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FIRE SAFETY CHALLENGES OF TALL WOOD BUILDINGS: LARGE-SCALE CROSS LAMINATED TIMBER COMPARTMENT FIRE TESTS

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ABSTRACT

This study investigates the contribution of cross laminated timber (CLT) building elements to compartment fires. Six compartments (9.1 m long × 4.6 m wide × 2.7 m high) were constructed using 175 mm thick 5-ply CLT structural panels and fire tested using residential contents and furnishings to provide a fuel load density of 550 MJ/m^2. The results show that gypsum board can delay or prevent the involvement of the CLT in the fire, and that the ventilation conditions and exposed surface area of the CLT play a decisive role in the outcome of the test. The results highlight the need to use heat-resistant adhesives in cross laminated timber to minimize delamination.

Keywords: cross laminated timber, compartment fires, fire tests, delamination, ventilation

1 INTRODUCTION

Recent architectural trends include the design and construction of increasingly tall buildings with structural components comprised of mass timber including cross laminated timber (CLT). These buildings are cited for their advantages for sustainability resulting from the use of wood as a renewable construction material.

This research aimed to quantify the contribution of CLT building elements to compartment fires, and to characterize the fire protection of the CLT using gypsum board for delaying or preventing its involvement in the fire. Six large-scale CLT compartment fire tests were planned in consultation with the Project Technical Panel [1–3] and in consideration of gaps identified by a literature review [4]. Modelling was also conducted to support the choice of test parameters [5].

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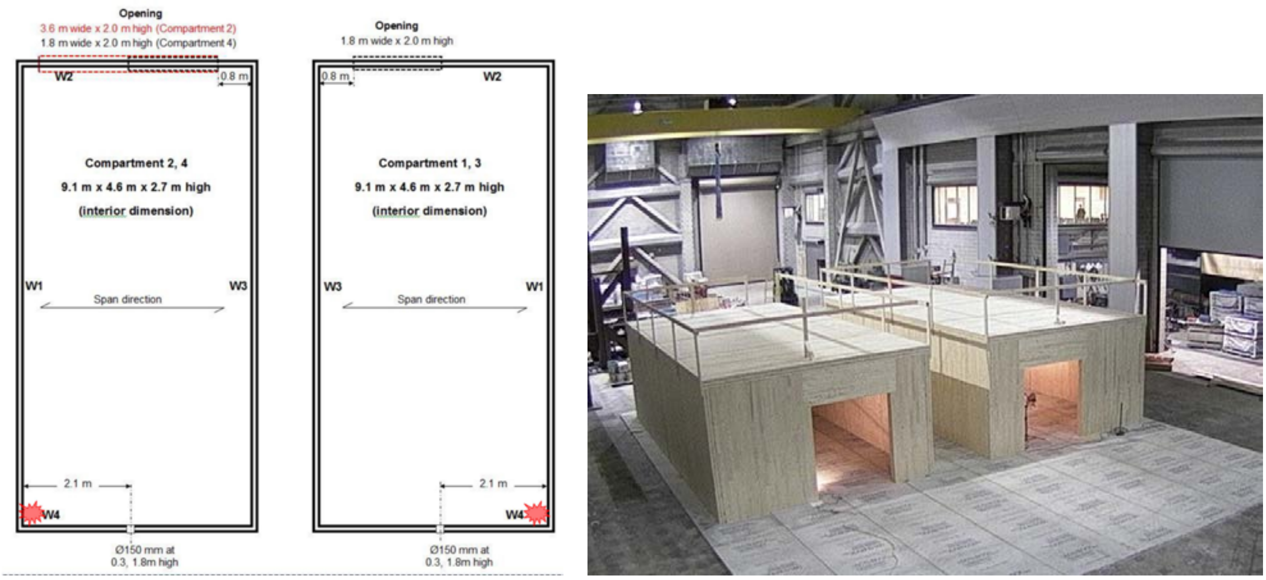
North American codes require that all tall buildings be fully sprinklered in accordance with National Fire Protection Association (NFPA) standard NFPA 13 [6] and that fire services are required to respond to fire incidents in accordance with NFPA 1710 and 1720 [7,8]. However, to achieve the project objective to quantify the contribution of CLT building elements, the CLT compartment fire tests were conducted without sprinklers and without firefighting intervention.

2 TEST SETUP AND PROCEDURE

2.1 Test structure

Six compartments (9.1 m long × 4.6 m wide × 2.7 m high) were constructed using 175 mm thick 5-ply CLT structural panels manufactured using 2×4 spruce-pine-fir lumber glued with a polyurethane adhesive for all wall and ceiling assemblies. All CLT panels conformed to American National Standard ANSI/APA PRG-320 [9]. The ceiling assembly spanned in the 4.6 m direction parallel to walls W2 and W4 (*Fig. 1a*). The wall panels were connected using lap joints and the adjacent walls were connected using butt joints with screws. The ceiling panels were connected to the walls using butt joints with screws (*Fig. 1b*). The inside of the compartments was fully or partially lined using multiple layers of 15.9 mm thick Type X gypsum board.

The compartment had a rough opening in Wall W2 (front) of 1.8 m wide × 2.0 m high in four tests and 3.6 m wide × 2.0 m high in two tests. The ventilation factor was 0.03 $m^{½}$ with the 1.8 m x 2.0 m opening, and 0.06 $m^{½}$ with the 3.6 m × 2.0 m opening, respectively. Additionally, two small openings of 150 mm diameter were created in wall W4 at 0.3 m and 1.8 m heights to provide an equivalent leakage of 0.035 m^2 without actually having a door located in the rear wall. Additional details and drawings for the compartments can be found in the final report [10].



a) b)

Fig. 1. a) Plan view schematic of test compartments; b) Photograph of test compartments (bare structure)

2.2 Test program

Table 1 provides the test matrix. Test 1-1 served as a baseline for the tests with the 1.8 m × 2.0 m opening. Three layers of the gypsum board were used to cover the CLT walls and ceiling in Test 1-1 so that the CLT would neither contribute to the fire nor develop char during the test. Test 1-2 served as a baseline for the tests with the 3.6 m × 2.0 m opening. An exposed wall (W1) was tested in both ventilation configurations (Test 1-3 and Test 1-5). Test 1-4 and Test 1-6 involved an exposed ceiling and a combination of exposed ceiling and wall, respectively, with the 1.8 m × 2.0 m opening. In all tests, a structural load of 0.95 kN/m^2, which is one half of the design live load for a residential occupancy, was superimposed on top of the ceiling using eight cylindrical water tanks.

Table 1. Test matrix

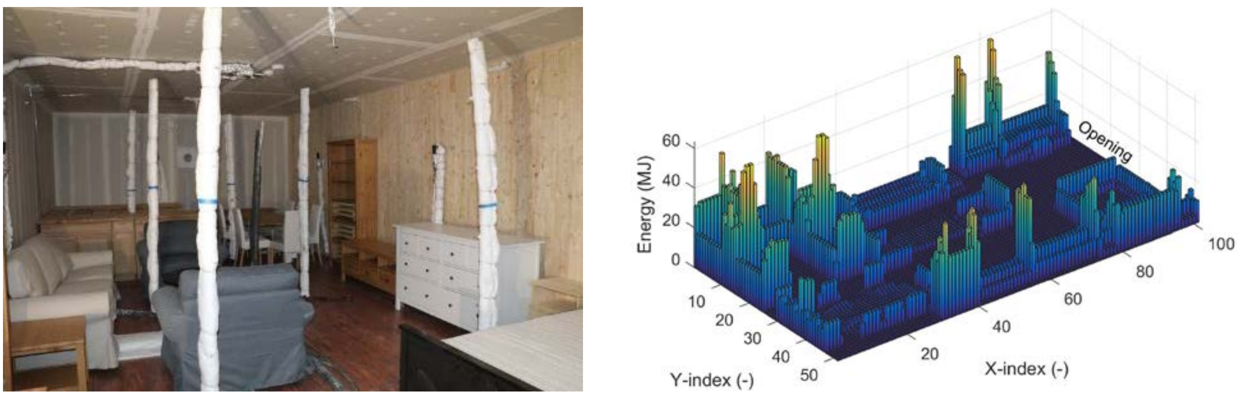
Rough Opening in Wall W2	Compartment Surface					Test	CLT Compartment
	W1 9.1m x 2.7m	**W2** 4.6m x 2.7m	**W3** 9.1m x 2.7m	**W4** 4.6m x 2.7m	**Ceiling** 9.1m x 4.6m		
1.8m wide x 2.0m high	3GB	3GB	3GB	3GB	3GB	1-1	1
	3GB	3GB	3GB	3GB	exposed	1-4*	1*
	exposed	3GB	3GB	3GB	3GB	1-5	4
	exposed	3GB	3GB	3GB	exposed	1-6	3
3.6m wide x 2.0m high	2GB	2GB	2GB	2GB	2GB	1-2	2
	exposed	2GB	2GB	2GB	3GB	1-3*	2*

GB: 15.9 mm (5/8 in.) thick Type X gypsum board; 2GB: 2 layers of GB; 3GB: 3 layers of GB
** Reused CLT structure.*

2.3 Ignition scenario and fuel load

Since the primary objective of the experiments was to evaluate the effect of the CLT structural elements on the fire growth and fire dynamics, the contents fire load and ignition scenario were designed to produce a medium fire growth rate. The movable fuel[8] represented residential contents in a studio apartment with sleeping, living and kitchen areas (*Fig. 2a*) and had target a fire load density of 550 MJ/m^2. The mass, dimensions and position of all combustible material were measured prior to placement in the compartment. These measurements along with assumed calorific values for each material were used to create a 3D model of the fuel energy distribution in the compartment (*Fig. 2b*). The highest fuel density was in the kitchenette at the rear of the compartment, however, the rest of the fuel density was roughly evenly distributed throughout the compartment.

The ignition source was a natural gas burner (200 mm × 400 mm) placed in the corner adjacent to walls W1 and W4 partially under a sideboard. A heat release rate of 50 kW (similar to a burning waste basket) from the burner was maintained until the total measured heat release rate from the compartment exceeded 1000 kW (due to ignited contents), at which time the burner was shut off.



a) b)

Fig. 2. a) Photograph of movable fuel as installed; b) Model of fuel energy distribution in the compartment

[8] Movable fuel refers to all combustible material inside of the compartment (including the laminated flooring) that is not a CLT structural element.

2.4 Measurement systems and instrumentation

Data was collected from multiple systems during the experiments. These systems can be grouped into four categories related to: (1) the calorimeter – dedicated to measuring fuel flow to the small ignition burner and performing oxygen depletion calorimetry, (2) gas sampling in the compartment, (3) the constituent measurements for the test specimens, and (4) imaging and video. 185 specimen-related data channels were recorded. A detailed description of the instrumentation and the estimated uncertainty of the measurements are provided in the final report [10].

3 RESULTS

A large amount of technical data was produced, including measurements of the heat release rate, temperatures inside and outside the compartment, as well as through the encapsulation material and structural assemblies, simulated sprinkler response time, gas species concentrations (O_2, CO_2, CO), pressure and flow conditions, interior and exterior heat fluxes, smoke density, and char depth. In this paper, we limit our discussion to the fire development, select temperature measurements, and comparisons of heat release rates. All of the measured data, as well as videos can be downloaded at [11].

Although the tests were conducted without sprinklers, simulated thermal elements (STEs) were placed at typical sprinkler heights to replicate the time temperature response of a quick-response sprinkler. The time from ignition for each STE to reach the temperature of 68 °C (a typical temperature rating for residential sprinklers) was always less than 5.8 minutes. At these times, the fires were still limited to the first item ignited. Had sprinklers been installed, flashover would not have occurred with effective sprinkler operations.

3.1 Fire development for the baseline ventilation conditions

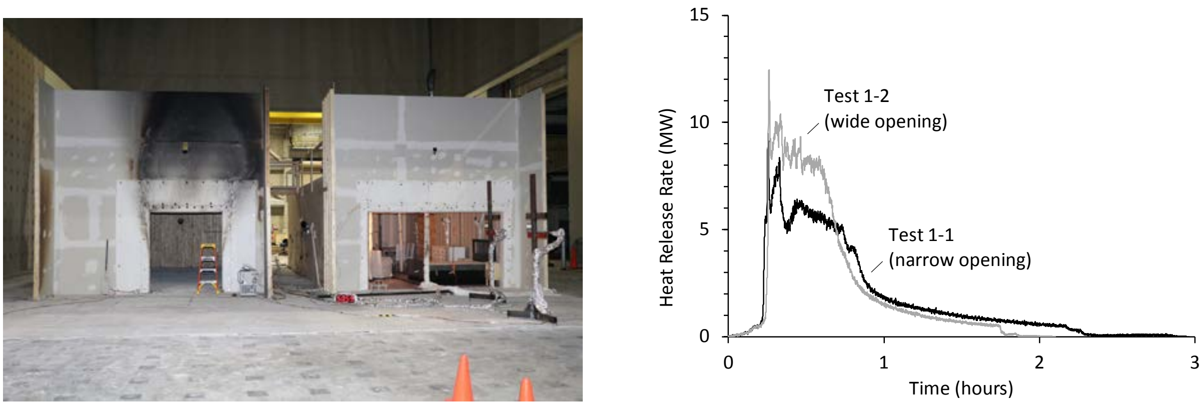
Fig. 3 shows the typical pre-flashover condition of the compartment and a subsequent view of the compartment when most of the movable fuel has been consumed by the fire. In this example (Test 1-2), all CLT surfaces on the walls and ceiling were protected using two layers of gypsum board and the opening was 3.6 m × 2.0 m (wide opening). Test 1-2 served as a baseline to define the contribution of the movable fire loads and to quantify CLT contribution to the fire in a subsequent test with the same ventilation conditions (Test 1-3).

The test started with the ignition of a sideboard in the room corner and progressed through the dining area. The smoke layer descended to the mid height in the compartment and stayed at this height until flashover. After flashover, an intense burning of room contents lasted for approximately 24 min. The fire started to decay at 37 min and the fire plume ceased to issue from the opening at 40 min. The test lasted for 104 min and was terminated after the heat release rate fell below 500 kW. A hose was used to lightly mist the debris on the floor with water to terminate the test.

The fire development described above was similar for both tests in which the CLT was fully protected by the gypsum and did not contribute to the heat release rate; i.e., Test 1-1 and Test 1-2. *Fig. 4* shows comparisons of the heat release rates during these tests. Test 1-2 with the larger ventilation opening had a higher heat release rate but earlier fire decay than Test 1-1. The two tests released virtually the same amount of total heat of 18 000 MJ, which is equivalent to the total energy of the movable fuel with 80 % combustion efficiency. However, the heat exposure conditions inside the compartment were more severe in Test 1-1 than in Test 1-2, because more intense burning occur outside the fire compartment in Test 1-2 [10]. The fire development for Test 1-3 to Test 1-6, which were affected to varying degrees by contributions from the burning CLT, is illustrated by the heat release rate comparisons in Section 3.3.

a) at 7 min 49 s after ignition b) at 67 min

Fig. 3. Photographs of the CLT compartment during Test 1-2 (wide opening)



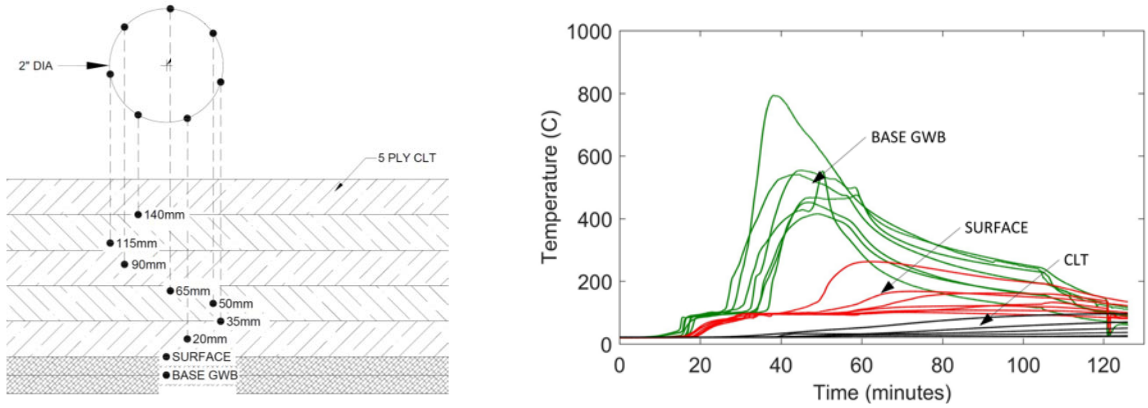
a) b)

Fig. 4. Influence of opening size on the measured heat release rate for the same movable fuel load of 550 MJ/m^2 and no participation of CLT: a) Test 1-1 with narrow opening; b) Test 1-2 with wide opening

3.2 Encapsulation material and structural assembly temperatures

In this section we show temperature time-histories for a wall assembly that successfully prevented participation of the CLT in the fire for the compartment with a wide opening, as well as an unprotected wall assembly under the same compartment ventilation conditions.

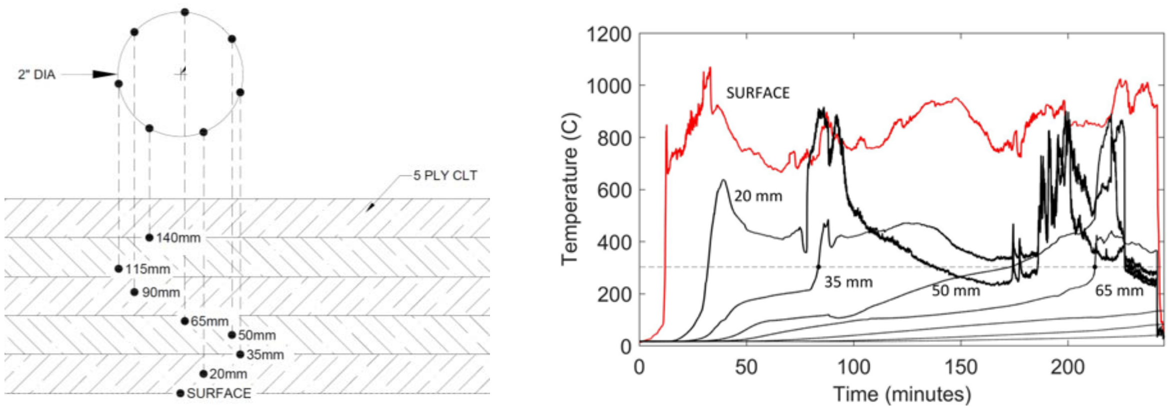
Fig. 5 shows the temperatures measured at the interfaces between the adjacent gypsum board layers, and between the CLT interior surface and the gypsum board base layer, as well as inside the CLT panels at various depths for Wall W1 in Test 1-2 (wide opening) with two layers of gypsum. The heat transfer through the gypsum board followed the typical three-stage pattern as indicated by the temperature profiles at the interfaces: an initial temperature rise up to 100 °C, a period of gypsum calcinations at the constant temperature of 100 °C, then temperature increasing again after the calcination. Although the temperatures at the interface between the face and base layers of gypsum board increased significantly (up to 800 °C) at various locations in the wall, the face layer gypsum board stayed intact until the end of the test (*Fig. 3*b). The maximum temperature measured at the CLT interface with gypsum board was 263 °C on wall W1 at the 1.8 m height; at other measurement locations, the CLT wall interface temperatures were 100 °C to 170 °C. The CLT wall panels were at the ambient temperature on the exterior surface. For Test 1-1, which provided a baseline for the compartments with a narrow opening, three layers gypsum board were necessary to successfully protect the CLT structure, preventing the ignition and involvement of CLT structural elements in the fire.



a) b)

Fig. 5. Temperatures in a wall assembly with two layers of 15.9 mm thick Type X gypsum protection in Test 1-2 (wide opening): a) Details of embedded thermocouples in Wall W1 with the drilled holes in a circular pattern and sealed from the outside; b) Temperatures in Wall W1 at various depths from the fire exposed surface (1 inch = 25.4 mm)

Fig. 6 shows temperatures measured on the surface of and inside the CLT panels for Wall W1 in Test 1-3 (wide opening) which had no gypsum protection. The temperature profiles show that before the flashover, the upper portion of the exposed W1 wall was already ignited. Based on the timing when the embedded thermocouples in Wall W1 (mid-length at 1.8 m height) measured 300 °C, the char front reached 20 mm, 35 mm, 50 mm and 65 mm deep at 32 min, 83 min, 172 min, and 213 min, respectively. The embedded thermocouple in 35 mm depth of the W1 wall shows a sharp temperature rise at around 80 min. The starting point of this temperature rise, 220 °C, is below the wood charring temperature. The end point of this temperature rise, 500 °C, is the prevailing compartment temperature. Given that 35 mm inside CLT corresponds with a glue line and that the char front should be at around 300 °C, this temperature rise indicates that the delamination of the first ply of the CLT occurred prior to the char front reaching the first glue line. The embedded thermocouple in 65 mm depth of the W1 wall shows a similar temperature rise at around 210 min, indicating the delamination of the second ply of the CLT prior to the char front reaching the second glue line. At the end of the test (242 min), the temperatures at the 90 mm, 115 mm and 140 mm depths in the CLT panel were 132 °C, 80 °C, and 40 °C, respectively.



a) b)

Fig. 6. Temperatures in a wall assembly without gypsum protection in Test 1-3 (wide opening): a) Details of embedded thermocouples in Wall W1 with the drilled holes in a circular pattern and sealed from the outside; b) Temperatures in Wall W1 at various depths from the fire exposed surface (1 inch = 25.4 mm)

3.3 Heat release rate

The influence of exposing CLT under the investigated fuel load density and ventilation conditions is illustrated by comparing the measured heat release rates.

Fig. 7a compares the baseline case for the wide opening and no CLT participation (Test 1-2) with the case where one wall of the compartment is exposed (Test 1-3). With the exposed W1 wall in Test 1-3, flashover occurred 3 min earlier and the heat release rate was approximately 2 MW higher than the baseline (Test 1-2) in the growth and fully developed fire stages. The CLT contribution is most prominent, however, during the decay phase of the fire when flaming in the compartment reoccurred as the first and second plys in Wall W1 delaminated. Based on the volume (depth × area) of the CLT charred, which was measured after the test, the CLT panels were estimated to contribute approximately 1100 kg of timber to the fire (mainly by the W1 wall panels), which translated to 540 MJ/m^2 fuel load density to the floor area in addition to the movable fuel load. This brought the effective fuel load density to 1090 MJ/m^2 in Test 1-3.

Fig. 7b compares the baseline case for the narrow opening and no CLT participation (Test 1-1) with various combinations of ceiling and wall CLT exposure (Test 1-4 to Test 1-6). In the three investigated cases (one wall exposed, ceiling exposed, and one wall and ceiling exposed), exposure of the CLT with the narrow opening resulted in a decreased time to flashover (3.4 min to 5.1 min sooner) and ultimately to runaway fire growth that required manual fire suppression. The exposed CLT panels translated to more fuel loads in addition to the movable fuel load (room contents) in the compartment. Due to the intensity and duration of the thermal exposure in the compartment, the CLT surfaces protected by three layers of 15.9-mm thick Type X gypsum also contributed to the fire in the later part of the tests. The estimated contributions of the CLT to the total fuel load for these tests depended on the time at which the fire was suppressed and can be found in [10].

Comparing the heat release rates for Tests 1-3 (*Fig. 7a*) and Test 1-5 (*Fig. 7b*) in which both tests had one exposed CLT wall, illustrates the importance of the ventilation conditions on the outcome of the test. In Test 1-3 with a wide opening (ventilation factor = 0.06 $m^{½}$), the delamination in the exposed wall does not prevent the fire from continuing to decay, whereas in Test 1-5 with a narrow opening (ventilation factor = 0.03 $m^{½}$), the delamination of the plys led to runaway growth of the fire.

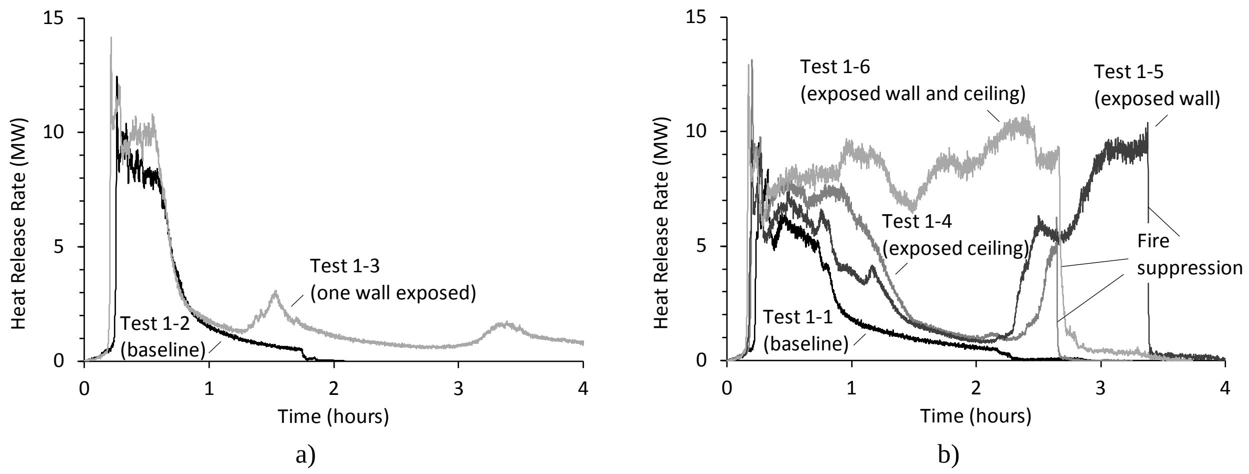


Fig. 7. Comparison of CLT compartment heat release rates: a) compartments with wide openings. b) compartments with narrow openings

4 CONCLUSIONS

The following conclusions are made based on the results:

- *Ventilation conditions had significant impacts on the fire development in the compartments;*
- *The larger opening (ventilation factor = 0.06 $m^{1/2}$) increased the peak heat release rate, but reduced the fire challenges to the CLT compartment structure inside;*
- *The CLT contribution to the fire increased with increasing exposed surface area of the CLT; and,*
- *There is a need to use better heat-resistant adhesives in CLT for exposed CLT applications to minimize delamination.*

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