire Operations

At the end of Test 4, the CLT floor was glowing red, flickers were around the DLT ceiling perimeter and on the beams and columns. Post fire operations lasted for two hours. **Figure 63** shows some photographs of the post fire operations.For the first 20 min immediately after the test, hose streams were directed to the interior using multiple short and pulsed water sprays for a total of 150-s spray time. Visible flames were fairly easy to extinguish but deep-seated fires hidden in joints and junctions kept coming back, particularly in the southeast upper corner where beam B302, column C202 and the DLT ceiling met. The rest of the operations switched to the outside attack, involving removal of the exterior walls and roof covering to directly attack the hidden fires and hot spots in the joints and junctions. All hot spots were fully extinguished by the post test operations. The test structure maintained its integrity and facilitated the fire department intervention. Subsequent fire watches observed no more hot spots.

before test

maximum plume > 6 m at 8 min

Figure 61. Fire plumes issued from openings in Test 4.

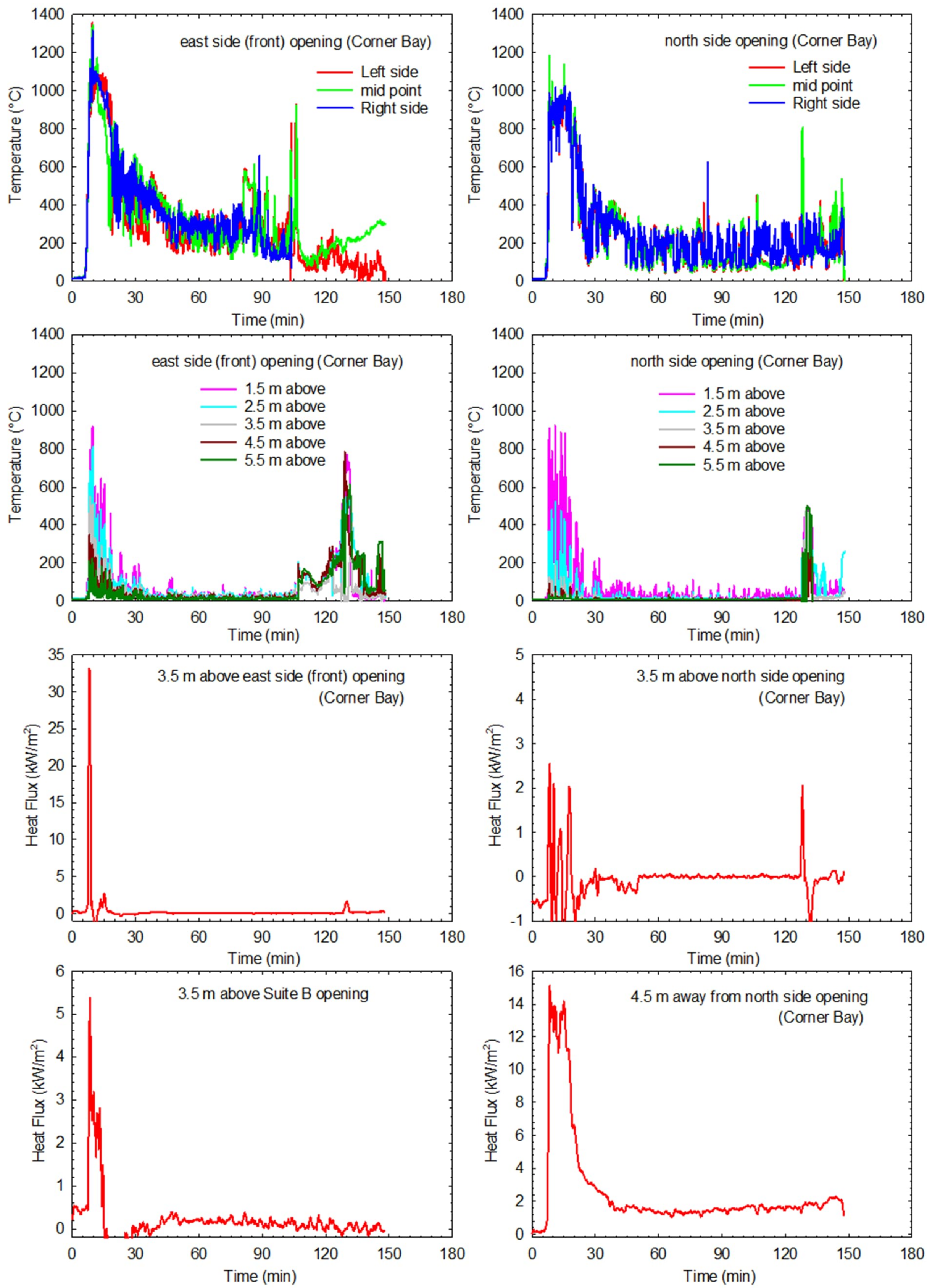


Figure 62. Temperatures and heat fluxes above openings and at distance during Test 4.

hose streams to the interior

small flames in the DLT ceiling perimeter

removal of exterior walls to attack outside

removal of roof cover to attack outside

attack hidden fire in B302, C202 and DLT connections

attack hidden fire in B302, C202 and DLT connections (zoom in)

Figure 63. Post fire operations after Test 4.

5.4 Test 4 Summary

Test 4 was conducted in the 7.1 m × 7.5 m × 3.0 m high space representing a portion of a mass timber building under construction. The space included the exposed DLT ceiling, CLT floor, Glulam columns and beams with a total of 124.6 m^2 exposed mass timber surfaces. In addition to the exposed mass timber elements, the fuel load simulating materials on construction sites was added at the density of 224 MJ/m^2 in the form of wood cribs and light wood open framing. Test 4 was designed to study a severe construction site fire scenario with exposed mass timber structure. The fuel load used in the test was higher than those typically found on the mass timber construction sites, and there was no firefighting intervention during the test. The severe test conditions were exacerbated by the strong wind on the test day.

After ignition, the fire took approximately 8 min to fully involve the compartment and followed by a 10-min period of fully-developed burning with large fire plumes issued from the window openings reaching over 6 m high. During this period, the compartment reached the peak temperatures exceeding 1100 °C.

For the exterior fire exposure, the strong predominantly north wind drove the fire plumes away from the measurement masts, which lowered the temperatures and heat fluxes being registered by the thermocouples and heat flux meters on the masts. Nevertheless, the sensors still measured a heat flux of 33 kW/m^2 at 3.5 m above one of the window openings, and 15 kW/m^2 at 4.5 m away from the north openings.

The fire started to decay at 18 min when most added fuel was consumed or fallen onto the floor. The flaming combustion was quickly reduced on the mass timber elements and the fire plumes ceased to issue from the openings by 19 min. As the fire continued to decay, visible flaming on the mass timber elements mostly ceased after 30 min. The compartment temperatures decreased to 300-400 °C at 60 min. However, the fire did not go all the way to the full extinguishment – the floor remained glowing, the mass timber elements exhibited intermittent small flames in the joints and junctions, and the compartment temperatures ascended to 400-600 °C by the end of the test. The test was terminated at 148 min.

During Test 4, the mass timber structure endured approximately 20-min flaming combustion and 120 min smouldering combustion. The averaged char depths were within the design allowance for the 2-hour rated structural elements according to CSA O86-19: 70 mm average char depth for the DLT ceiling; 34-53 mm for each exposed side of the beams; 56-73 mm for each exposed side of columns. However, there was deeper charring near the connections and junctions of the beams, columns and ceiling with some deep-seated hidden hot spots. This was partly due to the test structure was not built as airtight as normal buildings, and also indicated the importance of post test firefighting operations.

For the firefighting operations after the test, visible surface flames were fairly quick and easy to extinguish. Most of the firefighting operations was devoted to tackle the deep-seated flames hidden in joints and junctions. Extinguishment required the removal of the exterior walls and roof covering to directly attack the hidden flames and hot spots in the joints and junctions.

6 TEST 3: CONSTRUCTION SITE FIRE SCENARIO

Test 3 was conducted in Suite B with all mass timber elements exposed to simulate a realistic construction site fire scenario with a garbage bin fire. The exposed mass timber surface included 22.7 m^2 CLT ceiling, 22.7 m^2 CLT floor and 9.7 m^2 CLT shaft wall tallied to a total of 55.2 m^2. The mass timber ceiling and floor surfaces were completely exposed (100% of the total area). The exposed surface of the mass timber wall was 16% of the total wall area of the perimeter of the suite.

Suite B had already been used in the baseline Test 1, Suite A in Test 2 and Suite C in Test 4. With some repairs, Suite B was reused for Test 3. The two suite-to-suite separation walls were repaired on one side only by installing new double layers of 15.9 mm Type X gypsum board on the existing lightweight steel studs on the Suite B side. The Suite A or Suite C side of the separation wall was not repaired. Particularly, the suite separation wall between Suite B and Suite C had only two layers of 15.9 mm Type X gypsum board in Test 3 (the mineral wool insulation in the stud cavity and the gypsum board on the Suite C side had already been removed during the post fire operations of Test 4). The exterior wall of Suite B was completely rebuilt. **Figure 64** shows the interior of the test space (the dark charring spots were caused by the preceding Test 1).

6.1 Fuel Load and Ignition

A garbage bin fire source, which had been developed separately from open calorimeter tests by Bwalya et al [32], was used in Test 3. A 28-galon steel garbage bin with 10% ventilation openings was filled with 17 kg of 38 mm × 38 mm × 300 mm lumber pieces, arranged as a wood crib in 17 layers and 5 pieces each layer. One litre of methanol was introduced to the bottom of the bin and the garbage bin fire was initiated by manually ignite the methanol using a propane torch. In the previous open calorimeter test, this garbage bin fire had produced a peak heat release rate of 300 kW and a free burning time of 27 min. In Test 3, this garbage bin provided a movable fuel load at the density of 15 MJ/m^2 and was placed against the CLT shaft wall with a 25-mm gap. The garbage bin fire was designed to be as severe and repeatable as practical.

6.2 Instrumentation and Measurement

Test 3 used the instrumentation already existed in Suite B for measurements (see **Figure 48** and section 4.4). In addition, a distant heat flux meter was installed at 4.5 m away facing the centre of the window opening. The thermocouples existed in the adjacent spaces that were still functional at the time were also utilized.

6.3 Test 3 Results and Discussions

Test 3 was conducted on September 29, 2022 with the northwest wind of 11 km/hour and ambient temperature of 16.1°C. The moisture content of the mass timber structural elements was in the range of 7.4-9.7% with an average of 8.7% ± 0.6%. The test started with ignition at 9:20 am and terminated at 1:22 pm with data recorded for 4 hours 2 mins. There was no firefighting intervention until the end of the test.

a) Suite B after repairs

b) garbage bin placed against CLT wall

c) 2×2 lumber pieces in garbage bin

d) before Test 3

Figure 64. Simulated construction site with garbage bin (before Test 3).

6.3.1 Fire Development

Figure 65 and **Figure 66** graphically illustrate the fire development during Test 3. After the garbage bin fire was initiated by igniting the methanol at the bottom of the bin, the flame slowly incubated within the bin for the first 10 min, then emerged from the bin and grew in height for the next 10 min. Flame ignited the CLT wall behind the bin at 20 min 50 s and impinged on the CLT ceiling above at 20 min 52 s.

Once hitting the ceiling, the flame quickly spread over the whole CLT ceiling with the fire plume issued from the opening at 22 min 13 s. The long preheating allowed the quick ignition of the whole ceiling. The space reached flashover at 23 min but quickly died down within 1 min with only garbage bin burning. The temperature profiles in **Figure 67** show that immediately after the flashover, the temperatures in the space reached the peaks of around 1000 °C at 23 min 10 s but plunged to below 400 °C at 25 min. No more flames were visible on the CLT ceiling, wall or floor at 25 min because the garbage bin fire source did not have sufficient energy to sustain the flaming combustion of the mass timber elements. By 30 min, the temperatures in the space dropped to below 160 °C.

The remaining contents in the garbage bin was completed consumed and no more flame was visible in the bin by 35 min. Note that the four thermocouples on the surface of the CLT shaft wall surface at 0.75 m, 1.5 m, 2.25 m and 2.7 m above the floor were just beside or above the garbage bin, which provided the temperature data of the fire source. The temperature profiles beside and above the garbage bin (on the CLT wall surface) clearly indicate that the bin was out of the fuel at this point.

At 57 min 30 s, a small flame appeared in the top right back corner at the junction of the ceiling and two walls. As described earlier, the separation wall between Suite B and Suite C had only double layers of 15.9 mm Type X gypsum board on the steel studs without insulation or gypsum board on the other side, and was expected not to be airtight at the junction. Driven by the gusting predominantly north wind, this intermittent flame persisted until the end of the test. At the end of the test (242 min), the temperatures in the space were below 30 °C.

Figure 65. Initial fire development in Test 3 (interior view).

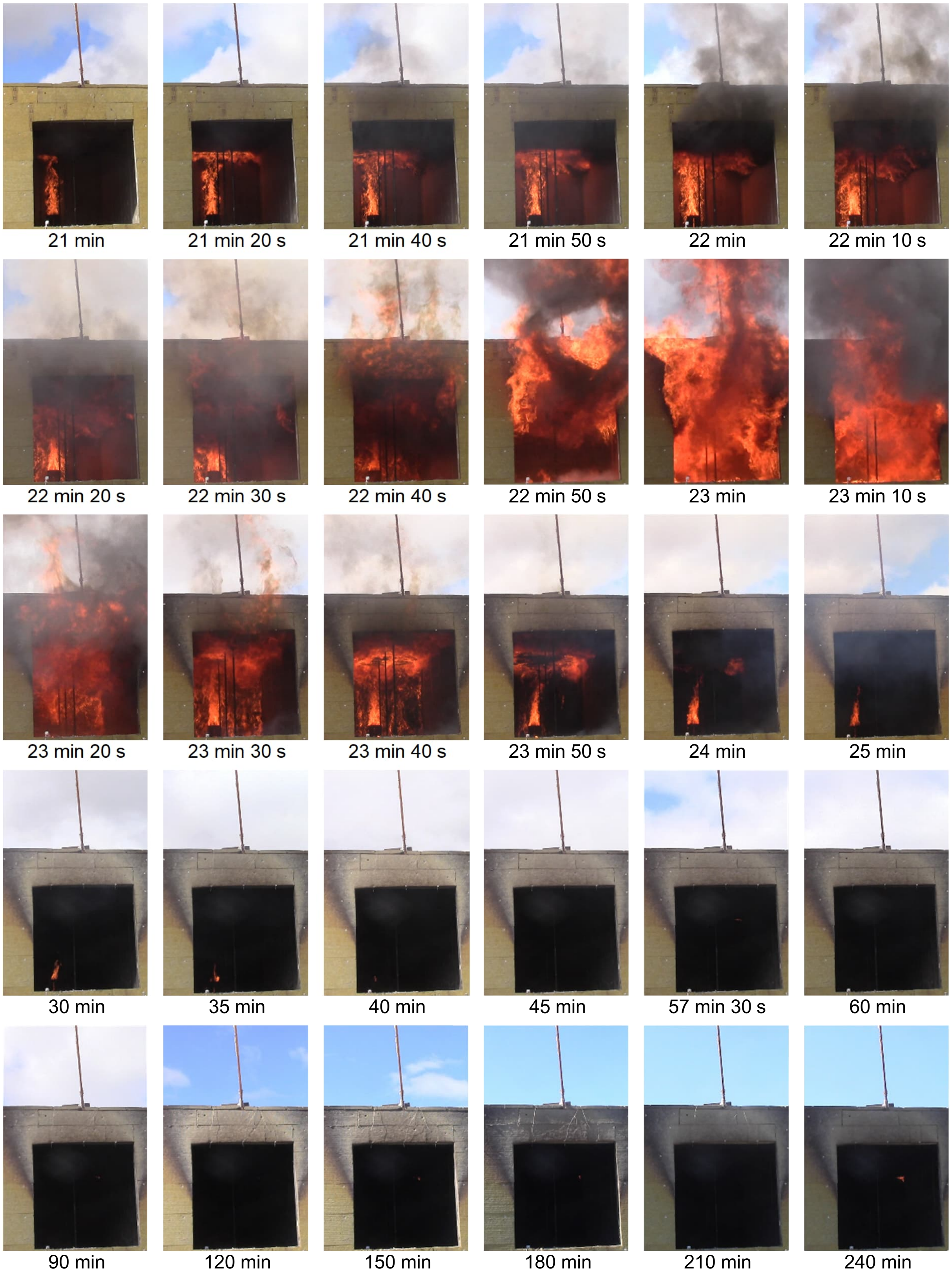


Figure 66. Fire development in Test 3 (exterior view).

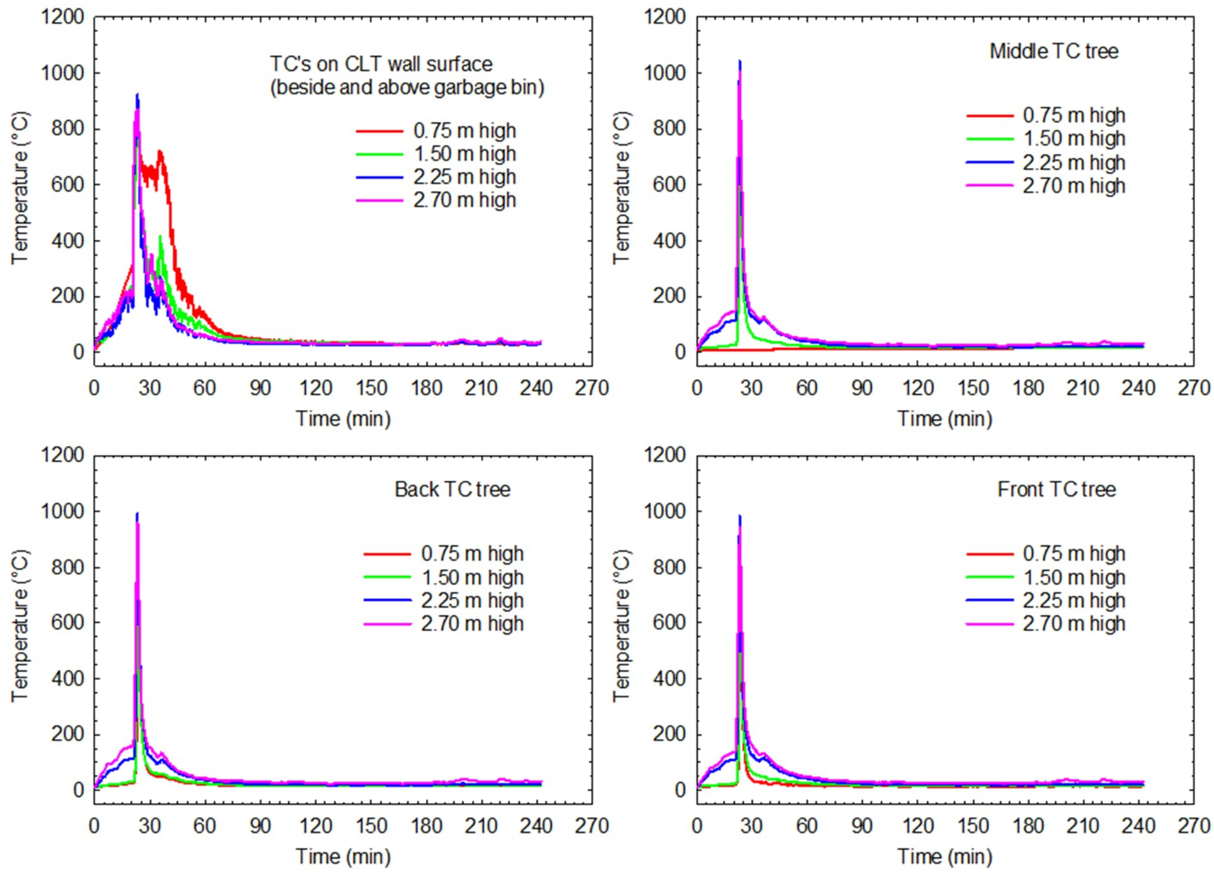


Figure 67. Room temperatures during Test 3.

6.3.1.1 Comparison of fire development in Test 3, Test 4 and Test 5

Based on visual observation and video records, Test 3, Test 4 and Test 5 were compared and analyzed in order to help understand the potential impact of using the aggressive ignition package in Test 5 on the fire development and, when possible, to make quantitative estimates.

In Test 3, a small 0.72 m high wood crib was placed inside the garbage bin for ignition. It took more than 20 min for the flame to impinge on the 3-m high ceiling. Then, the fire spread across the exposed CLT ceiling at a speed of 89 mm/s.

In Test 4, one wood crib, which was 0.71 m high, was ignited. This wood crib was surrounded by two other wood cribs (also 0.71 m high) but they were not stacked. It took more than 6 min for the flame to impinge on the 3-m high ceiling. After that, the fire spread across the exposed DLT ceiling at a speed of 92 mm/s (very similar to the speed in Test 3).

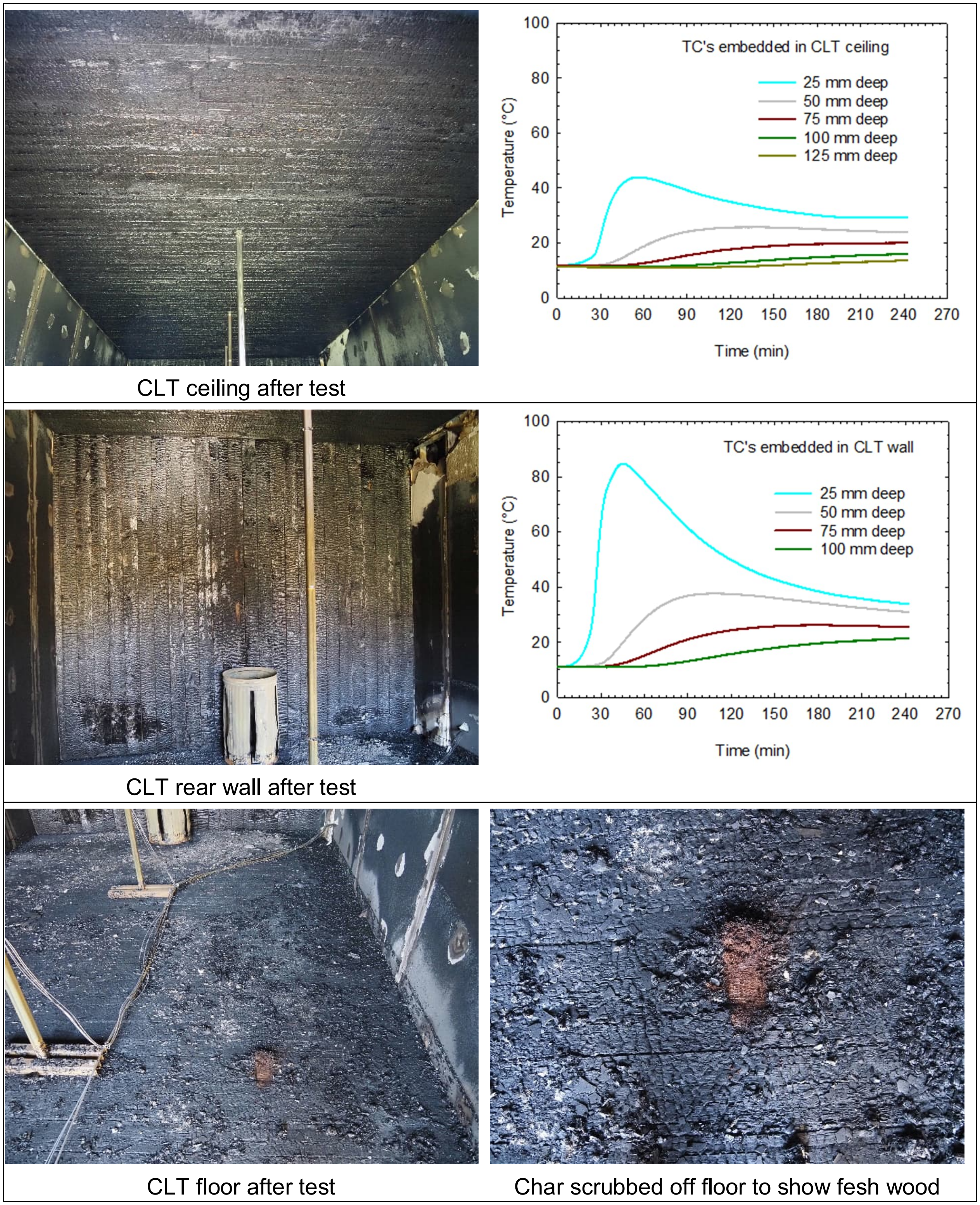
Test 5 used the aggressive ignition package in order to ensure the initial flame would impinge on the 4-m high ceiling. The wood cribs were stacked to 1.8 m high for ignition. It took 3 min 40 s for the flame to impinge on the 4-m high ceiling and the fire spread across the exposed CLT ceiling at the speed of 140 mm/s in Test 5 (see Section 3.3.1.1).

Compared to the ignition packages used in Test 3 and Test 4, the aggressive ignition package used in Test 5 was likely to have impacted the fire development. The primary impact would be on the timing of the initial flame impingement on the ceiling but this is hard to reliably estimate in a quantitative term; qualitatively the initial fire growth from ignition to flame impingement on the ceiling was accelerated in Test 5 and its timing would probably be close to Test 4. Secondly, once the flame impinged on the ceiling, the speed of fire spread across the ceiling would have accelerated by approximately 50% in Test 5, compared to the speeds in Test 3 and Test 4.

6.3.2 Fire Impact on Structural Elements

Since the CLT floor, wall and ceiling only experienced up to three minutes of flaming combustion, char depths were generally quite low – up to 10 mm on the CLT floor (charring on the floor was accumulated from both Test 1 and Test 3), 5 mm on the CLT shaft wall and 2 mm on the ceiling. **Figure 68** shows the charring and temperatures in the CLT ceiling, wall and floor panels. The embedded thermocouples in the CLT panels indicated that the maximum temperatures in 25 mm deep were below 45 °C in the ceiling and below 85°C in the shaft wall, confirming the CLT having only the surface charring.

There was deeper charring on the ceiling directly above the garbage bin, along the junction of the CLT ceiling and the CLT wall, and particularly in the top right back corner where the ceiling and two walls met. **Figure 69** shows the intermittent small flame in that rear corner during the test and the charring damages to the CLT in that corner. It also shows the temperature profiles measured in the neighbouring corner in the adjacent space using the embedded thermocouples in the B302-C106 connection (which had been installed for the preceding Test 4). This neighbouring corner in the adjacent space experienced up to 700 °C during this test. Again, this was due to the suite separation wall between Suite B and Suite C not being airtight. After the preceding test (Test 4 in Suite C), the suite separation wall had only double layers of 15.9 mm Type X gypsum board on the Suite B side of the steel studs without any insulation or gypsum board on the other side, which provided passage for air and flames in the junction during Test 3.



CLT ceiling after test

CLT rear wall after test

CLT floor after test

Char scrubbed off floor to show fesh wood

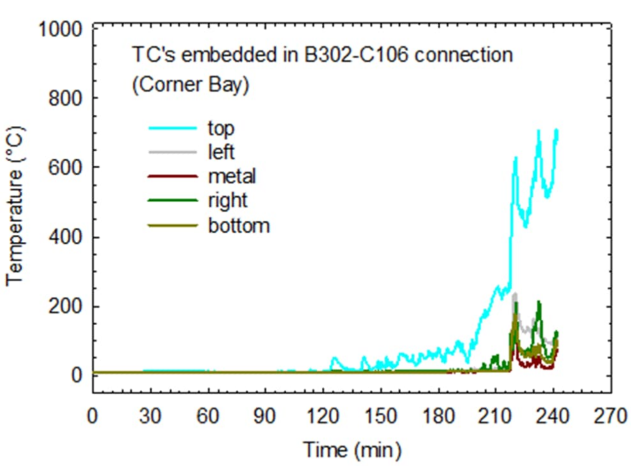
Figure 68. Charring and temperatures in CLT ceiling, wall and floor (Test 3).

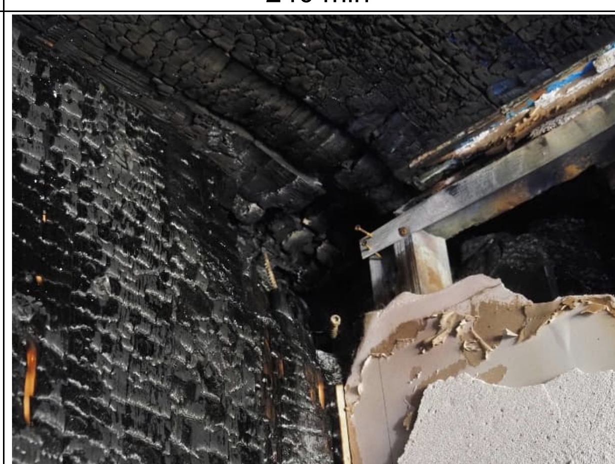
60 min

160 min

200 min

240 min





right rear corner at junction of the ceiling and two walls after post fire operations

Figure 69. Intermittent small flame in top right rear corner and temperatures in neighbour's corner.

6.3.3 Fire Exposure outside Fire Compartment

Immediately after the flashover, fire plumes issued from the window opening reached 6 m above the opening. However, the fire plumes were short lived for only one minute, and the peak height only stayed for a few seconds. The temperatures and heat fluxes measured above the opening and at distance are presented in **Figure 70**. The strong wind (predominantly from north) might have lowered temperatures and heat fluxes being registered by the thermocouples and heat flux meters on the masts since it pushed the fire plumes away from the masts.

In the stairwell, all temperatures including those on the CLT surface in the stairwell were below 18 °C. The fire did not affect the conditions in the adjacent stairwell in the test.

6.3.4 Post Fire Operations

The fire test left some hot spots with continued smouldering, especially in the junctions of the ceiling and walls and in the top right rear corner, which was due to the separation wall between Suite B and Suite C not being airtight with only double layers of 15.9 mm Type X gypsum board on one side in addition to the wind driven effect. Thorough firefighting operations were conducted after the test. These hot spots were fully extinguished by the post test operations. Subsequent fire watches observed no more hot spots or smouldering.

6.4 Test 3 Summary

Test 3 was conducted in the 3.2 m × 7.0 m × 3.0 m high space representing a portion of a mass timber building under construction. The space included the exposed CLT ceiling, CLT floor, and CLT wall (shared with the stair shaft) with a total of 55.2 m^2 exposed mass timber surfaces. A 28-galon steel garbage bin filled with 17 kg lumber pieces was used as the fire source, which provided additional fuel load at the density of 15 MJ/m^2. Test 3 was designed to simulate a realistic construction site fire scenario with garbage bin fire.

The garbage bin fire grew very slowly after the ignition. It took over 20 min for the flame to reach the ceiling height. Once hitting the ceiling, the flame quickly spread over the whole CLT ceiling and the space reached flashover at 23 min with the temperatures almost instantly raising to 1000 °C. But the fire died down almost immediately within a minute. The fire plumes issued from the window were short lived for only one minute, staying at the peak height for only a few seconds. No more flames were visible on the CLT ceiling, wall or floor by 25 min. The garbage bin fire source did not have sufficient energy to sustain the flaming combustion of the mass timber elements. By 30 min, the temperatures in the space dropped to below 160 °C. The remaining debris in the garbage bin fully burnt out on its own within the bin by 35 min.

During the test, the exposed CLT floor, wall and ceiling experienced less than three minutes of flaming combustion, resulting quite low char depths (mostly surface charring of a few millimetres). However, the char depth was up to 20 mm on the ceiling directly above the garbage bin along the junction of the CLT ceiling and the CLT wall. The ceiling char depth in the top right rear corner where the ceiling and two walls met was much deeper than 20 mm, and there were hot spots and smouldering remaining in these junctions at the end of the test. This was caused by the separation wall between Suite B and Suite C not being airtight which provided flow paths for air and flames in the junctions. Thorough firefighting operations were conducted after the test in order to ensure the hot spots were extinguished.

Fire plume reached up to 6-m height briefly.

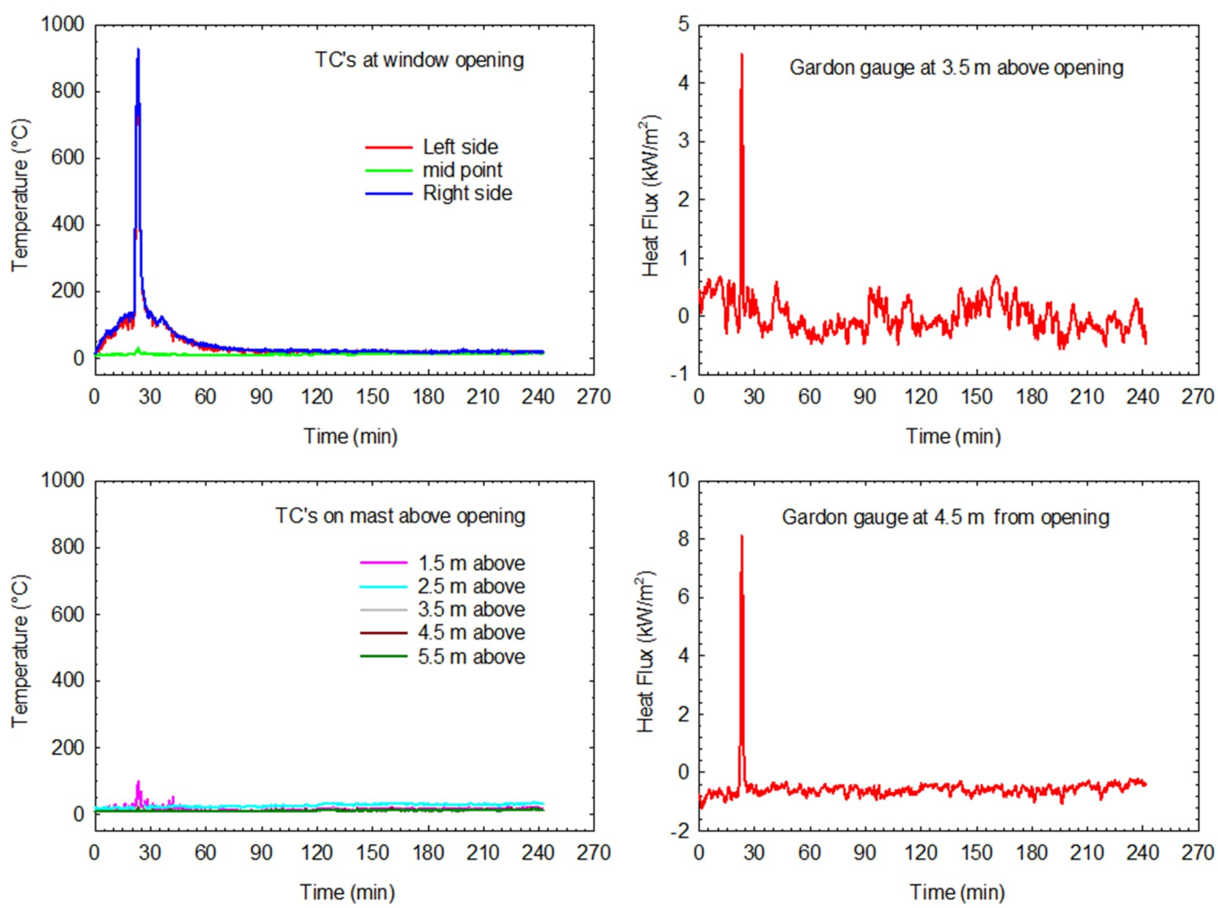


Figure 70. Temperatures and heat fluxes from fire plume exited the opening in Test 3.

7 CONCLUSIONS

As a part of the MTDFTP, a series of five large scale fire tests on a mass timber structure were conducted in summer 2022 to study fire safety during construction, fire dynamics and performance in the open plan office space and residential suites, as well as influence of exposed mass timber structural members on fire severity and duration. These fire tests were conducted without sprinklers and without firefighting intervention for extended hours, representing rare scenarios in which sprinkler systems would not operate or would be ineffective in controlling the fire and the fire department would fail to respond to the fire emergency. Such a probability of sprinkler failure and fire department response failure would be extremely low for completed buildings. For buildings under construction where sprinklers have not been installed, the probability of fire department failing to respond for extended hours would also be very low. Therefore, the results of the MTDFTP large scale fire tests should be interpretated within this context. The analysis of the experimental data and results has produced the following key findings and conclusions.

<u>Test 5 – Fully furnished open plane office space</u>

Test 5 represented a fully furnished open plan office space with exposed mass timber columns, beams, wall and ceiling. The mass timber ceiling surfaces were entirely exposed (100% of the total ceiling area). The aggregate exposed surface area of the mass timber beams, columns and wall was equal to 35% of the total wall area of the perimeter of the compartment.

By design, Test 5 represented a worst case scenario combining several severe testing conditions including the high fuel load, the aggressive ignition package, the rough openings with high ventilation and oxygen supply (instead of real windows), the absence of sprinklers, and the absence of firefighting intervention during the test. It was under these severe conditions that Test 5 was conducted in order to uninterruptedly demonstrate the fire dynamics and performance of the mas timber structure.

- Test 5 used the aggressive ignition package in order to ensure the initial flame would impinge on the 4-m high ceiling. With the aid of the aggressive ignition package, the initial fire growth – from ignition to flame impingement on the ceiling – took 3 min 40 s. Once the ceiling jet was formed above the ignition location, the fire spread across the exposed ceiling within 2 min and fully engulfed the entire open plan office space within 3 min. If real windows had been used instead of the rough openings, it would have taken some time for heat to build up to break the window glass in order to obtain enough oxygen supply for combustion.
- A comparative analysis of the fire development in conjunction with data from other tests (Test 3 and Test 4) indicated that the aggressive ignition package used in Test 5 (wood cribs stacked to 1.8 m high) was likely to have impacted the fire development in two ways. Firstly, the initial fire growth from ignition to flame impingement on the ceiling was accelerated. Secondly, once the flame impinged on the ceiling, the speed of fire spread across the ceiling was likely to have accelerated by approximately 50%, relative to unstacked wood cribs. The primary impact would be on the timing of the initial flame impingement on the ceiling but a quantitative estimate was not feasible.
- Thermal radiation from the large fire plumes reached the building facades above the rough window openings and the surrounding area at distance, with the peak heat fluxes reaching 37-50 kW/m^2 at 3.5 m height above the openings, 58 kW/m^2 at 3 m away and 28-39 kW/m^2 at 4.5 m away from the test structure.

- Fire dynamics in this large open-plan office space exhibited the highly heterogeneous temperature distribution. The fire started to decay after 18 min of fully-developed burning, visible flaming combustion was ceased completely by 30 min and the office space was continuously cooled down until the end of the test. The test lasted for more than four hours.

Test 1– Noncombustible construction (baseline) versus Test 2 – Mass timber construction

Test 1 simulated a code-prescribed noncombustible construction baseline residential suite with code-compliant combustible interior linings. Test 2 involved a residential suite constructed of mass timber columns, beam and ceiling with greater exposed surfaces than allowed by the NBC 2020. The mass timber ceiling was 100% exposed and the aggregate surface area of the exposed mass timber beam and columns was equal to 12% of the total wall area of the perimeter of the suite. Test 2 was directly compared to Test 1 in terms of fire dynamics and performance.

- In general, the fire in the mass timber suite behaved similarly to the fire in the baseline suite for the residential test scenario, including the growth, full developed and decay stages. Both tests lasted for more than four hours.
- In both Test 1 and Test 2, flashover occurred at similar times, the fire plumes reached similar heights, and the room temperatures peaked at 1200 °C with similar temperature distributions both temporally and spatially during the fully developed fire stage.
- The fire severity in the mass timber room test was not any greater than the baseline test. In fact, the fire decayed earlier and quicker in the mass timber suite (5 min earlier) than in the baseline suite.
- Both tests presented similar external fire exposures. Test 1 was more under-ventilated inside and resulted in more vigorous exterior combustion due to the greater quantity of combustible interior lining than the exposed timber in Test 2.

Test 4 – A severe construction site fire

Test 4 represented a portion of a mass timber building under construction. The space included the exposed mass timber ceiling, floor, columns and beams. The mass timber ceiling and floor surfaces were completely exposed (100% of the total area). The aggregate exposed surface area of the mass timber beams and columns was equal to 25% of the total wall area of the perimeter of the suite.

Test 4 was designed to study a severe construction site fire scenario. Simulated construction debris and light wood open framing were positioned in the test space. Today's mass timber construction projects are dominated by prefabrication and do not have much other combustible products on site. Test 4 used a higher fuel load density than those typically found on the mass timber construction sites. The test lasted for two and half hours. There was no firefighting intervention during the test in order to uninterruptedly demonstrate the fire dynamics of a severe construction site fire. The severe test conditions were exacerbated by the strong wind on the test day.

- After ignition, the fire took approximately 8 min to fully involve the compartment and followed by a 10-min period of fully-developed burning. The construction site fire reached the decay stage at 18 min. Visible flaming mostly ceased on the mass timber elements after 30 min. The compartment temperatures decreased to 300-400 °C at 60 min. However, the decay became stagnant after 60 min – with the floor glowing, small flames frequently coming out of the joints and junctions and the compartment temperatures ascending slowly to 400-600 °C by the end of the test.

- Thermal radiation from the large fire plumes reached 33 kW/m^2 at 3.5 m above the opening on the building facade and 15 kW/^{2} at 4.5 m from the leeward side of the building in the wind.

Test 3 – A garbage bin fire on construction site

Test 3 also represented a portion of a mass timber building under construction to simulate a realistic construction site fire scenario with a garbage bin fire source. The test space included the exposed mass timber ceiling, floor and wall. The mass timber ceiling and floor surfaces were completely exposed (100% of the total area). The exposed surface of the mass timber wall was 16% of the total wall area of the perimeter of the suite.

- This garbage bin fire scenario created a slow initial fire growth which took over 20 min to reach the ceiling height. The preheating of the ceiling for over 20 min allowed the quick ignition of the ceiling and the flashover. Once the garbage bin fire formed the ceiling jet with the aid of the flame path via the CLT wall behind the bin, the fire quickly spread over the CLT ceiling and reached flashover at 23 min. However, the fire started to decay almost instantly. As soon as the garbage bin fire jet stopped hitting the ceiling, the flaming combustion disappeared quickly from all CLT surface at 24 min 10 s. The garbage bin fire source did not have sufficient energy to sustain the flaming combustion of the mass timber elements.
- The garbage bin fire was designed to be as severe and repeatable as practical for use in Test 3 although it had limited movable fuel load added to the space, compared to Test 4. The results show that controlling the quantity of combustible materials on the construction site is an important strategy to limit the potential fire hazard. Also, if this garbage fire scenario occurs on a construction site, there could be an opportunity for workers to extinguish the fire within the garbage bin if the fire could be detected early and operable extinguishers readily accessible.

Common findings in all tests

In addition to the findings and conclusions above which are specific for each test, some common findings and general conclusions are as follows:

- The average char depths in the exposed mass timber members were well within the design allowance according to CSA O86-19 for the structural members of 2-hour fire-resistance rating in all the tests.
- Some exposed CLT ceiling experienced localized delamination in the cooling period during the tests but this did not cause any re-ignition or fire regrowth.
- Since deep-seated hot spots and smouldering remained after the tests, firefighting operations were required in order to ensure the hot spots were fully extinguished.
- The conditions in the stairwell were not adversely affected in any test.
- The test structure remained stable and solid after enduring the five severe fire tests with a total of 19 hours of fire exposure. This became more obvious in the demolition process of the test structure.

This series of the large scale fire tests produced new scientific data on the fire performance of mass timber in open plan office and residential buildings, fire safety at mass timber construction sites, as well as influence of exposed mass timber on fire severity and duration. This knowledge and data can be used to assist the fire safety design, evaluation and approval of alternative solutions for tall and large mass timber buildings; to assist the development of firefighting strategies in construction sites; to assist the code development and harmonization pertinent to mass timber construction.

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