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Compartment Fire Testing of a Two-Story Mass Timber Building

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Abbreviated version (without appendices)

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Abstract

Five full-scale fire experiments were conducted to observe the performance of a two-level apartment-style structure constructed of mass timber. Each level consisted of a one bedroom apartment, an L-shaped corridor, and a stairwell connecting the two levels. One of the primary variables considered in this test series was the amount and location of exposed mass timber. The amount of mass timber surface area protected by gypsum wallboard ranged from 100% to no protection. For each experiment, the fuel load was identical and the fire was initiated in a base cabinet in the kitchen. In the first three experiments, the fire reached flashover conditions, and subsequently underwent a cooling phase as the fuel load from combustible contents was consumed. The first three experiments were carried out for a duration of up to 4 h. In the fourth experiment, automatic fire sprinklers were installed. Sprinklers suppressed the fire automatically. In the fifth experiment, the activation of the automatic fire sprinklers was delayed by approximately 20 minutes beyond the sprinkler activation time in the fourth experiment to simulate responding fire service charging a failed sprinkler water system. A variety of instrumentation was used during the experiments, including thermocouples, bidirectional probes, optical density meters, heat flux transducers, directional flame thermometers, gas analyzers, a fire products collector, and residential smoke alarms. In addition, the experiments were documented with digital still photography, video cameras, and a thermal imaging camera.

The experiments were conducted in the large burn room of the Bureau of Alcohol, Tobacco, Firearms and Explosives Fire Research Laboratory located in Beltsville, Maryland, USA. This report provides details on how each experiment was set up, how the experiments were conducted, and the instrumentation used to collect the data. A brief summary of the test results is also included. Detailed results and full data for each test are included in separate appendices.

Keywords: fire, tall wood buildings, mass timber, compartment fire, fire dynamics

Most dimensional measurements were taken in American units and were later converted to metric units. Any inconsistencies between the two units are caused by rounding when converting from one system to the other.

Nominal lumber size (in.)	Standard lumber size (mm)
1 by 3	19 by 64
2 by 4	38 by 89
2 by 6	38 by 140
2 by 10	38 by 235

Contents

This is an abbreviated version of the full report. The complete report with appendices is available at www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr247.pdf.

This is a revised version. On page 16, 20 mm/min (0.5 gpm/ft^2) sprinkler flow rate was corrected to 2 mm/min (0.05 gpm/ft^2).

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Compartment Fire Testing of a Two-Story Mass Timber Building

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Introduction

Because of advances in technology, new products, and building systems, the past decade has seen an increase in the ability and interest to build mid-rise and high-rise wood structures. However, the height of timber buildings permitted by prescriptive building codes the United States is six stories (ICC 2014). For mid- and high-rise wood buildings to be approved, they must follow a performance-based design or alternative solution approach, requiring that the design provides an equivalent or greater level of safety compared with the prescribed requirements. A limited number of these buildings have been approved for construction in the United States. Several tall wood buildings have been constructed internationally such as the 9-story Murray Grove building in London, the 10-story Forté Docklands in Melbourne, Australia, and the 18-story Brock Commons in Vancouver, Canada (Green and Karsh 2012, Lehmann 2012).

These buildings have been realized through the use of “mass timber” construction. Mass timber is a class of wood and wood composites that includes solid sawn timber, glue-laminated timber (glulam), structural composite lumber, and cross-laminated timber (CLT). CLT is made of dimensional lumber stacked in layers with each layer oriented 90° from the previous layer to form a massive panel. The panels range in size from approximately 50 to 500 mm (2 to 20 mm) thick and up to 18 m (60 ft) long and can be delivered to the jobsite with fenestrations precut (Mohammad and others 2012). The size, strength, and workability of CLT panels have allowed them to be used for both floor and wall systems in mass timber buildings.

To date, only a handful of tall (greater than six stories) mass timber buildings (tall wood buildings) have been constructed in North America. One reason for this is that current prescriptive provisions do not permit these buildings according to the height and area limitations set forth in the International Building Code (IBC). The International Code Council (ICC), which publishes the IBC, established an ad hoc committee (ICC-TWB) to study the issue of tall wood buildings and potential, future prescriptive provisions permitting tall wood buildings in the IBC. As part of this, a fire subgroup was established to examine possible issues pertaining to the fire safety of tall wood buildings and to perform research to address knowledge gaps in the fire performance of tall wood buildings.

In a previous research assessment, understanding the fire dynamics in compartments constructed with combustible materials was identified as one of the biggest research needs to achieve fire-safe, tall wood structures (Gerard and others 2013). In the research assessment, Gerard and others noted that in certain cases, a second flashover has been observed in wood structures. In general, second flashover occurs when passive fire protection falls off, thereby exposing a fresh, preheated surface of wood, which ignites and causes the heat release rate to rise (Osborne and others 2012, as cited in Brandon and Östman 2016). In CLT structures, a second flashover can occur when unburned wood is exposed to hot gases within the compartment if the gypsum wallboard falls off, if there is char fall-off from the CLT, or if there is delamination of a layer from the CLT. Whereas both char fall-off and delamination involve a portion of the charred CLT falling off and exposing a fresh surface, delamination is a term that is applied specially to failures that occur at the interlaminate interface (Osborne and others 2012, Brandon and Östman 2016). CLT delamination has been highlighted as an important research need because certain adhesives can fail at a temperature lower than the char temperature of wood (Frangi and others 2004, 2012; Craft and others 2008; König and others 2008; Tannert and others 2009; Clauß and others 2011a, 2011b; Klippel and others 2013; Lehringer and Gabriel 2014).

In response to the research needs assessment, Brandon and Östman (2016) conducted a literature review on compartment fires in mass timber structures, especially looking for what could be applied to better understand fire dynamics in tall wood buildings. They reviewed 41 different tests including compartments framed with light timber, light steel, and mass timber (including CLT). Of the 41 tests examined, 21 tests used some form of mass timber.

The largest tests performed had an area of 6.3 by 8.3 m (52.54 m^2) (20.7 by 27.2 ft (565.5 ft^2)) (Su and Lougheed 2014). The most extensive testing on CLT was in a series of tests performed at Carleton University (Ottawa, Ontario, Canada), which all used a compartment size of 3.5 by 4.5 m (15.75 m^2) (11.5 by 14.8 ft (169.5 ft^2)) (McGregor 2014, Medina Hevia 2014, Li and others 2015).

The tests performed at Carleton University examined the effects of passive protection on heat release rate and delamination of the CLT (McGregor 2014, Medina Hevia 2014, Li and others 2015). Importantly, it was determined that in a fully protected all-CLT compartment, the CLT does not contribute to the duration or intensity of the fire. When only one CLT wall was exposed (that is, not protected), the heat release rate was similar to that of a fully protected compartment and no second flashover occurred. When there were two exposed CLT walls, however, delamination and a second flashover occurred, regardless of whether the walls were adjacent or opposite of each other at 2.44 m (8 ft) apart. These tests give valuable insight into the potential contribution of exposed CLT surfaces to the fire dynamics of an all-CLT compartment. However, the compartment size tested was smaller than a typical apartment size, and therefore, the results need to be scaled to understand the fire dynamics in anticipated tall wood buildings.

Of the 41 tests examined in the literature review of Brandon and Östman (2016), only six used oxygen consumption calorimetry to determine the heat release rate, which is considered the most important variable used to evaluate fire hazard (Babrauskas and Peacock 1992). Li and others (2015) found that CLT compartments with passive fire protection had similar heat release characteristics to those of light-steel-framed compartments. Furthermore, in a completely unprotected all-CLT compartment (that is, all wall and ceiling CLT exposed), the total heat released was approximately double that of the encapsulated room, although the gas temperatures were similar to the encapsulated room.

In summary, the data on CLT compartments show that CLT does not contribute to the fire in fully protected compartments. Although there has been limited work exploring what happens when CLT surfaces are exposed, these tests have been performed on compartments that are smaller than traditional dwelling units and may or may not have had the heat release determined during the tests.

This report presents the results of five full-scale compartment fire tests performed under an oxygen calorimetry heat release rate hood on a two-story CLT building. The tests examined the effect of exposed walls and ceilings on a realistic, full-size apartment to better understand the contribution of CLT to a compartment fire, life safety of occupants, and firefighter safety. Additionally, two tests examined the effect of automatic sprinkler systems. The research was carried out in support of the mission of the ICC Ad Hoc Committee on Tall Wood Buildings.

Experiment Setup

Experiments were conducted inside of a structure designed to represent a two-story apartment building. The design was developed with the input and approval of the ICC Ad Hoc Committee on Tall Wood Buildings and was based on high-rise construction. Each apartment contained areas designated for a living room, kitchen, bedroom, bathroom, and utility–laundry room. A corridor ran along two sides of the apartment, with one end connecting to a stairwell and the other end opened to the laboratory space. The overall layout of each floor was identical, except for a doorway between the stairwell and the laboratory space on the first floor of the structure. Figure 1 is a plan view drawing of the test structure, illustrating the basic layout. Figure 2 is an elevation view of the front of the structure.

Each apartment was 9.14 m wide by 9.14 m deep by 2.74 m high (30 ft wide by 30 ft deep by 9 ft high). The L-shaped corridor was 1.52 m wide and 2.74 m high (5 ft wide and 9 ft high). The stairwell was 2.44 m wide by 4.88 m deep (8 ft wide by 16 ft deep).

Building Construction

An overview of the test structure is provided in this section. The test structure was built by Lendlease Corporation (Sydney, Australia) with industry-standard CLT construction methods and techniques according to the ICC Ad Hoc Committee on Tall Wood Buildings (TWB) proposed Type IV-A (test 1), IV-B (tests 2 and 3), and IV-C (test 4 and 5) construction. For the proposed Type IV-A, a 3-h fire resistance rating is required for primary structural frame and exterior bearing walls and a 2-h rating is required for floor construction. For proposed Type IV-B and IV-C, a 2-h fire resistance rating is required for the primary structural frame, exterior bearing walls, and floor construction.

Walls

The load-bearing walls of the test structure were made of CLT. The interior walls in the apartment were non-load-bearing walls and were constructed with metal studs, glulam columns, and gypsum wallboard. The walls of interest in this report are identified by the letters A through G, as illustrated in Figure 3. Walls A through F are CLT walls, and Wall G is an interior wall.

CLT Walls

The CLT structure was built with a balloon frame construction method, with the walls extending from the bottom of the first floor to the top of the second floor. Each complete wall was a series of CLT panels fastened together. Wall panels were connected together with half lap joints, with 152-mm- (6-in.-) long self-tapping screws at 203 mm

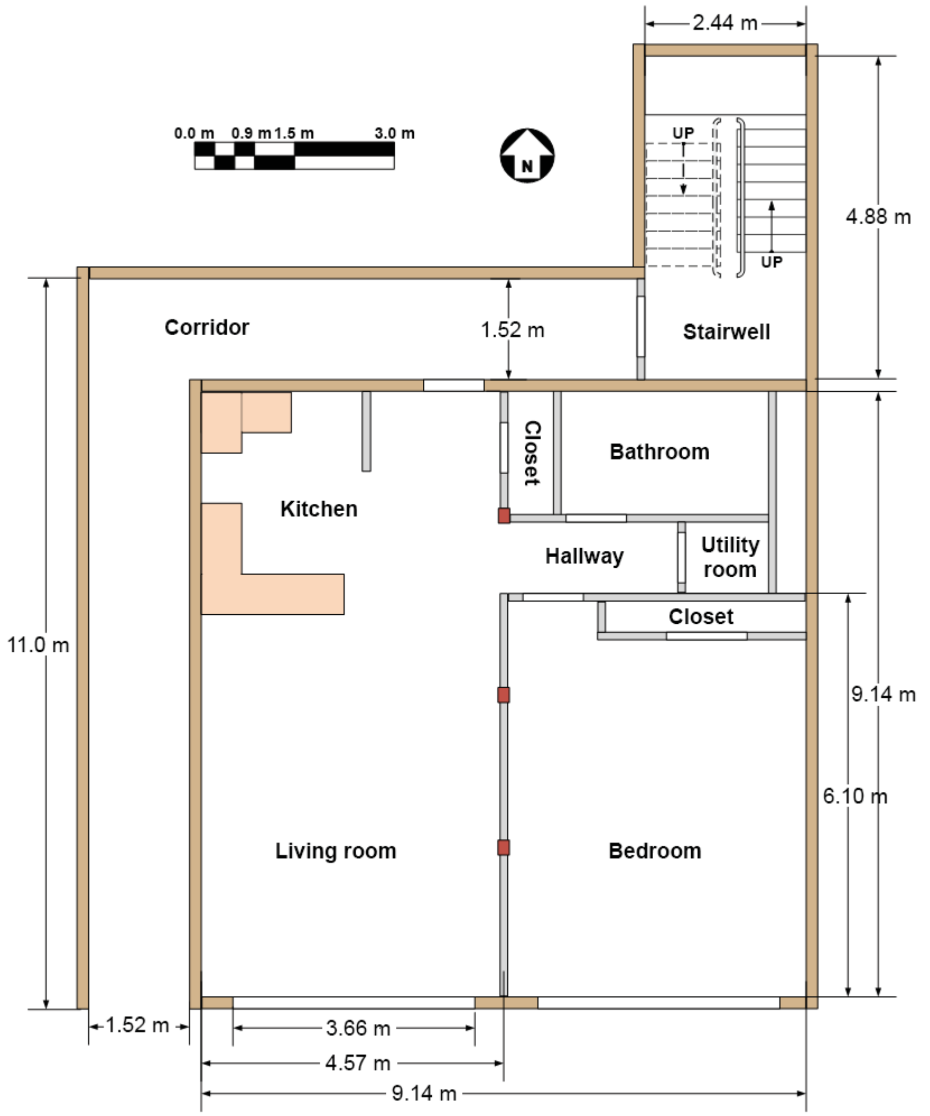


Figure 1. General plan view of cross-laminated timber test structure.

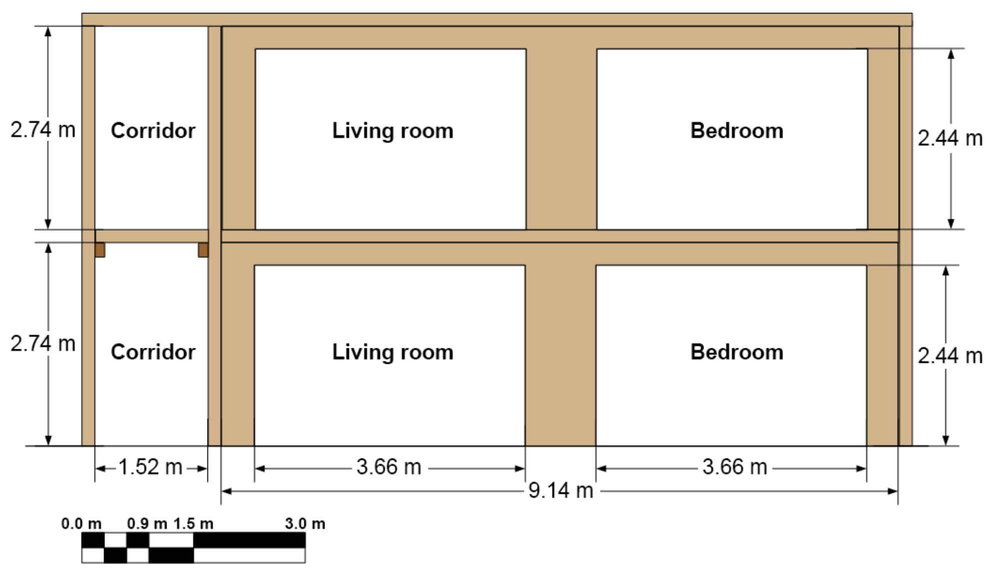


Figure 2. Elevation view of the front of the cross-laminated timber test structure.

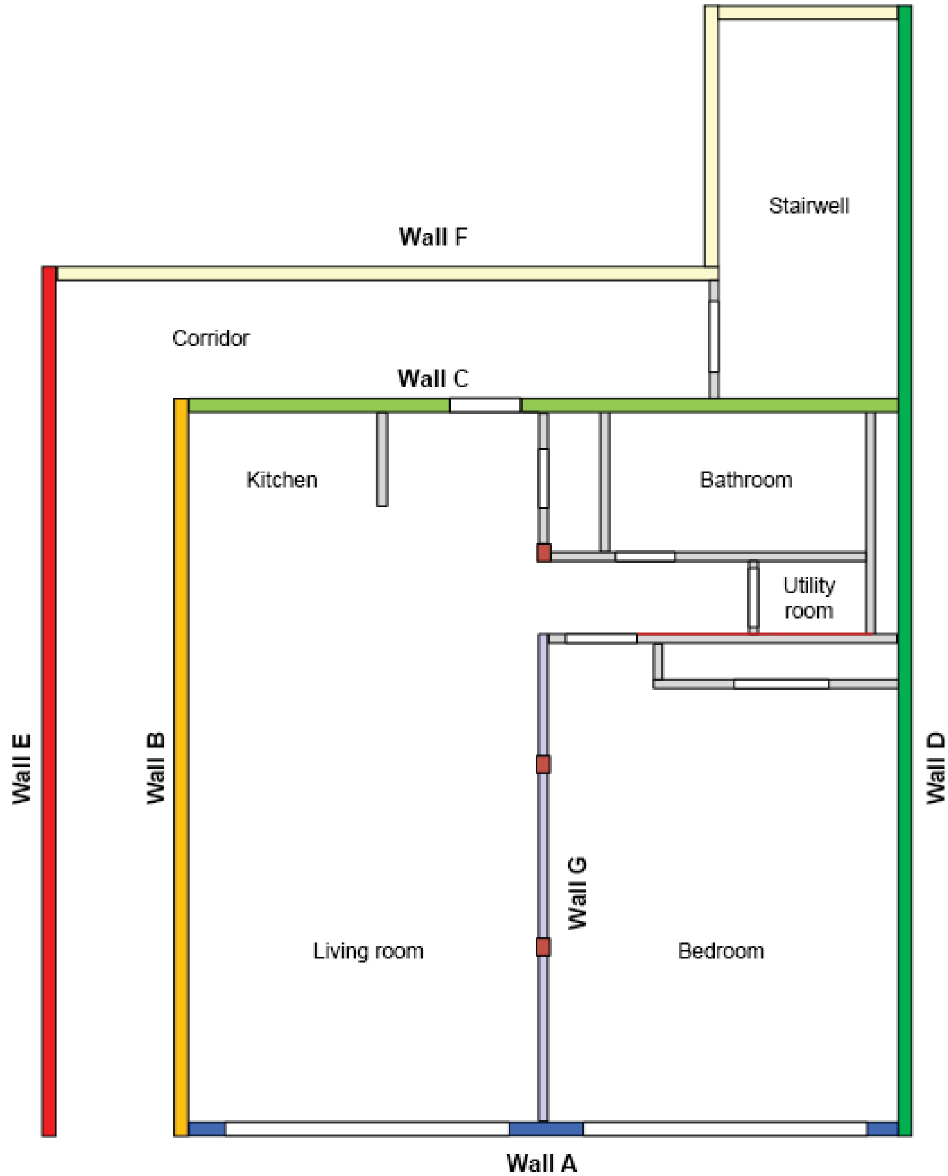


Figure 3. Letter designations for the walls.

(8 in.) on center along the joints. A continuous bead of intumescent caulk was applied at the panel interface along the half lap joints. The floor and roof panels were joined together with a spline joint. Self-tapping screws were installed at opposing 45° angles, 607 mm (24 in.) on center, and staggered on each side of the joint. The CLT wall panels ranged in size up to 2.44 m (8 ft) wide and approximately 5.79 m (19 ft) tall. The wall panels were installed using a crane and variable reach fork lift. Figure 4 shows one of the wall panels being installed.

The structure had six walls constructed of CLT. The walls consisted of five-ply CLT, resulting in a total thickness of approximately 175 mm (6.89 in.). The CLT was manufactured with Douglas Fir-Larch and a polyurethane adhesive. Figure 5 shows a cross section of a CLT panel.

Walls B, E, and F did not contain any fenestrations. Wall C contained an opening for the apartment door. Wall D contained a doorway from the stairwell to the laboratory space on the first floor (not shown in Fig. 3). Wall A contained two openings on each floor, and each opening measured 3.66 m wide by 2.44 m high (12 ft wide by 8 ft high). A large opening also existed in the corridor that was created between Walls B and E. The opening in the corridor measured approximately 1.52 m wide by 2.74 m high (5 ft wide by 9 ft high).

Interior Walls

Interior walls were used to define spaces within the apartment (Fig. 1). The interior walls were framed with steel studs and then covered with a single layer of 12.7-mm-(1/2-in.-) thick gypsum wallboard (UltraLight Brand

Figure 4. Installation of a cross-laminated timber wall panel.

Figure 5. Cross section of the five-ply cross-laminated timber panel.

Sheetrock, USG Corporation, Chicago, Illinois, USA) on each side of the metal studs. The wallboard seams and joints were taped and covered with joint compound. The walls were not painted.

Floor–Ceiling

First-Level Floor

The test structure was built directly on the concrete floor of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL) large burn room. Therefore, no CLT floor assembly was present on the first floor of the structure. To protect the concrete floor during the tests, two layers of 12.7-mm- (1/2-in.-) thick cement board (Durock Brand Cement Board, USG Corporation) were placed on top of the concrete floor. The cement boards were staggered to overlap the seams.

Second-Level Floor

The second-level floor in the apartment and corridor was constructed of the same five-ply CLT as the CLT walls. The floor in the apartment was a series of CLT panels fastened together, and each panel spanned the width of the apartment from Wall B to D. Figure 6 shows one of the floor panels being installed. Each floor panel in the apartment was 9.14 m (30 ft) long and ranged up to 2.44 m (8 ft) wide.

Figure 6. Installation of a second-level floor panel.

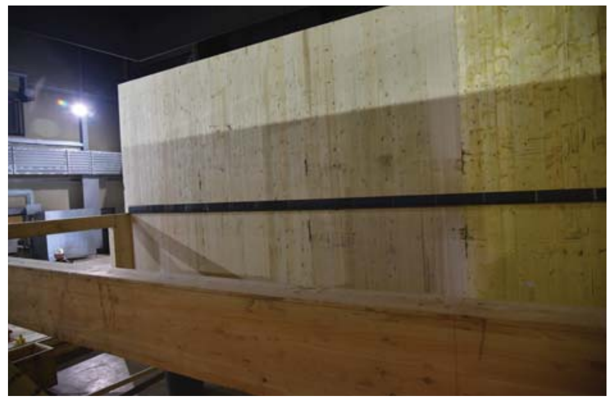


Figure 7. Steel angle located on Wall B to support the second-level floor in the apartment.

The floor in each corridor was a single CLT panel that was 1.52 m (5 ft) wide and ranged up to approximately 9.45 m (31 ft) long. The CLT floor assemblies were protected on top with two layers of 12.7-mm- (1/2-in.-) thick cement board (Durock Brand Cement Board, USG Corporation) to simulate the protection from a typical noncombustible subfloor layer such as gypsum concrete. The cement boards were staggered to overlap the seams.

The CLT used in the second-level floor was elevated 2.74 m (9 ft) above the first floor with a combination of support methods, including steel angles, glulam ledgers, and glulam beams and support columns.

Steel Angle

The second-level apartment floor was supported along Wall B with sections of steel angle (Fig. 7). The steel angle was 178 mm high by 102 mm wide by 9.5 mm thick (7 in. high by 4 in. wide by 3/8 in. thick). Each section of steel angle was 610 mm (24 in.) long.

As shown in Figure 8, the bottom of the CLT floor panel was notched, which allowed the CLT panel to be approximately flush with the bottom of the steel angle. After the second-level floor was installed, the bottom of the steel angle was protected with 2 by 10 dimension lumber (Fig. 9).

Figure 8. Cross-laminated timber floor panel on steel angle.

Figure 9. Wood covering bottom of steel angle.

Figure 10. Ledger on Wall D to support second-level floor in the apartment.

Figure 11. Second-level floor on top of the ledger.

The seams and joints along the 2 by 10 dimension lumber were sealed with an intumescent firestop sealant (FS-One Max, Hilti Corporation, Schaan, Liechtenstein), which can also be seen in Figure 9.

Ledger

The second-level apartment floor was supported along Wall D with a ledger (Fig. 10). The ledger consisted of five-ply glulam timber and was approximately 187 mm high by 130 mm wide (7-3/8 in. high by 5-1/8 in. wide). The bottom of the floor panel sat on top of the ledger (Fig. 11). The seams and joints along the ledger were sealed with an intumescent firestop sealant (FS-One Max).

The floor in the corridors was also supported with glulam ledgers. Ledgers were located on Walls E and B and on Walls F and C. Figure 12 shows the ledgers along Walls C and F.

Midspan Beam and Support Columns

The second-level apartment floor was supported midspan with glulam beams and support columns (Fig. 13). The midspan beam consisted of nine-ply glulam timber and was

Figure 12. Ledgers in the corridor along Walls C and F.

Figure 13. Original midspan beams and support columns on the first floor.

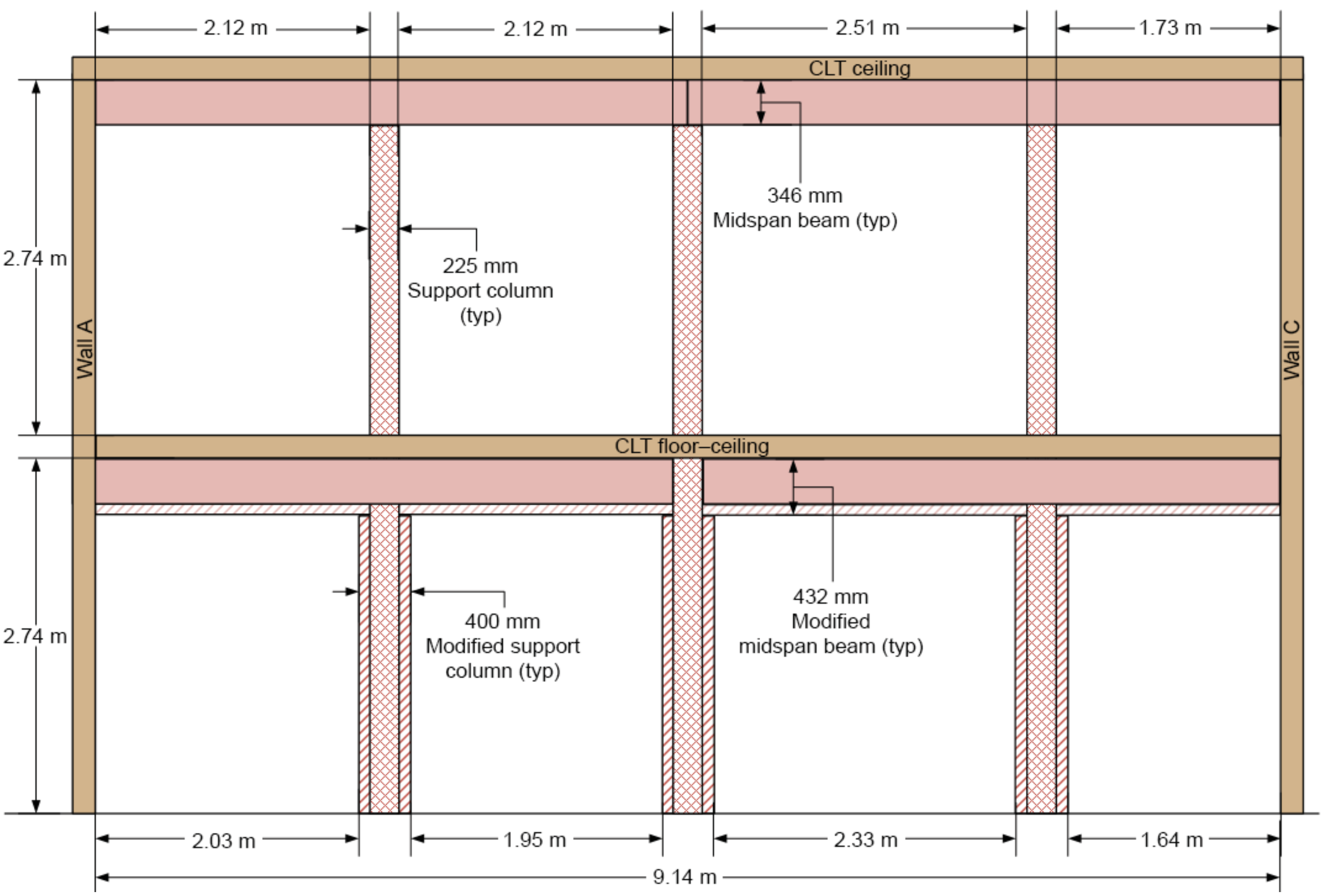


Figure 14. Cross-sectional view of apartment showing locations of support columns.

divided into two sections. Each section was approximately 4.46 m (14.7 ft) long, and the beam was 346 mm high by 171 mm wide (13-5/8 in. high by 6-3/4 in. wide). As illustrated in Figure 14, the first beam spanned from Wall A to the side of the middle support column and the second beam spanned from the side of the middle support column to Wall C. The three support columns consisted of six-ply glulam timber and were approximately 225 mm wide by 171 mm deep (8-7/8 in. wide by 6-3/4 in. deep). The middle column was 2.74 m (9 ft) tall, and the other two columns were approximately 2.41 m (7 ft 11 in.) tall. The seams and joints at connections between the beam and support columns were sealed with an intumescent firestop sealant (FS-One Max).

The beams and support columns on the first level were protected with additional wood cover to achieve a 2-h fire resistance rating, designed in accordance with Chapter 16 of the National Design Specification (NDS). Therefore, total depth of the beams on the first level was approximately 432 mm (17 in.) and total width was approximately 343 mm (13-1/2 in.). Support columns on the first level had a total width of approximately 400 mm (15-3/4 in.) and a depth of approximately 343 mm (13-1/2 in.). This additional wood protection was added to the beams and columns on the first level because they were exposed (that is, no gypsum wallboard protection) in Test 4 and Test 5. Figure 15 shows the wood protection added to the support columns and beams on the first level. Figure 16 shows the protected beams and support columns. Although not shown in Figure 16, the seams and joints formed by adding the additional material were sealed with an intumescent firestop sealant (FS-One Max).

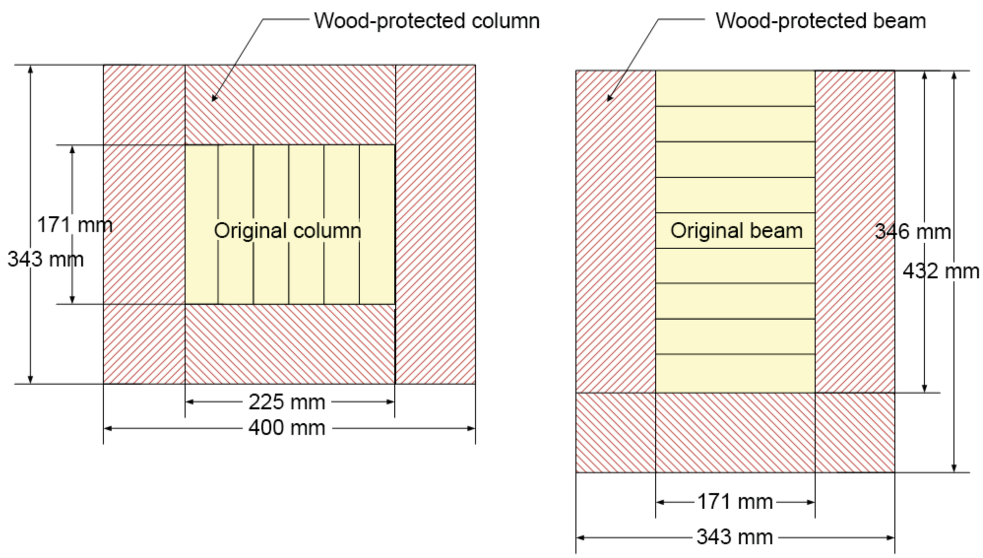


Figure 15. Cross-sectional view of a support column and midspan beam illustrating the wood protection added to achieve a 2-h fire resistance rating.

Figure 16. Wood-protected support columns and beams on first floor.

Second-Level Ceiling

The second-level ceiling was constructed of the same five-ply CLT as the CLT wall and floor assemblies. The ceiling was a series of CLT panels fastened together. Each panel spanned the entire width of the structure from Wall E to D. Figure 17 shows a ceiling panel being installed. The panels ranged up to approximately 11.3 m (37 ft) long and up to 2.44 m (8 ft) wide. The exterior surface of the CLT ceiling assembly (that is, the “roof” of the test structure) was protected with two layers of 12.7-mm- (1/2-in.-) thick cement board (Durock Brand Cement Board, USG Corporation) to simulate protection from a typical noncombustible subfloor layer such as gypsum concrete, which would generally be present on the level above in an actual tall wood building.

The CLT used in the second-level ceiling was elevated 2.74 m (9 ft) above the CLT floor. The ceiling panels were placed on top of the CLT walls; therefore, no additional supports were required at the edges of the ceiling panels. The seams and joints formed between the ceiling panels and the walls were sealed using an intumescent firestop sealant (FS-One Max). Figure 18 illustrates the interface between ceiling panels and the CLT wall. The ceiling was also supported midspan in the apartment by a support beam and columns (Fig. 19). The glulam support beam and columns were identical to the original ones discussed in the previous section. However, the beams and columns on the second level were protected with two layers of 15.9-mm (5/8-in.) Type X gypsum wallboard for each of the tests performed on that level. No additional wood protection was added to them. Figure 14 illustrates the location of the support columns on the second-level floor.

A 1.22-m- (4-ft-) high section of wall was constructed on the ceiling panel along Wall A (Fig. 20). This additional wall was built to simulate a portion of a third level. The wall was framed using standard dimensional 2 by 4 lumber and was sheathed with two layers of 15.9-mm- (5/8-in.-) thick fire-rated (Type X) gypsum wallboard.

Figure 17. A second-level ceiling panel being installed.

Figure 18. Second-level ceiling supported by Wall D.

Figure 19. Support beam and columns on the second floor.

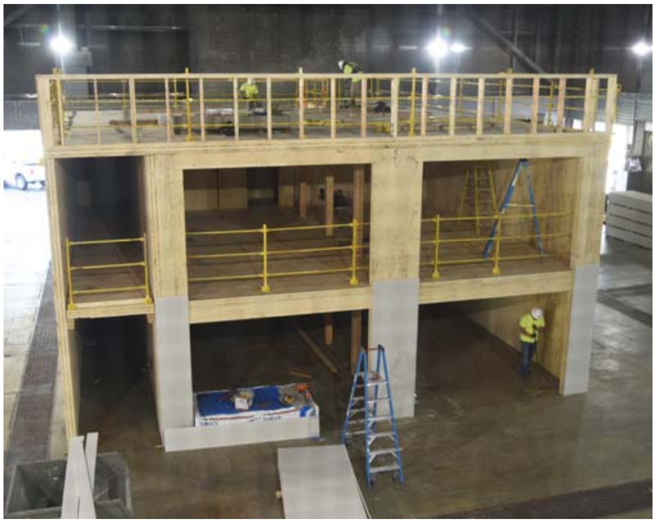


Figure 20. Partial wall constructed along the top of Wall A.

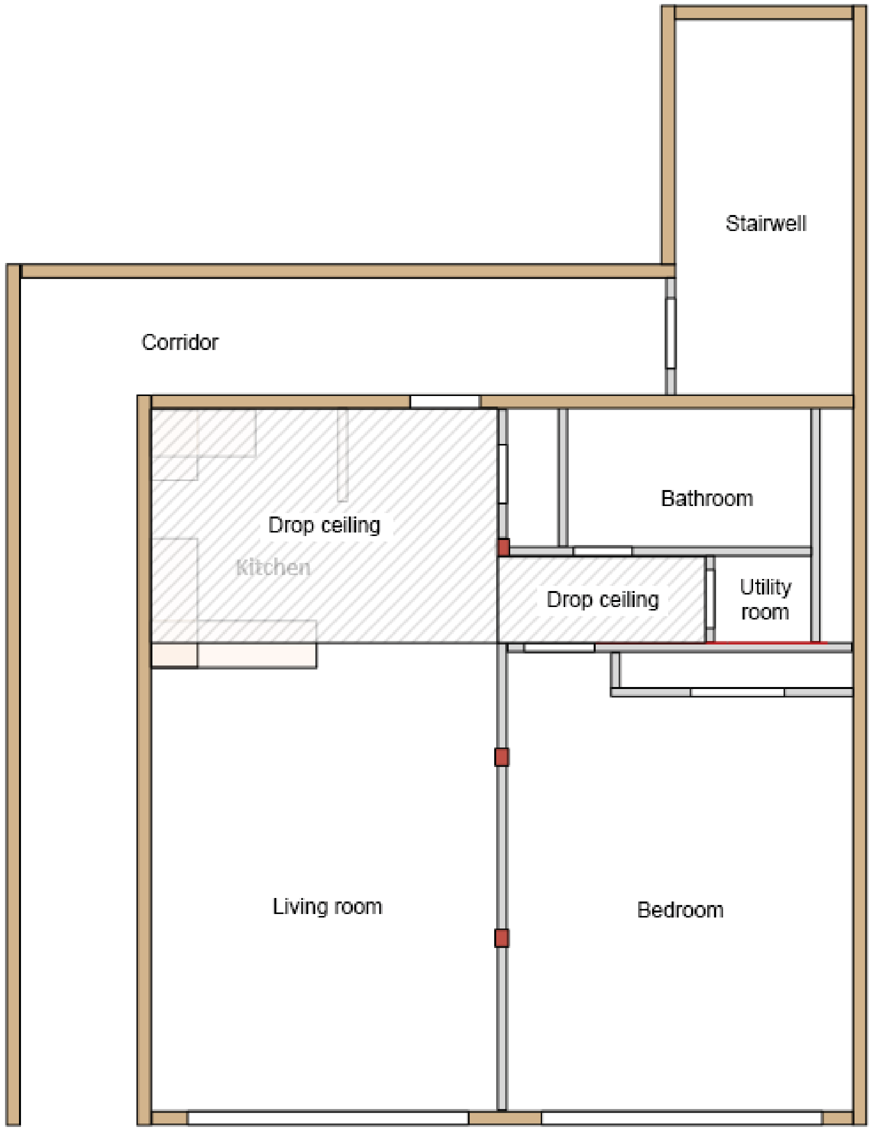


Figure 21. Drop ceiling locations.

Figure 22. Drop ceiling in the kitchen.

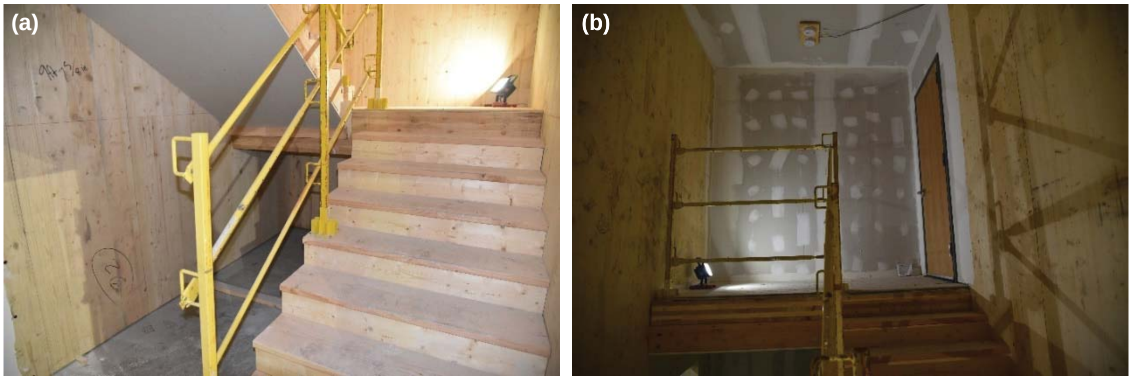


Figure 23. Stairwell: (a) first floor; (b) second floor.

Drop Ceiling

The nominal height between the floor and the CLT ceiling was 2.74 m (9 ft). The exception to this was in the kitchen area and in the hallway between the bedroom and the bathroom. As illustrated in Figure 21, these two areas had a drop ceiling. The drop ceiling was framed using metal studs and sheathed with a single layer of 12.7-mm- (1/2-in.-) thick gypsum wallboard. The nominal height between the floor and the drop ceiling was approximately 2.44 m (8 ft). Figure 22 shows the drop ceiling in the kitchen. The CLT above the drop ceiling was protected with two layers of 15.9-mm- (5/8-in.-) thick fire-resistant gypsum wallboard (Type X); the ICC code proposal states that all combustible surfaces within concealed spaces should be protected with noncombustible protection.

Figure 24. Fire door assembly between corridor and stairwell.

Stairwell

A stairwell was located on the northwest corner of the test structure and was connected to the corridor on each level. The stairwell was 2.44 m wide by 4.88 m long by approximately 5.79 m high (8 ft wide by 16 ft long by 19 ft high). Figure 23 shows the stairwell. A 0.9-m- (36-in.-) wide door with a fire protection rating of 90 min was located between the stairwell and the corridor. The door was hung in a metal frame and had an automatic door closer (Fig. 24). In addition to the fire door assembly, a doorway was located on the west wall (Wall D) of the stairwell on the first level, which opened to the laboratory space (Fig. 25).

Figure 25. Doorway in stairwell.

Doors

A fire door assembly was located between the apartment and the corridor (Fig. 26). The 914-mm- (36-in.-) wide door had a fire protection rating of 20 min. The door was hung in a metal frame, and it had an automatic door closer. This door was purposely propped open for Test 5 but left closed in all other tests.

In addition to the fire door assembly, the apartment had five standard, hollow-core interior doors. The bedroom and the bathroom each had a 0.9-m- (36-in.-) wide door. The closet near the apartment entrance and the utility room each had

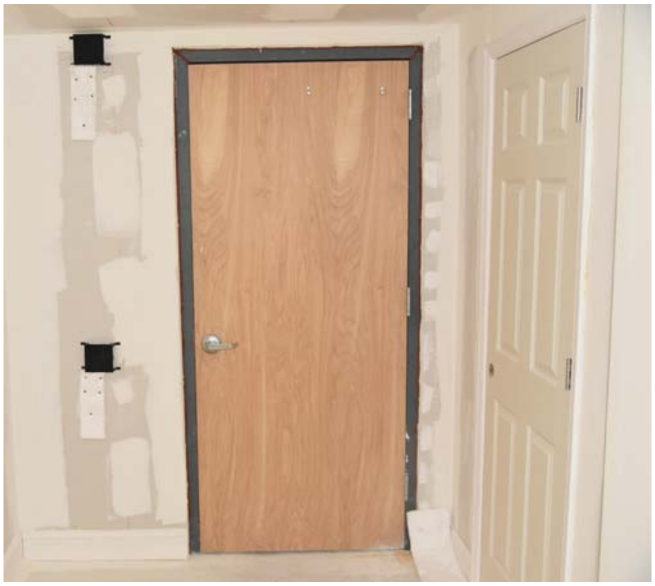


Figure 26. Fire door assembly in apartment.

Figure 27. Window installed in Wall A for Tests 4 and 5.

a 0.76-m- (30-in.-) wide door. The bedroom closet had a double door with an overall width of 1.2 m (48 in.).

Windows

Wall A had two large openings on each floor, one in the bedroom and one in the living room. Each opening measured 3.66 m wide by 2.44 m high (12 ft wide by 8 ft high). For Tests 4 and 5, tempered glass that was 6.35 mm (1/4 in.) thick was installed in each opening. A metal window frame with plastic trim was used to secure the glass. As shown in Figure 27, the window frame divided the opening into three sections. Each opening in the window frame was approximately 1.15 m (3.78 ft) wide by 2.34 m (7.67 ft) high.

HVAC, Electrical, and Plumbing Components

Although the test structure was designed to look like an apartment, it did not have functional utilities, such as electricity or water. However, for the first two tests, several components were included in the structure that were associated with a heating, ventilation, and air conditioning (HVAC) system, an electrical system, and a plumbing system.

HVAC System

Metal ducts were placed in the void space in the drop ceiling above the kitchen and in the hallway to simulate part of an HVAC system. Three sections of 203-mm- (8-in.-) diameter metal duct were used but were not connected to anything. Two ducts terminated at an opening into the living room, and one duct terminated at an opening to the bedroom. Each opening was covered with an air grille that was 254 by 254 mm (10 by 10 in.). Figure 28 shows the air grilles in the living room.

Figure 28. HVAC duct openings in drop ceiling.

Electrical System

To simulate electrical wiring in the apartment, metal conduit, electrical boxes, and receptacles were placed within Wall G and behind the baseboard along Walls B and D. Figure 29 shows the electrical components placed in Wall G between the living room and the bedroom. Figure 30 shows the electrical components placed behind the baseboard along Wall B in the living room.

Plumbing System

Several penetrations were made through the second level floor to simulate plumbing penetrations between the floors. For Tests 1 and 2, penetrations were made in the bathroom, utility room, and kitchen. Plumbing pipes were placed through the penetrations and were visible on the first and second floors (Figs. 31 and 32). In the kitchen, the plumbing pipes were not visible on the first floor because the pipes were hidden within the void space of the drop ceiling.

Figure 29. Electrical components in Wall G.

Figure 30. Electrical components along Wall B in the living room.

Figure 31. Plumbing penetrations in the utility room on second-floor level.

Figure 32. Plumbing penetrations in the utility room on the first-floor level.

Firestop plugs (CFS-PL 2”, Hilti) and firestop foam (Fire Foam CP620, Hilti) were used to seal the voids spaces around the pipes.

Passive Fire Protection

Fire-Resistant Gypsum Wallboard

Two layers of 15.9-mm- (5/8-in.-) thick fire-resistant gypsum wallboard (Sheetrock Brand Firecode X Type X, USG Corporation) were used as passive fire protection on various mass timber surfaces in each test. The gypsum wallboard was staggered during installation to overlap the seams. All drywall seams were taped and finished with joint compound.

Certain sections of mass timber within the test structure were protected with two layers of 15.9-mm- (5/8-in.) gypsum wallboard in all five tests. These sections included both the walls and ceiling in the kitchen, bathroom, utility room, and corridors and the ceiling in both the hallway and bedroom closet. Also, a portion of the stairwell was protected. Prior to the interior walls being constructed, the gypsum wallboard was installed on the CLT ceiling and walls in these areas. Passive protection of the other CLT wall and ceiling surfaces varied by experiment and is summarized in Table 1.

During Test 1, all mass timber surfaces were fully covered with passive protection. There were no exposed mass timber surfaces.

During Test 2, a portion of the ceiling in the living room and bedroom was exposed. Each exposed CLT section was 2.74 m wide by 3.05 m long (9 ft wide by 10 ft long), which represented 30% of the total ceiling in these areas. Figure 33 shows the exposed CLT on the living room ceiling. Also shown in Figure 33 is the wood trim that was used to protect the edge of the gypsum wallboard. As illustrated in Figure 34, the trim consisted of 2 by 4 dimension lumber that was placed along the edge of the gypsum wallboard. 2 by 6 dimension lumber was then placed on top, covering the 2 by 4 lumber and gypsum wallboard edge. The gaps

Table 1—Summary of cross-laminated timber wall and ceiling surfaces that were either exposed or protected with Type X gypsum wallboard during each experiment

Test	Wall A	Wall B	Wall C	Wall D	Ceiling
1	Protected	Protected	Protected	Protected	Protected
2	Protected	Protected	Protected	Protected	Partially exposed in living room and bedroom
3	Protected	Exposed in living room	Protected	Exposed in bedroom	Protected
4	Protected	Exposed in living room	Protected	Exposed in bedroom	Exposed in living room and bedroom
5	Protected	Exposed in living room	Protected	Exposed in bedroom	Exposed in living room and bedroom

Figure 33. Exposed cross-laminated timber ceiling in the living room for Test 2.

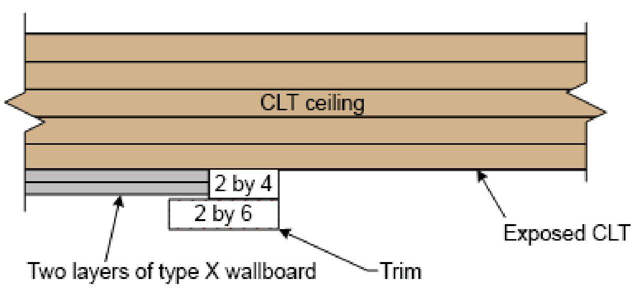


Figure 34. Trim added to exposed cross-laminated timber ceiling to protect edge of gypsum wallboard.

and seams around the trim, particularly the gap between the top edge of the 2 by 6 and the bottom surface of the gypsum wallboard, were sealed with an intumescent firestop sealant.

During Test 3, Wall B in the living room was exposed, as was Wall D in the bedroom. Figure 35 shows the exposed CLT wall in the living room (Wall B). The edge of the gypsum wallboards that ended at the exposed CLT wall was protected by placing a section of 2 by 4 dimension lumber or 2 by 6 dimension lumber there.

Figure 35. Exposed cross-laminated timber wall in the living room for Test 3.

Figure 36. Exposed cross-laminated timber ceiling and glulam support columns and beams in the living room for Tests 4 and 5.

Figure 37. Exposed ledger in the bedroom for Tests 4 and 5.

Figure 38. Exposed wood covering angle iron in the living room for Tests 4 and 5.

Figure 39. Wood trim placed along the edge of the gypsum wallboard on the ceiling.

Figure 40. Cross-laminated timber joints sealed with intumescent firestop sealant.

In Tests 4 and 5, all CLT walls and ceilings in the living room and bedroom were exposed. The glulam support columns and midspan beams were also exposed (Fig. 36). Although a portion of each column and beam was concealed by the steel stud infills of Wall G, the infills were unrated. In addition, the ledger and the wood covering the angle iron were also exposed, as shown in Figures 37 and 38, respectively.

Also in Tests 4 and 5, a small portion of the ceiling in the bedroom near the door and the closet were covered with gypsum wallboard. The edge of the wallboard next to the exposed CLT was protected with a section of dimensional 2 by 4 lumber that was placed along the edge of the wallboard (Fig. 39).

Firestop Sealants

Several different firestop sealants were used to inhibit the passage of smoke and flames through other penetrations in the CLT panels and between the CLT panel assemblies. An intumescent firestop sealant (FS-One Max) was used at various locations throughout the structure to fill any gaps formed between adjacent CLT assemblies and at other locations where hot gasses could otherwise pass through an assembly. Figure 40 shows an example of where the firestop sealant was applied. Firestop plugs (CFS-PL 2”, Hilti Corporation) and firestop foam (Fire Foam, CP620, Hilti Corporation) were also used to seal the annular spaces within penetrations such as those for the pipes supplying water to the fire suppression system.

Active Fire Protection

A fire sprinkler system was installed in the first floor apartment for Tests 4 and 5. The sprinklers were designed in accordance with National Fire Protection Association (NFPA) Standard 13, with a design area density of 2 mm/min (0.05 gpm/ft^2) (light hazard). This design density is less than that which would be required by code for this type of structure and can be conservatively applied to code-compliant tall mass timber construction. The sprinkler system was designed and installed by DC Fire Protection, LLC (Washington, DC, USA). Figure 41 provides the general layout of the sprinkler heads. Pendent-style sprinkler heads were placed in the interior areas of the apartment (kitchen, hallway, and utility room). Sidewall-type sprinkler heads were installed along the walls in the living room, bedroom, and bathroom. Details of the sprinkler heads are provided in Table 2.

The sidewall sprinklers in the living room were located approximately 0.25 m (99 in.) above the finished floor. The sidewall sprinklers in the bedroom were located approximately 0.24 m (94 in.) above the finished floor. The pendent sprinklers in the kitchen and the hallway were located approximately 50.8 mm (2 in.) below the drop ceiling or approximately 0.22 m (87 in.) above the finished floor. Although a drop ceiling was not present in the utility room, the pendent sprinkler was also located approximately 0.22 m (87 in.) above the finished floor.

A 102-mm- (4-in.-) diameter steel standpipe was located on the exterior of Wall D. Near the bottom of the standpipe was a shutoff valve and a connection for a fire hose. Near the top of the standpipe was a 38.1-mm (1-1/2-in.) steel pipe that connected the standpipe to the sprinkler circuit. The cross mains for the sprinkler circuit consisted of 38.1-mm- (1-1/2-in.-) diameter steel pipe, and the branch lines were 25.4-mm- (1-in.-) diameter steel pipe. All fittings were threaded.

The sprinkler system was connected to an isolated water supply (blue water) in the laboratory, which was separate from the municipal water supply. The standpipe on the test structure was connected to one of the blue water standpipes in the laboratory using two sections of 63.5-mm- (2-1/2-in.-) diameter fire hose, which were each 15.2 m (50 ft) long. The static water pressure in the blue water standpipe varied, based on the number of diesel pumps operating. Prior to sprinkler activation, the static pressure was approximately 1.1 MPa (160 lb/in^2).

For Test 4, the entire sprinkler system was charged with water prior to the start of the test. For Test 5, the entire system was not charged with water, to prevent the sprinklers from activating before the desired delay time had occurred. When it was time to activate the sprinklers during Test 5, a valve on the blue water standpipe was manually opened, allowing water to flow to the test structure.

Fuel Load

The fuel load for each experiment consisted of a variety of items and included furniture, kitchen cabinets, wood cribs, sheets of oriented strand board (OSB), and other miscellaneous items, such as books and plastic shelves. The calculated average fuel load provided by the furniture, books, cabinets, combustible flooring (OSB), and additional lumber and wood cribs was 550 MJ m^{-2}. If the additional fuel load of the paper on the gypsum wall board is included in the calculation, the total fuel load was 570 MJ m^{-2}. Thus, the specified fuel load of 550 MJ m^{-2}, as established by the ICC Ad Hoc Committee on Tall Wood Buildings, was met or exceeded in each test.

Furniture

Table 3 provides a summary of the furniture used in each experiment. Figure 42 is a sketch showing the general location of the furniture items in the apartment. For a given test, the exact location may have varied slightly, but the item would have still been in the same general location. Figures 43 and 44 show the furniture as positioned in the living room and bedroom, respectively, for Test 1.

Kitchen Cabinets

Cabinets were installed in the kitchen along Wall B, Wall C, and between the living room and kitchen. Details of the base cabinets and wall cabinets are provided in Table 4. The cabinets were obtained from two suppliers because of a lack of inventory at any one supplier. Therefore, information from both suppliers is provided in Table 4. The kitchen countertop for the base cabinets was simulated using 19.1-mm- (3/4-in.-) thick plywood.

Figure 45 shows the layout of the wall cabinets and the base cabinets. The bottom of the wall cabinets was installed approximately 0.46 m (18 in.) above the kitchen countertop, which resulted in a gap of approximately 0.25 m (10 in.) between the top of the cabinets and the drop ceiling. Figure 46 shows the cabinets as installed in the kitchen.

Additional Wood

Additional wood was added in the test structure to achieve the target fuel load specified by the ICC Ad Hoc Committee on Tall Wood Buildings. The additional wood included 20 sheets of 1.22-m-wide by 2.44-m-long by 11.1-mm-thick (4-ft-wide by 8-ft-long by 7/16-in.-thick) OSB. The OSB sheets, which were used to simulate a combustible floor covering by providing a similar amount of fuel load to that of hardwood flooring, were placed on top of the cement board, which made up the finished floor of the test structure. In addition, 300 pieces of 1 by 3 dimension lumber that was 2.44 m (8 ft) long were used. The 1 by 3 lumber was cut into smaller pieces and used for the wood slats in the bed frame and to make wood cribs. The wood cribs were placed

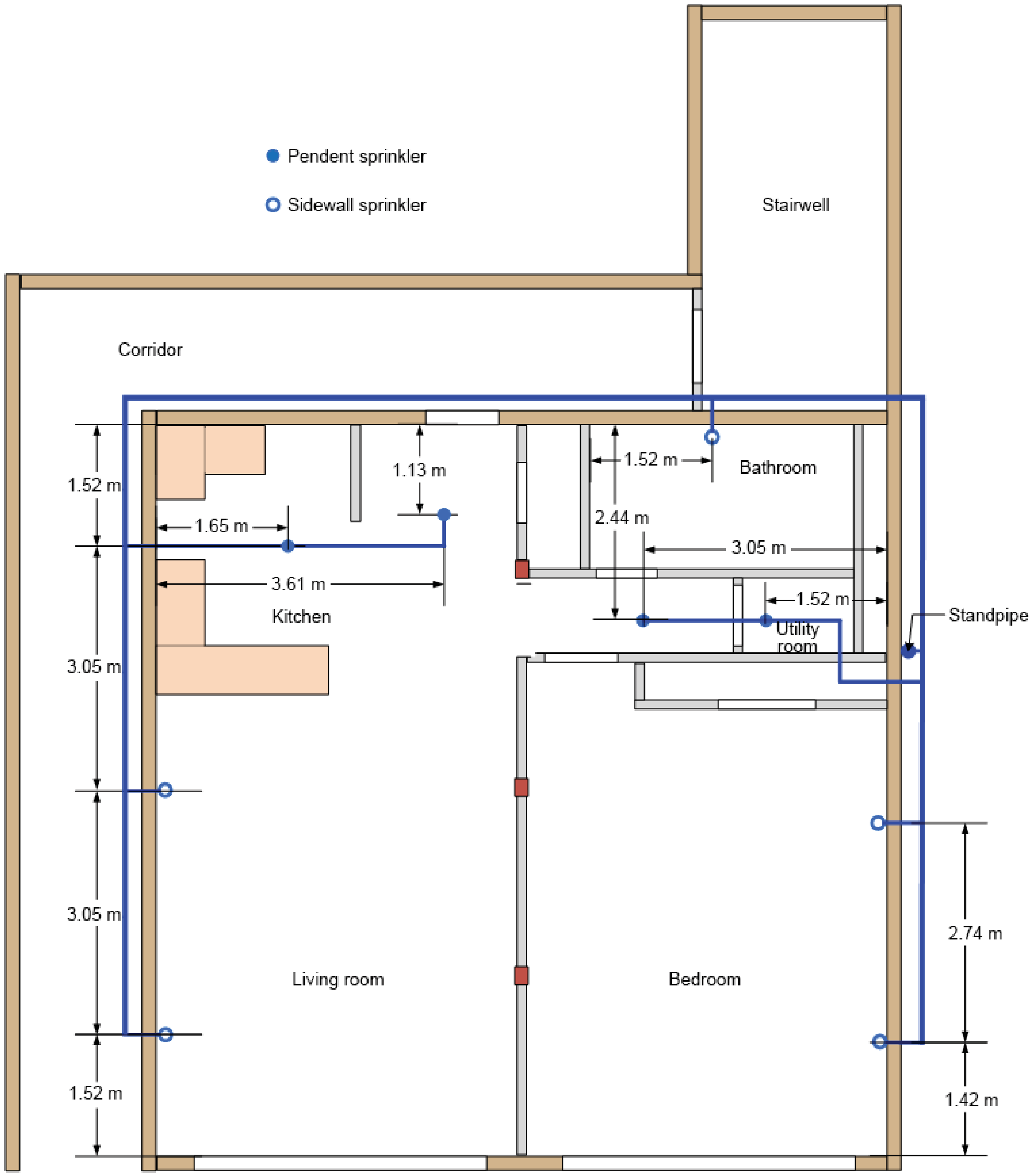


Figure 41. Sprinkler layout.

Table 2—Sprinkler head details

Type	Manufacturer	Model	K factor Lpm/bar$^{1/2}$ (gpm/psi$^{1/2}$)	Temperature °C (°F)	Quantity
Pendent	Globe[a]	GL3010	43.2 (3.0)	68.4 (155)	4
Sidewall	Tyco[b]	TY1334 Rapid Response	60.6 (4.2)	68.4 (155)	5

[a]Globe Fire Sprinkler Corporation, Standish, Michigan, USA.
[b]Tyco Fire Products, Lansdale, Pennsylvania, USA.

Table 3—Furniture

Description	Quantity	Supplier	Model	Item
Table	1	IKEA	Gamleby	602.470.27
Chairs	7	IKEA	Harry	201.058.31
Bookcases	4	IKEA	Billy	002.638.50
TV units	1	IKEA	Hemnes	702.970.45
8-drawer dresser	2	IKEA	Hemnes	003.185.98
Armchair frame	3	IKEA	Jennylund	300.475.48
Armchair cushions	3	IKEA	Jennylund	–
Sofa frame	2	IKEA	Ektorp	401.850.30
Sofa cushions	2	IKEA	Ektrop	–
Coffee table	1	IKEA	Hemnes	803.817.36
Night stands	7	IKEA	Tarva	502.196.09
Bed frame	2	IKEA	Hemnes	202.421.02
Mattress	2	IKEA	Morgedal	802.773.82
Desk	1	IKEA	Hemnes	502.821.44
Add-on unit for desk	1	IKEA	Hemnes	202.821.26

[a]IKEA, Leiden, The Netherlands.

Figure 42. General location of furniture.

Table 4—Kitchen cabinets

Description	Quantity	Supplier	Model	Item number
12-in.-wide base cabinet 305 mm wide by 889 mm tall by 610 mm deep (12 in. wide by 35 in. high by 24 in. deep)	2	Lowe's and Home Depot[a]	33 B12R B12OHD	336303 235119
60-in.-wide sink base cabinet 1.52 m wide by 889 mm tall by 610 mm deep (60 in. wide by 35 in. high by 24 in. deep)	1	Lowe's and Home Depot	33 SB60B SB60OHD	365987 369062
30-in.-wide base cabinet 762 mm wide by 889 mm tall by 610 mm deep (30 in. wide by 35 in. high by 24 in. deep)	2	Lowe's and Home Depot	33 B30B B30OHD	336288 356528
30-in.-wide wall cabinet 762 mm wide by 762 mm high by 305 mm deep (30 in. wide by 30 in. high by 12 in. deep)	2	Lowe's and Home Depot	33 W3030B W30300HD	336276 379839
24-in.-wide corner wall cabinet 610 mm wide by 762 mm high by 305 mm deep (24 in. wide by 30 in. high by 12 in. deep)	1	Lowe's and Home Depot	33 DC2430R W2430OHD	336287 377881
30-in.-wide bridge cabinet 762 mm wide by 305 mm high by 305 mm deep (30 in. wide by 12 in. high by 12 in. deep)	1	Home Depot	W3012OHD	756067
18-in.-wide wall cabinet 457 mm wide by 762 mm high by 305 mm deep (18 in. wide by 30 in. high by 12 in. deep)	2	Home Depot	W1830OHD	377811

[a]Lowe's Companies, Inc., Mooresville, North Carolina, USA; The Home Depot, Inc., Atlanta, Georgia, USA

Figure 43. Furniture and wood cribs in living room.

Figure 44. Furniture and wood cribs in bedroom.

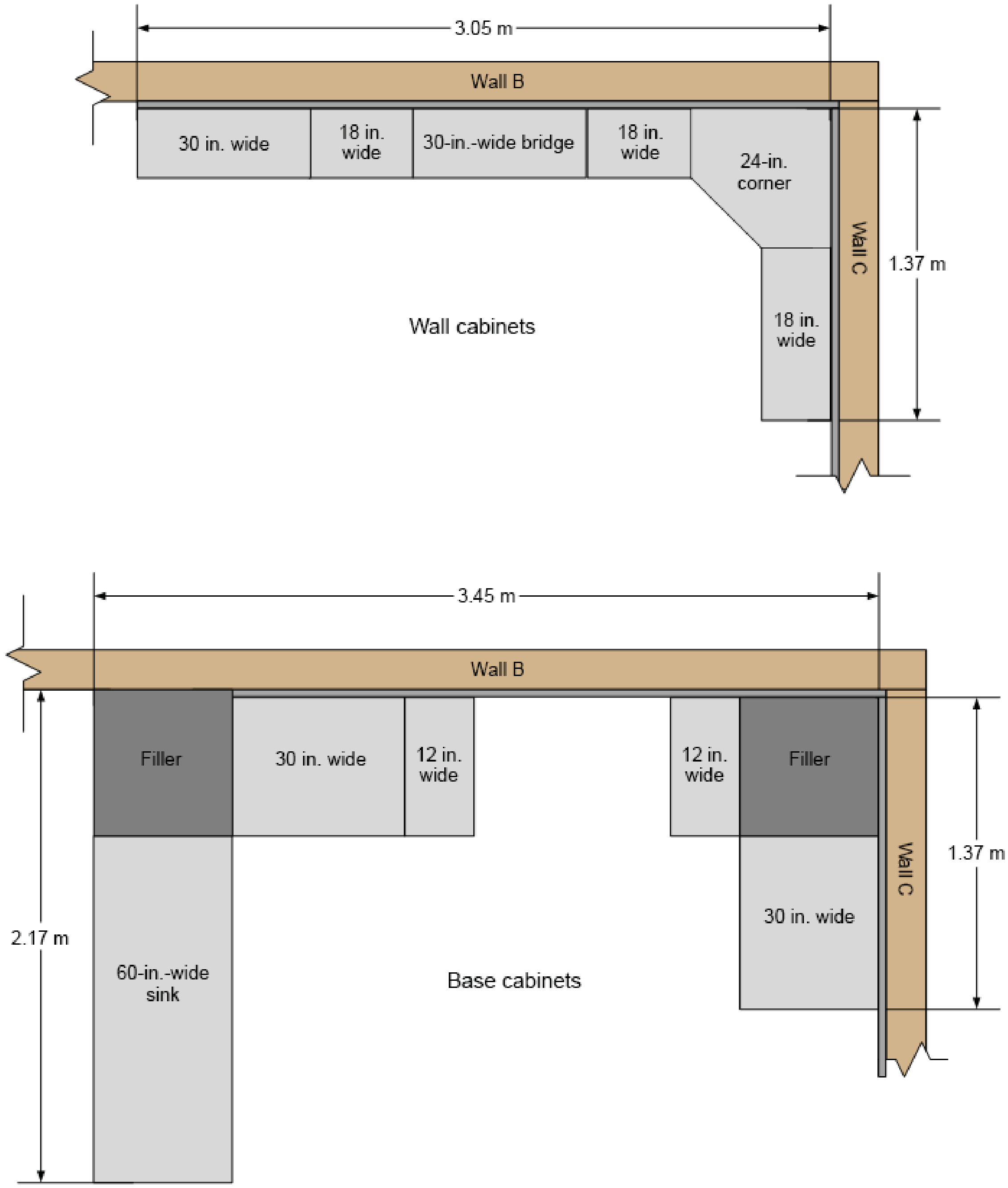


Figure 45. Plan view of wall cabinets and base cabinets in kitchen.

Figure 46. Kitchen cabinets and additional plywood covers.

Figure 47. Wood cribs and oriented strandboard added in the bedroom.

Figure 48. Plastic shelves and books in the bedroom.

Figure 49. Ignition package.

throughout the structure. Figure 47 shows several wood cribs that were added in the bedroom during Test 1. Also, sheets of OSB can be seen on the floor in Figure 47.

Miscellaneous Items

The overall fuel load in the structure was also increased by adding plastic shelves and paper books. Three plastic shelves were purchased from Walmart (Bentonville, Arkansas, USA) (Plano four-tier heavy duty, 1199594). Two plastic shelves were placed in the bedroom closet, and one shelf was placed in the utility room. In addition, 100 copies of the 2001 edition of the Wood Frame Construction Manual from the American Wood Council were added to the structure. The Wood Frame Construction Manuals added a total of 110 kg (243 lb) of paper books to the fuel load; 82 kg (181 lb) in the living room, and 28 kg (62 lb) in the bedroom. Figure 48 shows the plastic shelves in the closet and some books placed on the book shelf.

Ignition Package

The fire was initiated in a base kitchen cabinet along Wall C using an ignition package (Fig. 49). The ignition package was assembled by the FRL staff and consisted of a quart-size plastic bag that enclosed gasoline soaked paper towels and medical gauze rolled together.

The components of the ignition package consisted of rayon–polyester blend medical gauze (sterile premium rolled gauze, CVS Pharmacy, Woonsocket, Rhode Island, USA), ten sheets from a standard roll of paper towel, and a quart-size plastic Ziploc bag (S.C. Johnson & Son, Racine, Wisconsin, USA). The gauze had a listed unstretched length of 7.62 cm by 1.92 m (3 in. by 6.3 ft). Each sheet of paper towel measured 0.23 by 0.28 m (8-7/8 by 11 in.). The ignition packages were assembled by first unrolling the medical gauze and laying it out flat in the unstretched position. A continuous section of 10 paper towel sheets were then removed from the paper towel roll and folded width-wise in a trifold manner, such that the folded width of the continuous section of paper towels measured approximately

Table 5—Test matrix

Test number	Experiment ID	Amount and location of exposed cross-laminated timber (CLT)	Windows in Wall A	Fire sprinklers	Story
1	193825	None; all CLT surfaces encapsulated	No	No	1st
2	193871	Partially exposed CLT on ceiling in bedroom and living room	No	No	2nd
3	203923	Exposed CLT on walls in bedroom and living room	No	No	2nd
4	203924	Exposed CLT on ceiling and walls in bedroom and living room	Yes	Yes	1st
5	223940	Exposed CLT on ceiling and walls in bedroom and living room	Yes	Yes, but delayed	1st

73 mm (2-7/8 in.). The folded continuous section of paper towels were placed on top of the unstretched medical gauze. They were then rolled together such that the paper towels were on the inside and the medical gauze was on the outside of the roll. The roll was then placed inside the quart-sized plastic bag, and approximately 250 mL (8.5 fluid ounces) of gasoline was poured into the bag. For Test 2, approximately 225 mL (7.6 fluid ounces) of gasoline was unintentionally used instead of 250 mL.

End of Test Fire Suppression System

A deluge-type fire suppression system was used to extinguish the fire at the end of an experiment. The deluge system was separate from the fire suppression system installed in the apartment for Tests 4 and 5. The manually operated deluge system consisted of 11 fog hose type nozzles that were attached to steel pipes. Seven nozzles were positioned on the floor that was being tested and the remaining four nozzles were located on the other floor. The nozzles were elevated several feet above the floor using metal stands. The deluge system was connected to the blue water system in the laboratory. When not in use, the nozzles were covered with ceramic fiber to protect the nozzles during the fire. These nozzle covers blew off when the fire suppression system was activated. Figure 50 shows one of the nozzles positioned in the kitchen.

Figure 50. Deluge sprinkler system in the kitchen.

Experiment Details

Test Variables

Three variables were considered in this test series: (1) the amount and location of exposed mass timber surfaces, (2) the opening in Wall A (open or covered with glass), and (3) a fire sprinkler system (installed or not installed). Details related to each of these variables were discussed in previous sections.

Test Matrix

Five experiments were conducted to observe the performance of the mass timber structure when exposed to a fire in a multistory apartment-style building. Each experiment is summarized in Table 5. In Test 5, the sprinkler activation was delayed by approximately 20 min compared with the sprinkler activation time in Test 4.

Experimental Procedures

Each experiment followed the same general procedure. The ignition package was assembled and filled with approximately 250 mL of gasoline. The ignition package was then placed within the base kitchen cabinet along Wall C (Fig. 51). Inside the cabinet, 1 by 3 dimension lumber was placed that was either assembled into wood cribs or stacked randomly. A propane torch on a pole was then used to ignite the ignition package. After ignition, both cabinet doors were left in the open position and the test personnel exited the structure through either the opening in Wall A (Test 1) or the apartment door (Tests 2–5). After exiting through the apartment door, the test personnel verified that the door was closed. The exceptions to this were Tests 3 and 5. In Test 3, the automatic door closer was not attached to the door frame during the test and this was not noticed until after the test was complete. In Test 5, the door was intentionally left in the open position to increase ventilation and severity of the test scenario.

The experiment started when the ignition package was lit. The fire was then allowed to grow naturally. The experiment was terminated when either a predetermined time had elapsed (Tests 1–3) or after the fire sprinkler(s) activated

Figure 51. Ignition package located inside of kitchen cabinet.

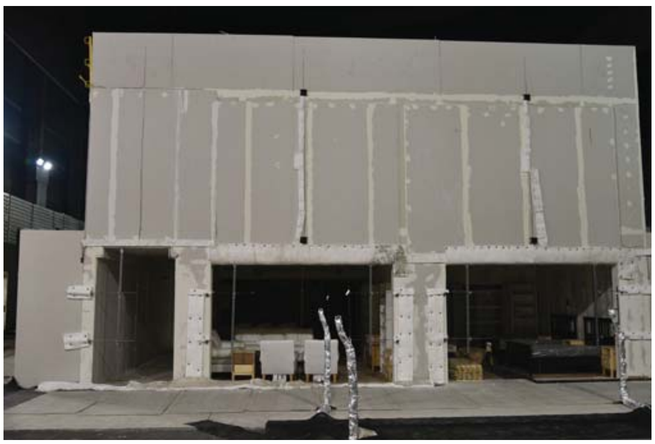


Figure 52. Second-level openings on Wall A covered with Type X wallboard for Test 1.

and had controlled the growth of the fire (Tests 4–5). ATF personnel then activated the deluge fire suppression system, and the fire was extinguished. The exception to this was Test 4, in which the fire was extinguished using a pressurized water fire extinguisher.

Additional Details

Test 1

During Test 1, all openings on the second floor of Wall A were enclosed with Type X gypsum wallboard (Fig. 52). The openings were covered to prevent the fire from spreading to the second level. Temporary walls were constructed in the wall openings using metal studs. In addition, most of the instrumentation on the second floor was active during Test 1, although the test was conducted on the first floor.

Test 2

For Test 2, a load was applied to the second floor's ceiling assembly using six vertical tanks filled with water. The polyethylene tanks were from Hastings Equity Manufacturing (Hastings, Nebraska, USA) (Model Nbr-T-0165-059). The tanks had a diameter of 0.79 m (31 in.), a height of 1.5 m (59 in.), and a dry weight of approximately 22.7 kg (50 lb). Each tank was filled with approximately 492 L (130 gallons) of water. The tanks were positioned to be centered along the width of each 2.44-m- (8-ft-) wide ceiling panel (Fig. 53). Three of the tanks were positioned to be centered over a line running parallel to and equidistant from Walls B and G over the living room and kitchen, whereas the other three were centered over a line running parallel to and equidistant from Walls D and G over the bedroom and hallway. The load resulted in the same maximum moment as would be induced by a 0.96 kPa (20 lb/ft^2) uniform load. This is equivalent to the induced moment used in the Fire Protection Research Foundation tests performed at the National Institute of Standards and Technology.

Figure 54 shows the water tanks on the ceiling assembly when viewed looking toward the front of the structure (Wall A). The water tanks were protected from the fire using gypsum wallboard (Fig. 54).

Test 3

The water tanks were reused for Test 3. However, prior to Test 3, two of the second floor ceiling panels were replaced because they had been partially exposed in Test 2. This required emptying the water from the tanks and moving them out of the way. After replacing the two ceiling panels, the tanks were positioned in their original locations. The day prior to Test 3, each tank was filled with approximately 492 L (130 gallons) of water. Upon arrival the following morning, ATF personnel discovered that one of the water tanks had leaked overnight (Fig. 55). Approximately 378.5 L (100 gallons) of water had leaked onto the ceiling assembly and then down into the structure through the joints between the CLT ceiling panels. A significant amount of water was found in the second level bedroom and living room. A wet vacuum was brought in to remove the standing water on the floor of the second level, and the wetted OSB sheets were replaced. Furthermore, both mattresses in the bedroom were replaced with dry ones that the FRL had on hand. Water stains were also visible on some of the exposed CLT wall panels. The moisture content of the CLT panels was measured using a reference (noncalibrated) moisture meter (Delmhorst J-2000, Delmhorst Instrument Company, Towaco, New Jersey, USA). The moisture content readings measured in the wetted areas of CLT were found to be as high as 27%, compared with 11% to 13% in areas unaffected by the water; however, this reading was most likely only a result of surface wetting as evidenced by the

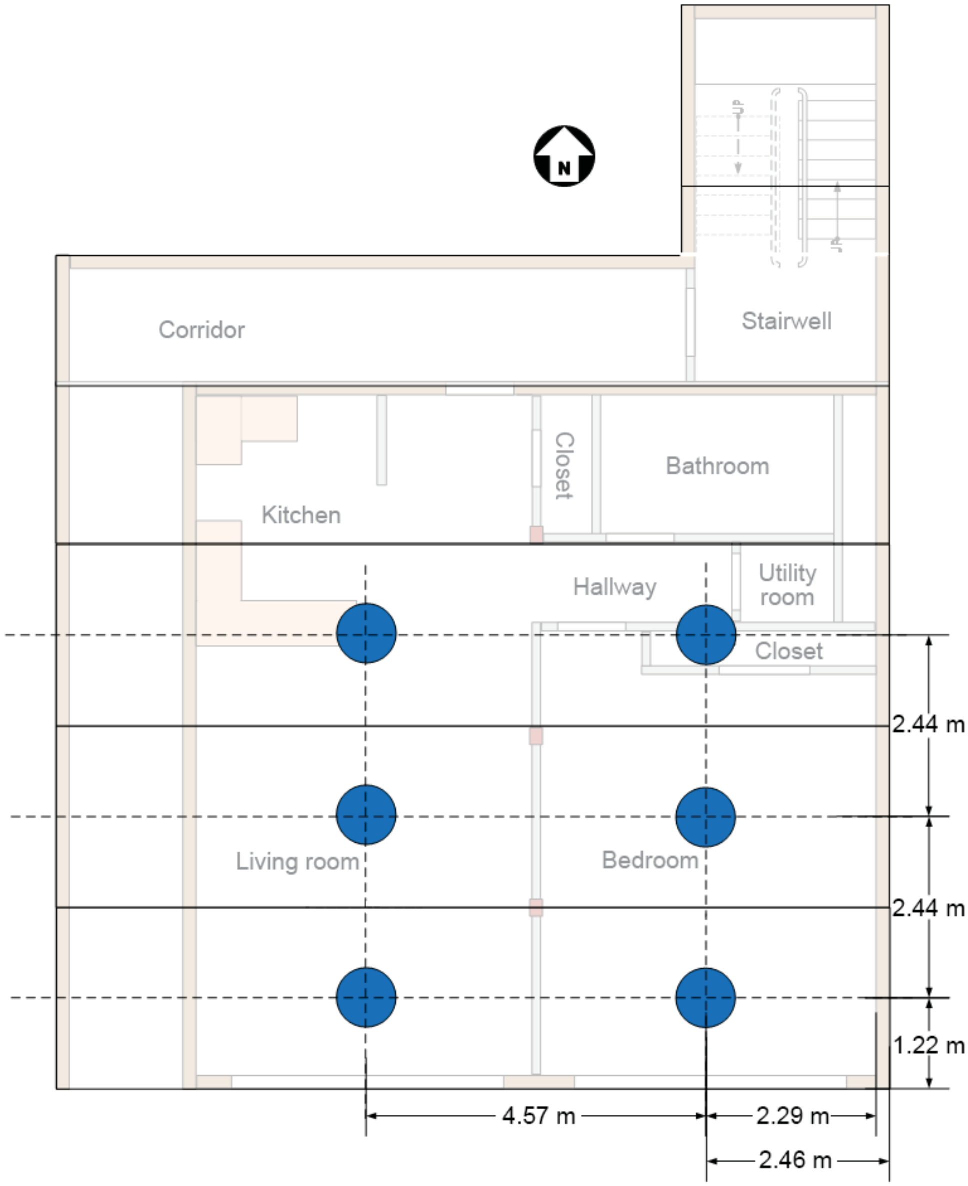


Figure 53. Location of water tanks on the second-level ceiling panel during Tests 2 and 3.

Figure 54. Water tanks on top of the second-level ceiling panels for Tests 2 and 3.

Figure 55. Water tank that leaked.

Figure 56. A plastic sheet placed over furniture during Test 4.

Figure 57. Apartment door propped open during Test 5.

lack of a char depth gradient between the wetted areas and unwetted areas following Test 3.

Test 4

A sheet of plastic was draped over some of the furniture in the living room to protect it from the water being discharged by the sprinkler head in the kitchen during the test (Fig. 56). The fire never spread beyond the cabinet, so the plastic had no effect on the fire growth.

Test 5

Prior to the start of Test 5, a decision was made to keep the apartment door open to allow for additional ventilation to feed fire grown. Therefore, the apartment door was propped open using a cement block (Fig. 57).

Restoration of Test Structure

Since Tests 2 and 3 were both performed on the second level, restoration of the interior was necessary between Tests 2 and 3. Figures 58 and 59 show the interior of the apartment after Tests 1 and 2, respectively. As part of the restoration, all of the gypsum wallboard was removed and then replaced in certain areas, based on the next test series. In addition, the unrated interior walls and drop ceiling were removed and replaced.

As part of the restoration, two of the second floor ceiling panels were also replaced. The ceiling panels were replaced because those two panels were the exposed CLT sections on the ceiling during Test 2. Figure 60 shows one of the ceiling panels as it was being removed.

The restoration of the test structure also involved repairing sections on the CLT wall assemblies that had sustained fire damage in the form of section loss caused by localized charring. Figure 61 is an example of the localized damage that occurred at the opening on Wall A on the second floor during Test 2. The wall was repaired by removing the damaged section (Fig. 62) and replacing it with equivalent

Figure 58. Interior view of apartment after Test 1.

Figure 59. Interior view of apartment after Test 2.

Figure 60. Second-level ceiling panel being removed after Test 2.

Figure 61. Localized section loss caused by charring on Wall A at the living room opening on the second floor.

Figure 62. Section of damaged cross-laminated timber removed from Wall A on second floor.

Figure 63. Localized section loss caused by charring around apartment door frame on the second floor.

Figure 64. Repair to damaged area around second-level apartment door.

Figure 65. Damage to support column and midspan beam.

material. In addition to the opening perimeters in Wall A, localized charring occurred around the apartment door frame during Tests 1, 2, and 3. Figure 63 illustrates some of the charring that occurred around the second-level door frame during Test 2. The damaged areas were removed, and the wall was repaired (Fig. 64).

Localized charring was also observed on the corners and intersections of support columns and midspan beams. An example of this charring is shown in Figure 65. The damage was limited to the corners and intersections of the wood that was added to the original support columns and beams. These damaged sections were removed and replaced with equivalent wood pieces.

Instrumentation

The ATF FRL uses a supervisory control and data acquisition (SCADA) system to collect and store data obtained from the various laboratory equipment. Data are collected at a rate of 1 hertz (1 sample per second). A variety of instrumentation was used during this test series and included thermocouples for temperature measurement, bidirectional probes for velocity measurement, optical density meters (ODM) to measure the optical density of the smoke, heat flux transducers and directional flame thermometers (DFT) to measure heat flux, gas analyzers to measure the concentrations of oxygen, carbon monoxide, and carbon dioxide within the test structure, a fire product collector to measure the heat release rate from the fire, and instrumentation to measure the atmospheric conditions in the laboratory. Smoke detectors were also used to determine smoke detector activation times in various parts of the test structure. In addition, the experiments were documented using a still camera, video cameras, and an infrared camera. The following sections discuss each of the instruments in more detail.

Thermocouples

Thermocouples are temperature measurement sensors that consist of two dissimilar metals joined at one end (a junction), which produces a small thermoelectrical voltage when the wire is heated. The change in voltage is interpreted as a change in temperature (Anon. 2000). There are many configurations of thermocouples, which affects the temperature range, ruggedness, and response time. Table 6 provides the information required to identify these factors for the thermocouples that were used during the experiments conducted for this test series. Thermocouples used during this test series were used in accordance with the method defined in FRL “Laboratory Instruction LI001 — Thermocouple” (Anon. n.d.-b).

Thermocouples were used in both a tree configuration (multiple thermocouples in a vertical line) and as single point measurements. The thermocouple trees had a thermocouple spaced every 0.6 m (2 ft), in addition to one placed at approximately floor level and one at the ceiling. Thermocouple trees that were 2.44 m (8 ft) tall and 2.74 m (9 ft) tall were both used because of the different ceiling heights in the test structure.

Figure 66 illustrates the location of the thermocouple trees in the test structure. One 2.44-m- (8-ft-) tall tree was located in the kitchen, and two trees were positioned inside of Wall G. Two 2.74-m- (9-ft-) tall thermocouple trees were located in the living room and bedroom, and three thermocouple trees were located in the corridor.

Temperature measurements were obtained at the ceiling in the living room and bedroom (Fig. 67). For Tests 1 and 3, two layers of Type X gypsum wallboard covered the CLT ceiling. For these two tests, two additional thermocouples were added at each measurement location on the ceiling. One thermocouple was located on the outermost layer of the gypsum wallboard, and one was placed between the two layers of the wallboard (Fig. 68).

In addition to the surface thermocouples at Location B on the living room ceiling, there were seven thermocouples embedded within the CLT. Holes of varying depth were drilled into the exterior of the CLT assembly. The holes were spaced evenly around a 50.8-mm- (2-in.-) diameter circle. After the holes were drilled, Type K thermocouples (30 American wire gauge (AWG)) were placed into the holes. As illustrated in Figure 69, the thermocouples were positioned at the following depths relative to the interior of the test structure: 12 mm (0.472 in.), 23 mm (0.906 in.), 35 mm (1.38 in.), 47 mm (1.85 in.), 58 mm (2.28 in.), 70 mm (2.76 in.), and 105 mm (4.13 in.).

Embedded thermocouples were also located along Walls B and D (Fig. 70). The thermocouples were placed 1.52 m (5 ft) above the finished floor. Surface thermocouples were also located at these same locations. If the CLT was encapsulated with gypsum wallboard, then two additional surface thermocouples were used (Fig. 68). The thermocouples located along Wall B were spaced evenly apart, every 2.29 m (7 ft 6 in.). However, this spacing resulted in the thermocouples at the third location (C) being placed behind a wall cabinet.

Table 6—Thermocouple details

Description	Manufacturer	Model	AWG No.	Insulation	Accuracy specification
Wire	Omega[a]	GG-K-24-SLE	24	Glass	Special limits of error
Extension wire	Omega	EXPP-K-24-SLE	24	Polyvinyl	Special limits of error

[a]Omega, Stamford, Connecticut, USA.

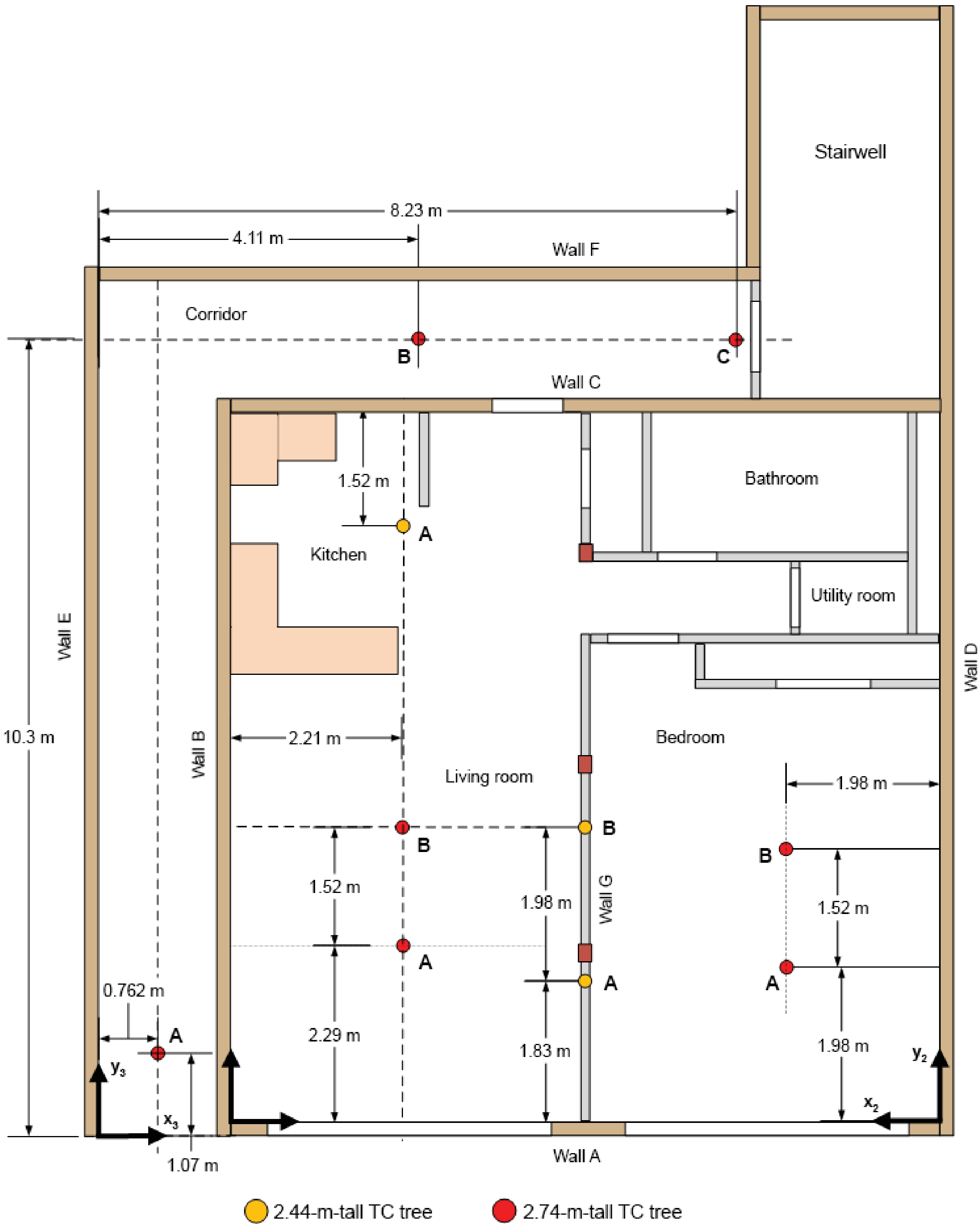


Figure 66. Location of thermocouple (TC) trees.

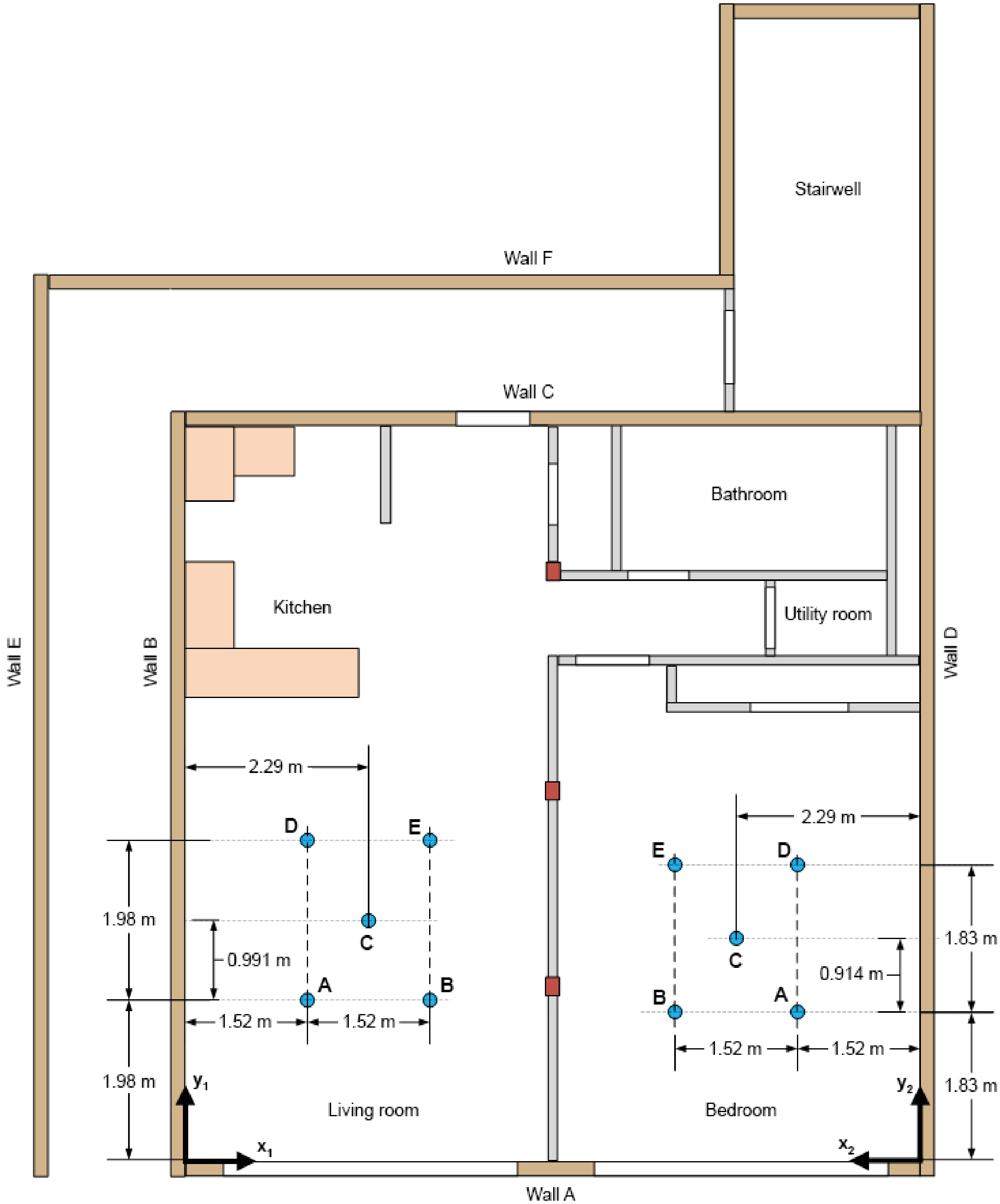


Figure 67. Location of ceiling thermocouples (blue circles).

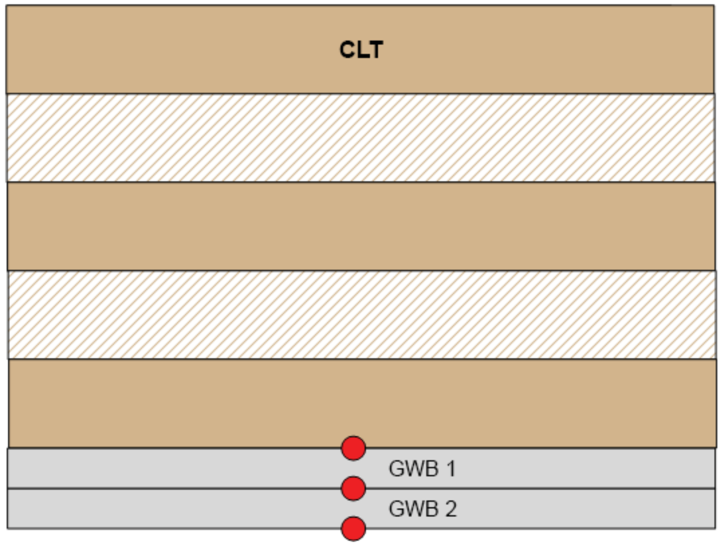


Figure 68. Additional surface thermocouples when the cross-laminated timber (CLT) was encapsulated (GWB, gypsum wallboard).

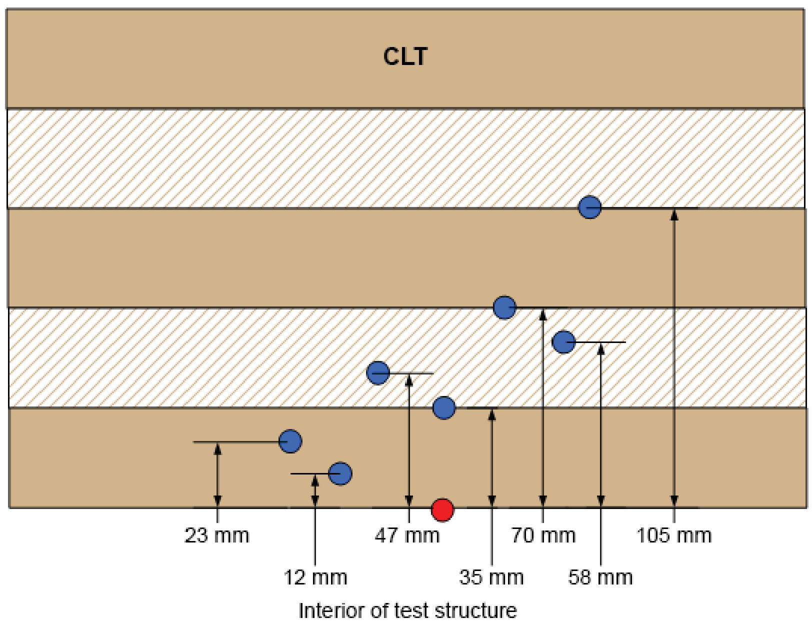


Figure 69. Location of embedded thermocouples in the cross-laminated timber (CLT).

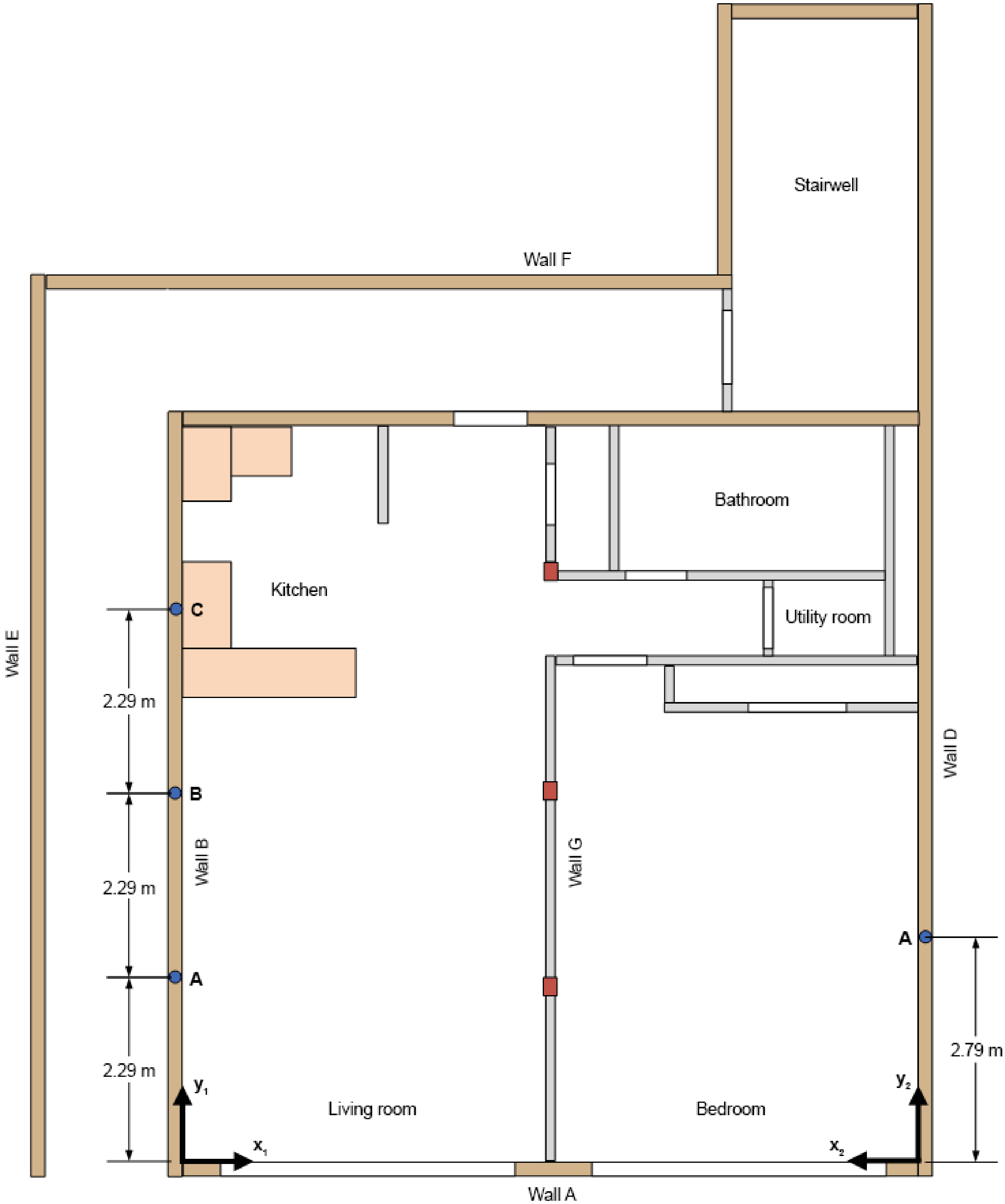


Figure 70. Location of embedded and surface wall thermocouples (blue circles) (thermocouples located 1.52 m above the finished floor).

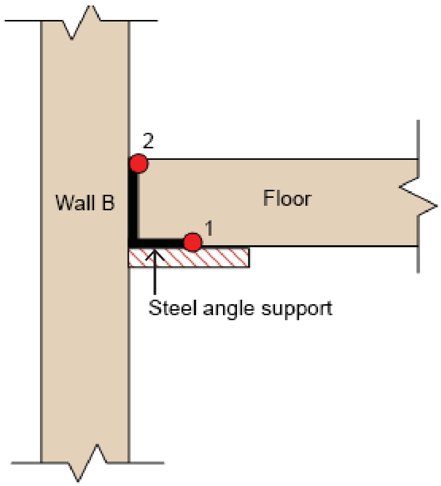
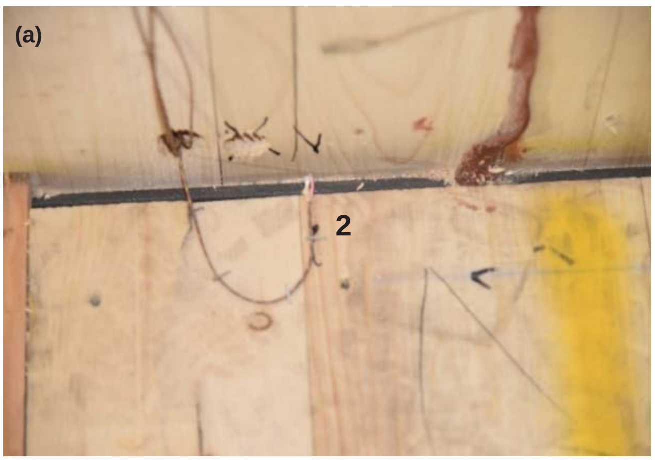


Figure 71. Joint temperature measurement at the steel angle–floor interface.



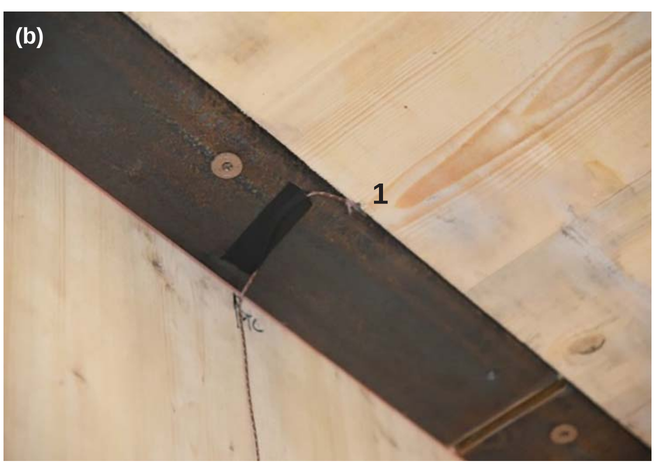


Figure 72. Thermocouples placed between the steel angle and the cross-laminated timber floor assembly to measure the joint temperatures: (a) top view; (b) bottom view (numbers correspond to locations shown in Fig. 71).

Temperature measurements were also obtained at the joints created between the CLT assemblies and their associated supports. Figures 71 and 72 show the joint temperature measurement location for the steel angle and floor assembly. The numbers shown in Figure 72 correspond to the thermocouples shown in Figure 71. The photographs were taken prior to the gaps being filled in with an intumescent fire caulk.

Figures 73 and 74 show the location of the joint temperature measurements for the ledger and floor assembly. The photograph in Figure 74 was taken prior to the floor assembly being installed. The numbers shown in Figure 74 correspond to the thermocouples shown in Figure 73.

Figures 75 and 76 show the location of the joint temperature measurement between the wall assembly and the ceiling assembly. The photograph was taken prior to the ceiling assembly being installed.

The locations for the joint temperature measurements along Walls B and D are shown in Figure 77. Joint temperatures were obtained every 1.14 m (3 ft 9 in.) along Wall B, in both the living room and the kitchen. Joint temperatures along Wall D were obtained every 1.14 m (3 ft 9 in.) in the bedroom.

Temperature measurements were also obtained at each opening in Wall A using 2.74-m- (9-ft-) tall thermocouple trees (Fig. 78). In addition, single thermocouples were used to measure temperatures above the second-level opening. The height of each thermocouple was measured relative to the finished floor for that particular floor level (1st, 2nd, or 3rd).

For Test 4, a single thermocouple was added near the fire sprinkler head in the kitchen (Fig. 79). This temperature measurement was used to determine sprinkler activation time. The thermocouple remained in the test structure for Test 5.

Bidirectional Probes

Velocity is commonly measured by application of the principal of conservation of mechanical energy through conservation of fluid velocity to pressure (head). If the fluid is forced to change its velocity, a change in pressure will occur (Avallone and Baumeister III 1996). Bernoulli's equation (Munson and others 2006) uses differential pressure and density measurements of a fluid to calculate the fluid's velocity. Differential pressure is the difference between the dynamic and static pressure measurements of the fluid and is measured using a differential pressure probe and differential pressure transducer. The density of the fluid is typically calculated from the fluid temperature.

There are various types of differential pressure and temperature probes that can be used to record the measurements necessary to calculate a fluid's velocity. The characteristics of the various types of pressure and

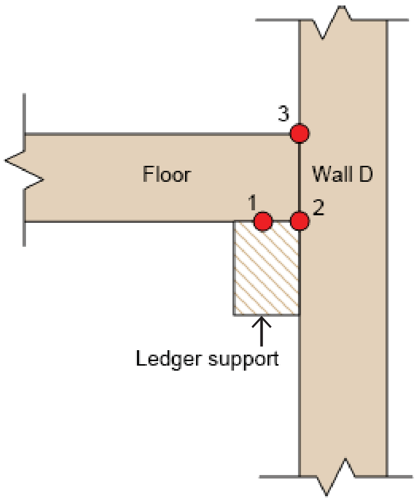


Figure 73. Ledger–floor joint temperature measurement loctions.

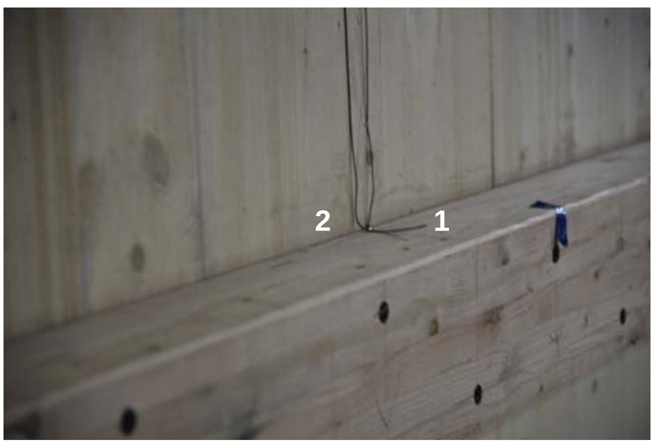


Figure 74. Thermocouples placed on the ledger to measure the temperature at the ledger–floor interface (numbers correspond to locations shown in Fig. 73).

temperature probes affect the response and sensitivity of the measurements. All devices used to calculate velocity were used in accordance with the method defined in FRL "Laboratory Instruction LI009 —External Velocity Differential Pressure Probes" (Anon. n.d.-d).

The air velocity through the openings in Wall A was measured using bidirectional probes (Fig. 80). Each bidirectional probe was connected to a differential pressure manometer (MKS Type 220DD-00001B2B) that had a pressure full range of 133 Pa (1 Torr). The air temperature near each probe was measured using a Type K thermocouple (24 AWG, glass insulated).

Figure 81 illustrates the location of velocity measurements. When tests were conducted on the second level, the bidirectional probes were elevated and placed at equivalent locations relative to the second-level floor. Figure 82 shows the bidirectional probes mounted by the living room.

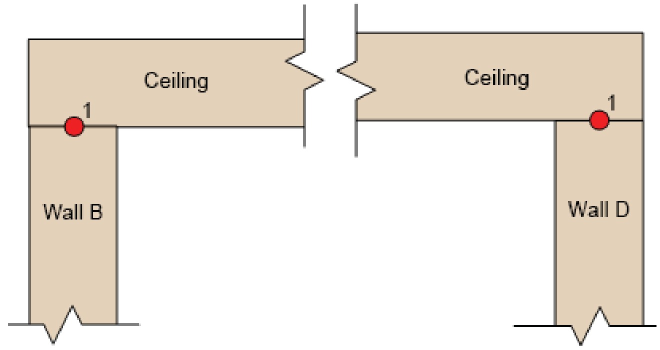


Figure 75. Ceiling–wall joint temperature measurement locations (second floor).

Figure 76. Thermocouple placed on wall to measure temperature at ceiling–wall joint interface on the second floor.

Heat Flux Transducers

A heat flux transducer is a device that measures the rate of absorbed incident energy and expresses it on a per unit area basis. The operating principle of the Schmidt–Boelter heat flux transducers used during this test series is based on one-dimensional heat conduction through a solid. Temperature sensors are placed on a thin, thermally conductive sensor element, and applying heat establishes a temperature gradient across the element. The heat flux is proportional to the temperature difference across the element according to Fourier's Law (Barnes 1999).

There are many configurations of heat flux transducers that affect range, size, mode, and sensitivity. The information required to identify these factors for the heat flux transducers that were used during the experiments conducted for this test series is provided in Table 7. Heat flux transducers were used in accordance with the method defined in FRL "Laboratory Instruction LI002 Heat Flux

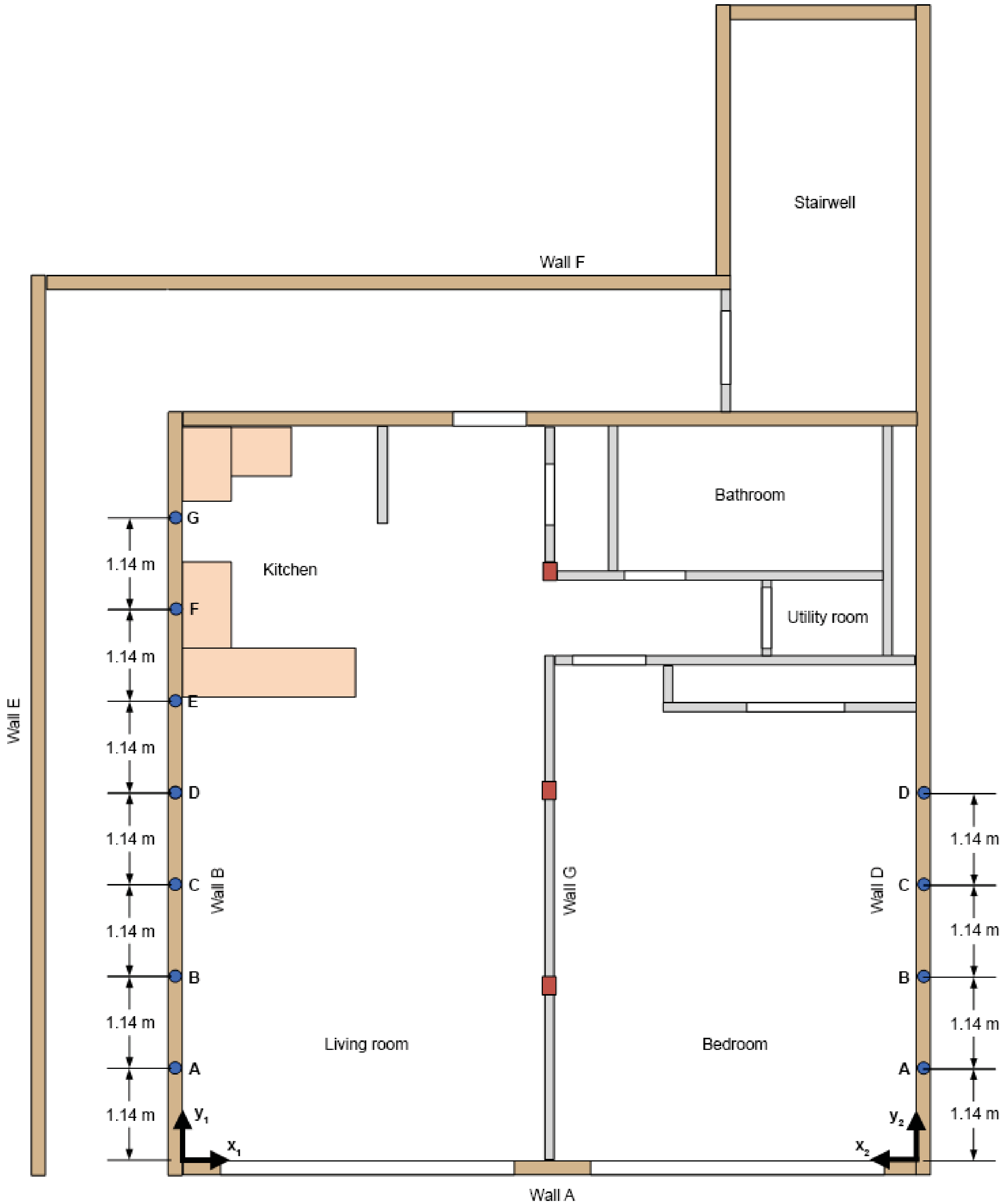


Figure 77. Locations of joint temperature measurements (blue circles).

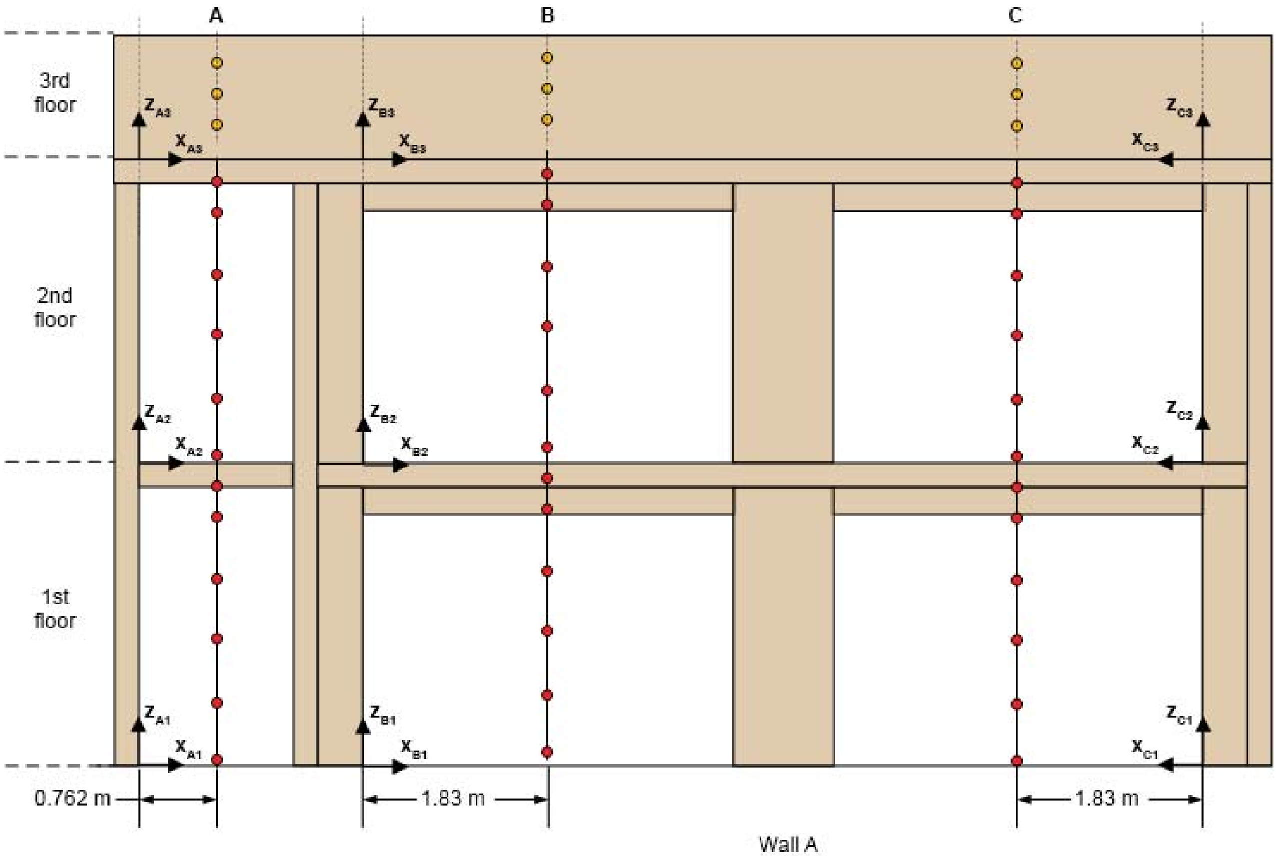


Figure 78. Location of thermocouples on Wall A (red and yellow circles).

Figure 79. Thermocouple placed near sprinkler head in kitchen for Test 4.

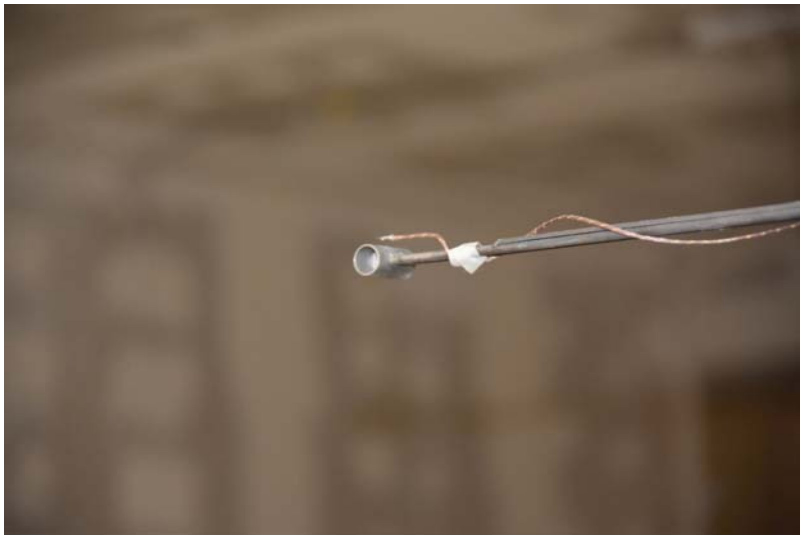


Figure 80. Bidirectional probe.

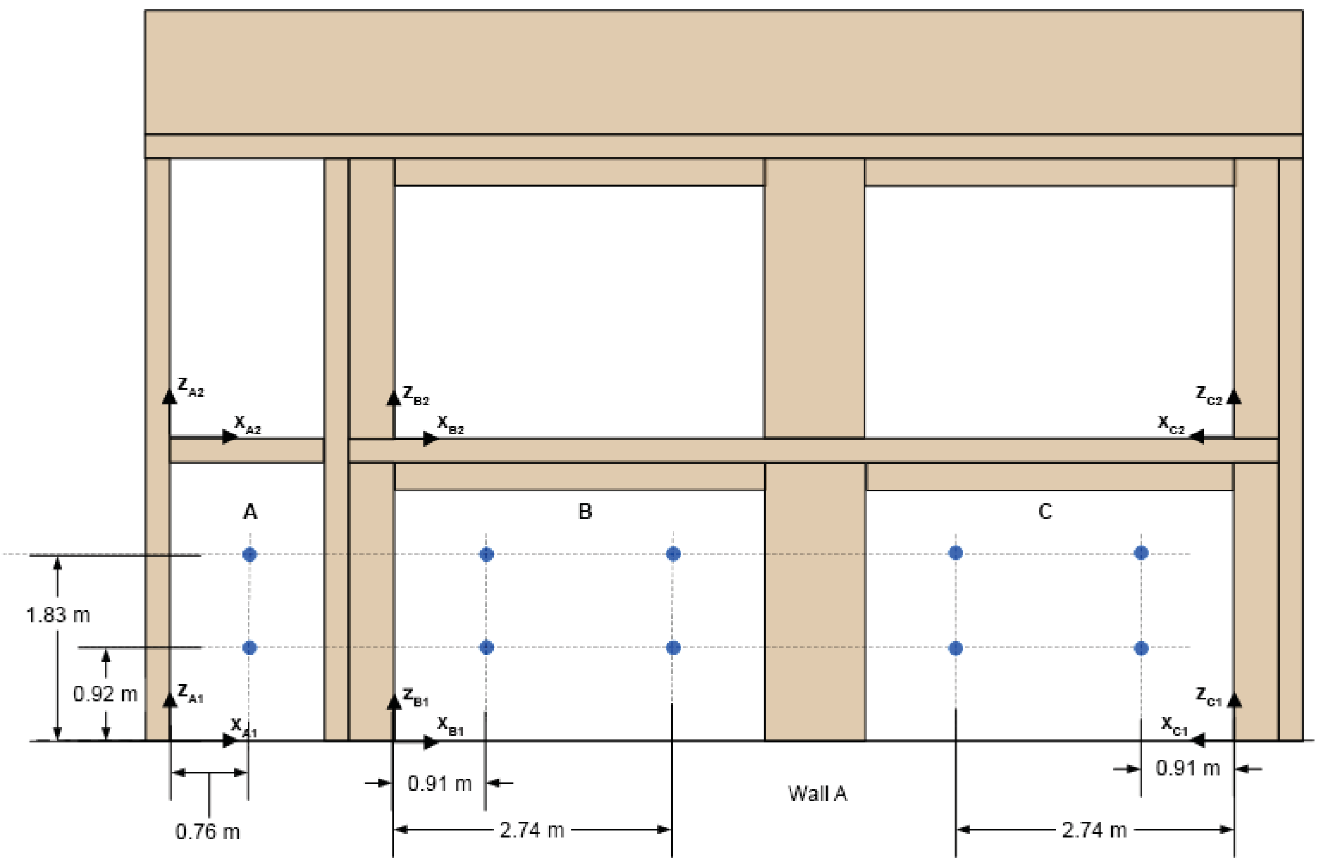


Figure 81. Location of bidirectional probes (blue circles).

Figure 82. Bidirectional probes mounted at the opening in Wall A.

Table 7—Description of heat flux transducers

Manufacturer	Model	Heat flux mode	Full-scale range (kW/m²)	Maximum over range (kW/m²)
Medtherm[a]	64-2.5-20	Total	25	37.5
Medtherm	64-5SB-20	Total	50	75
Medtherm	64-10SB-20	Total	100	150

[a]Medtherm Corporation, Huntsville, Alabama, USA.

Transducer” (Anon. n.d.-c). Figure 83 shows the location of the heat flux transducers. One transducer was positioned in the corridor across from the apartment door and was mounted 0.914 m (3 ft) above the finished floor. Four other heat flux transducers were located in front of Wall A (two in front of each opening), and they were located 1.52 m (5 ft) above the floor. When experiments were conducted on the second floor, the heat flux transducers were elevated and placed at equivalent locations relative to the second-level finished floor.

Directional Flame Thermometers

DFTs are another type of device to measure heat flux (ASTM 2016). A DFT consists of two metal plates separated by an insulating material and a thermocouple attached to each plate to measure the temperature of the plate. A thermal model is then used to calculate the heat flux, based on the temperature profiles and the temperature-dependent properties of the metal plates and insulating material.

The DFTs used in this test series were provided by the USDA Forest Service, Forest Products Laboratory (FPL). Figure 84 shows a DFT mounted on the ceiling. Only the temperature data from the DFTs are included in this report.

DFTs were mounted on both the walls and ceiling of the test structure. Figure 85 shows the location of the DFTs on the interior walls. The DFTs located on Walls B and D were mounted 1.52 m (5 ft) above the finished floor. Two DFTs were also mounted next to the apartment door on Wall C (Fig. 86). These DFTs were located 0.914 m (3 ft) and 2.18 m (7 ft 2 in.) above the finished floor.

Two DFTs were also mounted on the ceiling, one in the bedroom and one in the living room. Figure 87 shows the location of the DFTs on the ceiling.

For Test 1, four additional DFTs were mounted on the exterior of Wall A (Fig. 88). The location of each DFT is shown in Figure 89.

Optical Density Meter

ODMs were used to measure the smoke obscuration during the experiments. The ODM consists of two parts: a light source and a photo transducer, which responds to the intensity of light from the light source. The photo transducer produces an output voltage that is linear with the amount of light received from the light source. An increase in intensity of light results in an increase in output voltage, and a decrease in intensity of light results in a decrease in output

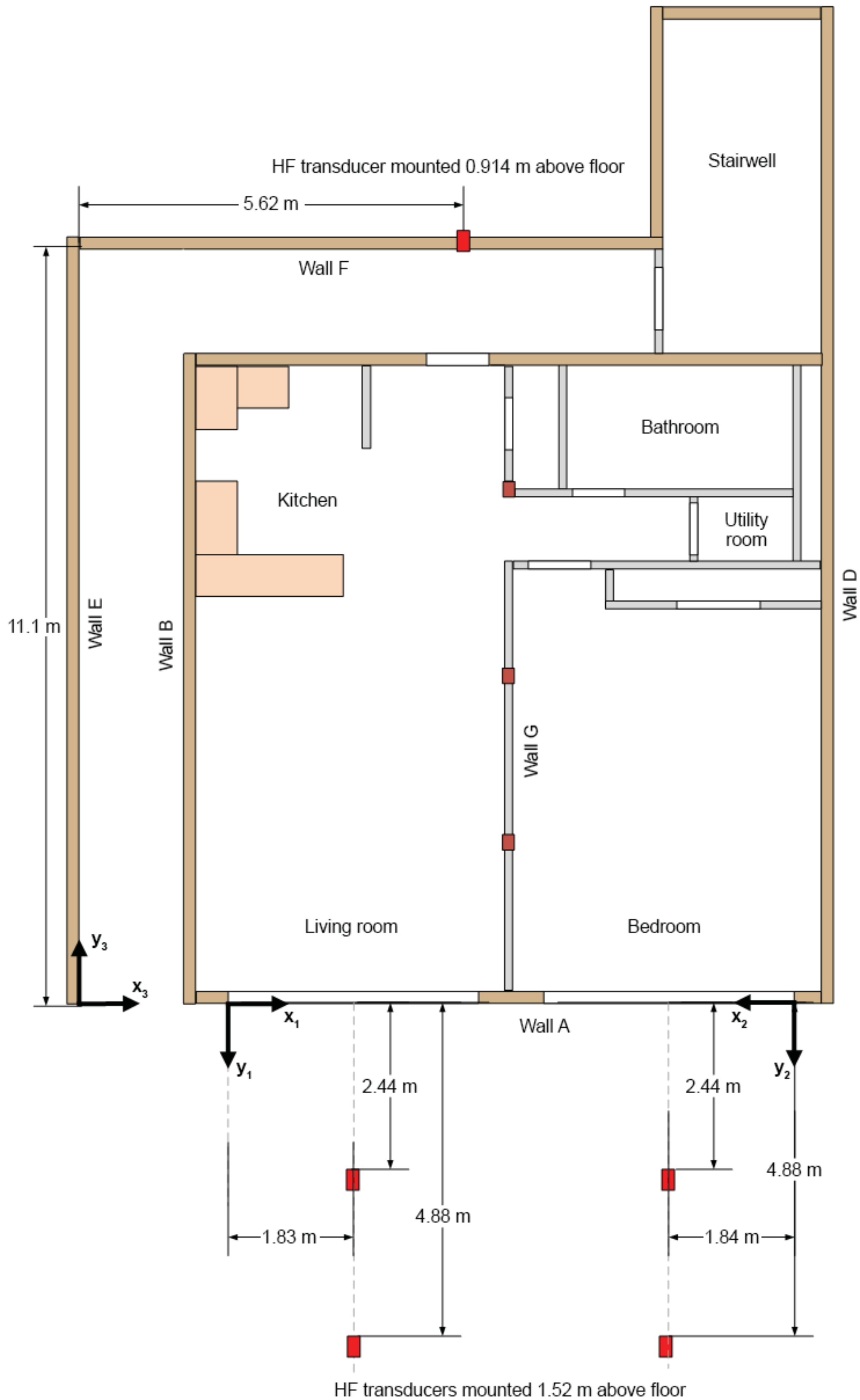


Figure 83. Location of heat flux (HF) transducers (red rectangles).

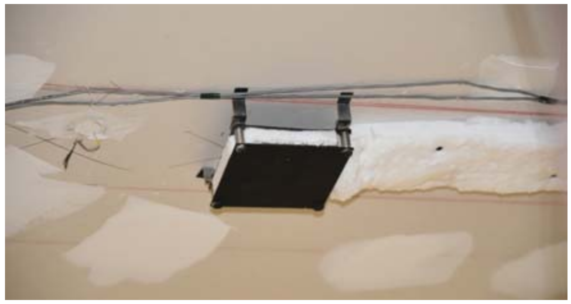


Figure 84. Directional flame thermometer mounted on ceiling.

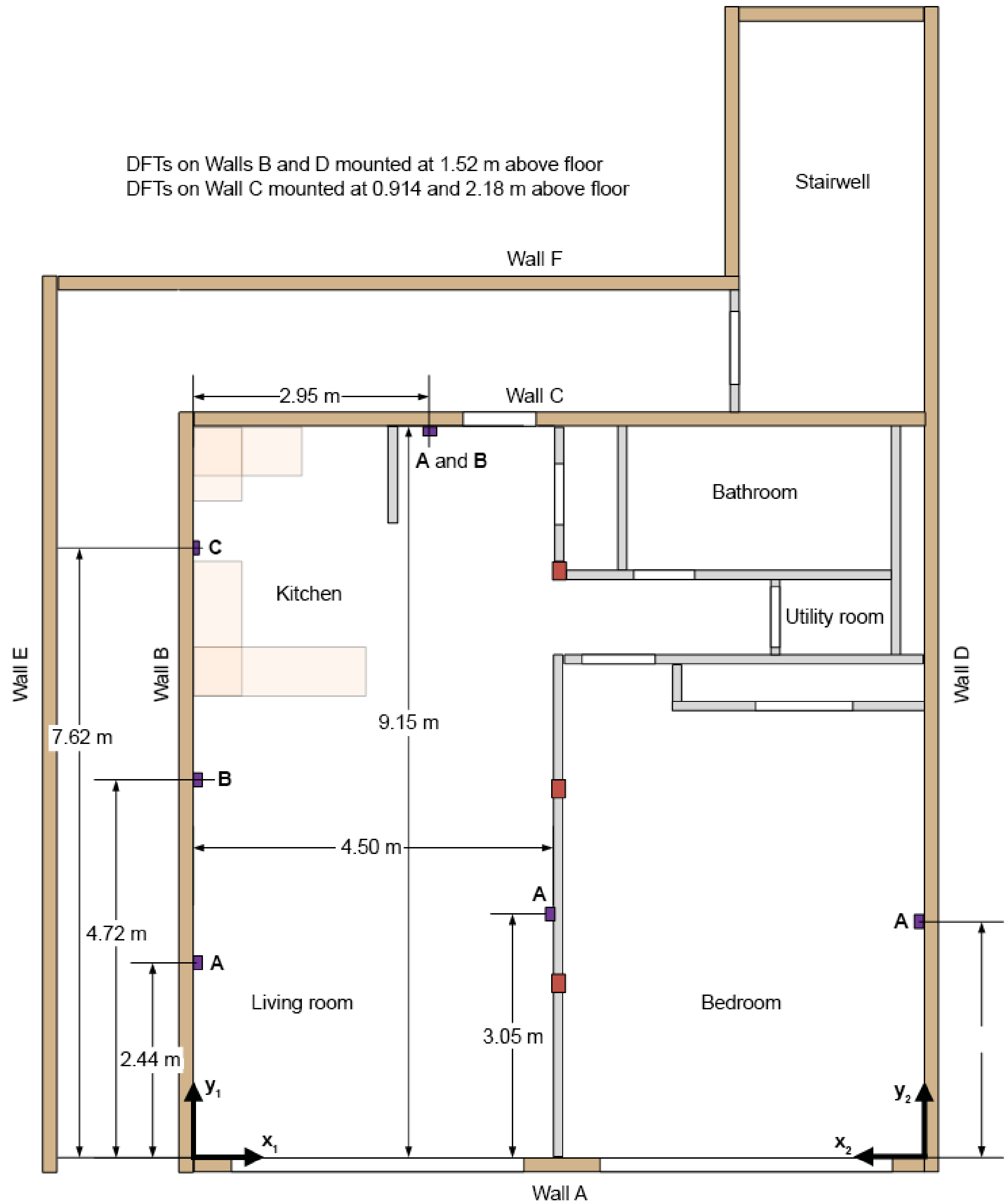


Figure 85. Location of directional flame thermometers (DFTs) on interior walls (purple rectangles).

Figure 86. Directional flame thermometers mounted on Wall C near the apartment door.

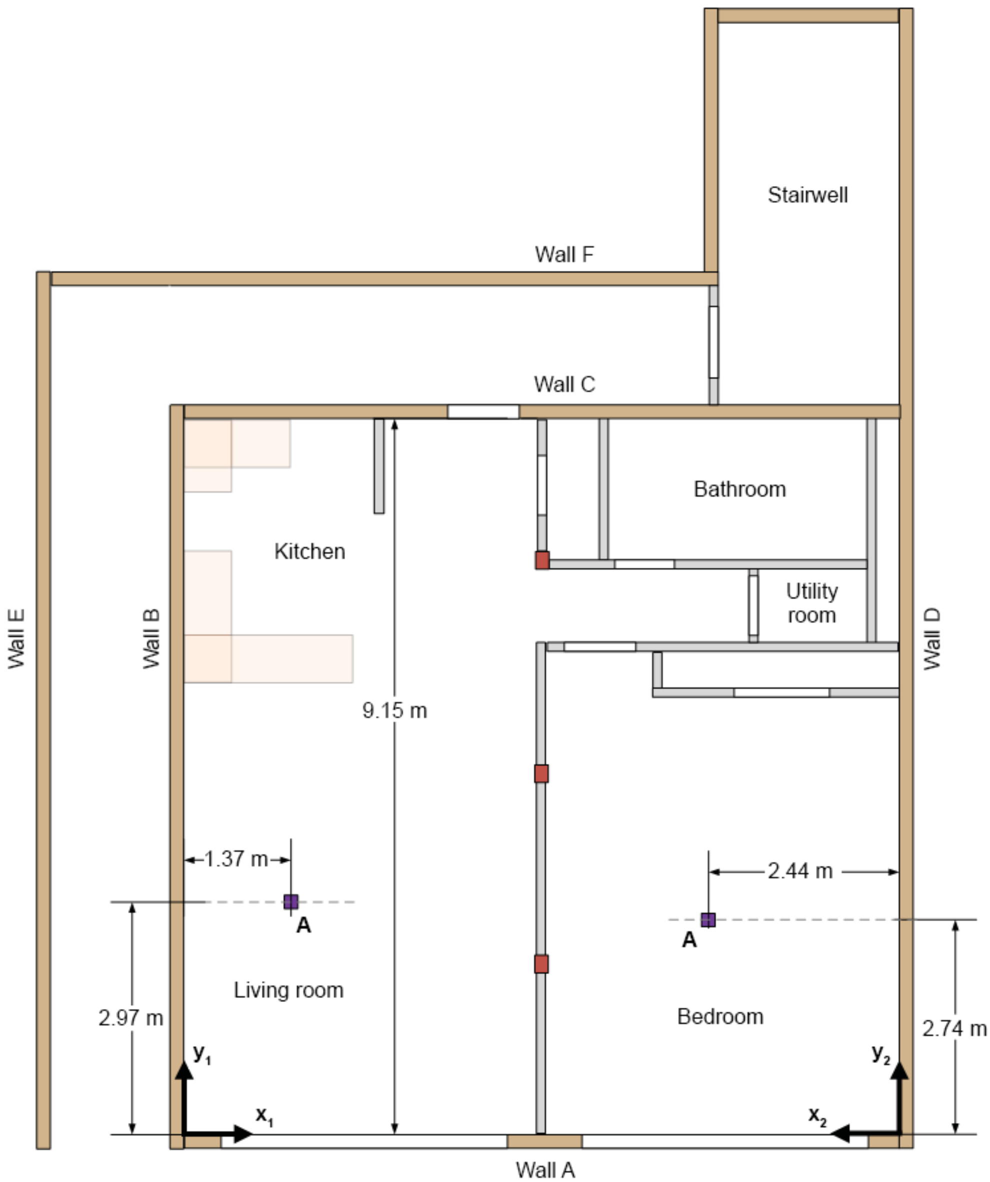


Figure 87. Location of directional flame thermometers on ceilings (purple squares).

Figure 88. Directional flame thermometers mounted on the exterior of Wall A.

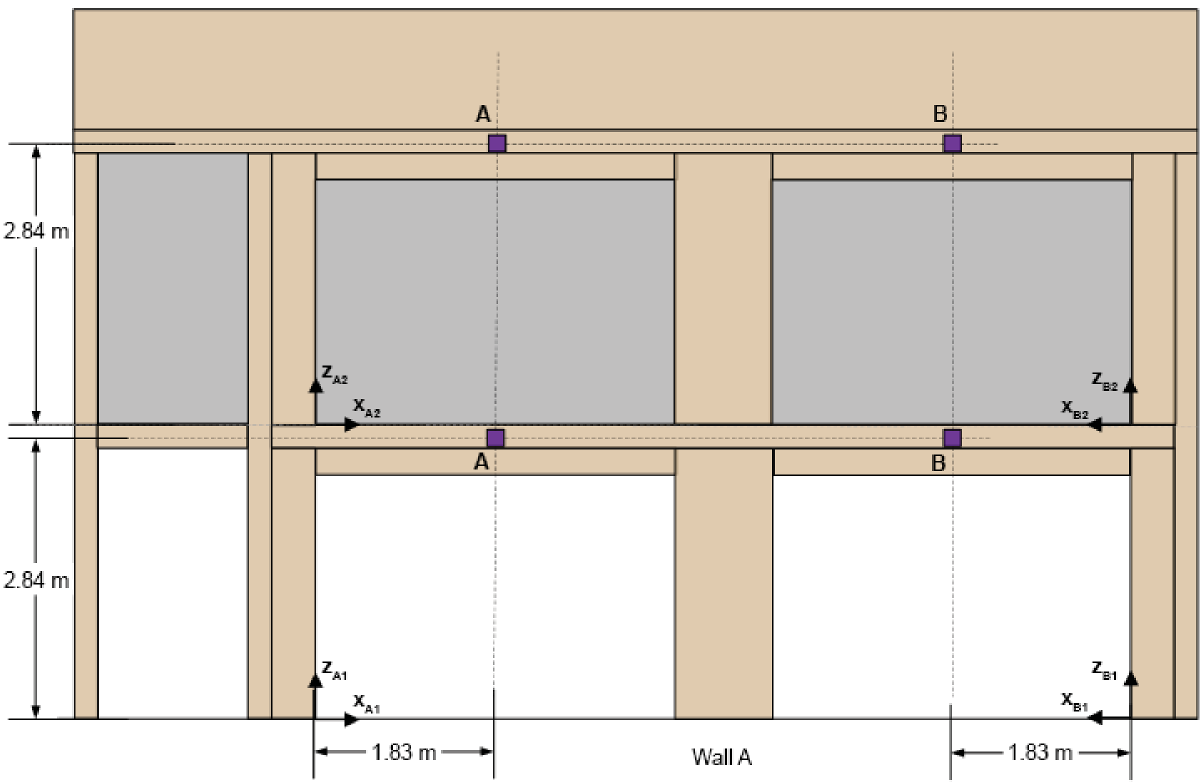


Figure 89. Location of directional flame thermometers on Wall A (purple squares) (see also photograph in Fig. 52).

voltage. Prior to the start of each test series, each optical density meter was functionally verified using neutral density filters.

The white light source for the ODM used in this test series was a GE model PAR 24671 incandescent lamp (General Electric Company, Boston, Massachusetts, USA). The light receiver was a Huygen 856 RRV photovoltaic cell (Huygen Corporation, Crystal Lake, Illinois, USA). It had a maximum operating temperature of 60°C (140°F). The light intensity was set using a Texio model PD18-30AD power supply (Texio Technology Corporation, Yokohama, Japan). The light receiver was located 0.914 m (3 ft) from the light source. Figure 90 shows the ODM mounted in the corridor. The ODM housing was protected from high air temperatures using a ceramic fiber blanket. A thermocouple was mounted near the ODM to monitor the air temperature. If the air temperature exceeded 60°C (140°F), the ODM was taken out of service. The ODM was not placed back into service until it had been functionally verified using the neutral density filters.

Figure 91 shows the location of the ODM, which was in the corridor near the apartment door. The ODM was mounted 1.52 m (5 ft) above the floor.

Smoke Detectors

Smoke detectors are devices used to activate an alarm in the presence of smoke. Smoke detectors send notifications in the form of audible, visible, and/or electrical responses. For this test series, interconnected-type smoke detectors were selected because detector activation could be determined by monitoring the electrical output produced by each detector. Table 8 provides a description of the smoke detectors used in the experiments. Figure 92 shows the smoke detectors as mounted to the ceiling. At each location, two smoke detectors were used, an ionization smoke detector and a photoelectric smoke detector. Figure 93 shows the location of smoke detectors in the test structure.

Oxygen Gas Analyzer

A gas analyzer was used to measure the oxygen (O_2) concentration at one or more point measurement locations. The oxygen analyzer operates according to the paramagnetic alternating pressure principal. The resolution of the oxygen transducer's output signal is less than 0.1% of the respective output signal span value. The analyzer was zeroed and calibrated prior to each test. Nitrogen was used as the zero gas, and dried ambient air, which is assumed to have an oxygen concentration of 20.95%, was used as the span gas. The gas concentration point measurements were conducted in accordance with the method defined in FRL "Laboratory Instruction LI016 — Point Source Gas Analysis" (Anon. n.d.-f). Table 9 provides a description of the oxygen gas analyzer used in this test series.

Figure 90. Optical density meters located in the corridor.

For each experiment, gas samples were taken outside of the apartment door in the corridor at a height of 1.52 m (5 ft) above the finished floor. For Tests 4 and 5, gas samples were also taken in the living room at a height of 1.52 m (5 ft) above the finished floor. Figure 94 shows the location of the gas samples in the test structure.

CO–CO_2 Gas Analyzer

A gas analyzer was used to measure both the carbon monoxide (CO) and carbon dioxide (CO_2) concentrations at one or more point measurement locations. The CO–CO_2 gas analyzer utilizes two separate nondispersive infrared (NDIR) type transducers to measure the concentration of each gas. The resolution of each transducer's output signal is less than 0.1% of the respective output signal span value. The span value is defined as the input value used to test the upper range of the analyzer. The analyzer was zeroed and spanned prior to each test. Nitrogen was used as the zero gas, and a premixed calibration gas with known concentrations of CO and CO_2 was used as the span gas. The gas concentration point measurements were conducted in accordance with the method defined in FRL "Laboratory Instruction LI016 — Point Source Gas Analysis" (Anon. n.d.-f). Table 10 provides a description of the CO–CO_2 gas analyzer used in this test series. The CO–CO_2 gas samples were obtained at the same locations in the test structure as the O_2 gas samples, which are shown in Figure 94.

Fire Products Collector

A fire products collector (FPC) measures several characteristics of a fire based on the measured properties of the fire plume. An FPC consists of a collection hood connected to an exhaust duct placed over a fire (Fig. 95). The primary fire characteristics calculated from an FPC include heat release rate (HRR), convective heat release rate (CHRR), gas species production, and smoke production. HRR measurements are based on the principle of oxygen

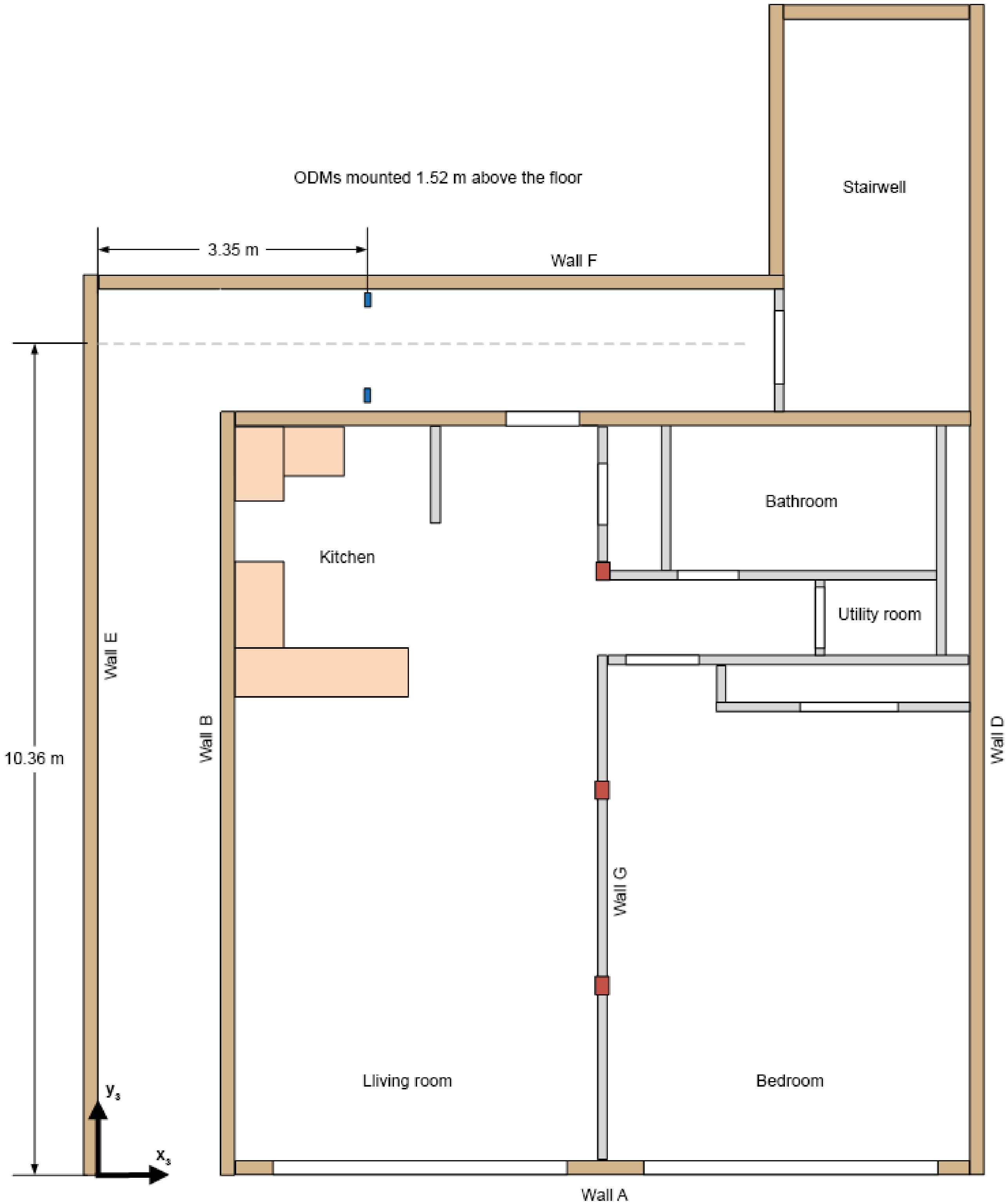


Figure 91. Location of optical density meters (ODMs) (blue rectangles).

Table 8—Smoke detector summary

Manufacturer	Model	Detector type	Sensor type	Nominal sensitivity (% obs/m)
Kidde[a]	p12040	Smoke	Ionization	3.94–11.0
Kidde	i12080	Smoke	Photoelectric	1.64–2.79

[a]Kidde, Inc., Mebane, North Carolina, USA.

Figure 92. Smoke detectors.

consumption calorimetry. CHRR is calculated as the enthalpy rise of gases flowing through the FPC. Gas species production is calculated based on the measured gas concentrations flowing through the FPC. Smoke production is quantified based on optical smoke measurements, which measure the attenuation of light as it passes through the smoke and fire gases in the FPC. The FPC was used in accordance with the method defined in FRL "Laboratory Instruction LI011 — Fire Products Collectors" (Anon. n.d.-e).

Experiments were conducted using the FRL's nominally rated 14-megawatt (MW) FPC (Fig. 96). The 14-MW FPC has a square apron that is 18.5 by 18.5 m (60.7 by 60.7 ft). The bottom of the apron is 9.14 m (30 ft) above the surface of the laboratory floor. The FPC can be operated above 14 MW for a period of time, as long as the safety of the FPC and its instrumentation is maintained.

Table 11 includes a description of the FPC, as well as the calibration factor (C factor) and E value, which are used to calculate the HRR during an experiment. The C factor is based on data from a fire with a known HRR. The net heat released per unit of oxygen consumed, E, is a property of the fuel being burned.

Laboratory Conditions

The ambient laboratory temperature, barometric pressure, and relative humidity were measured during the experiments. The laboratory conditions were measured using an industrial probe and microserver. The probe measured the ambient conditions using capacitive digital sensors. The sensor probe has surface-mounted circuitry, which responds to changes in the environment and outputs a digital signal. The laboratory conditions were measured in accordance with the method defined in FRL "Laboratory Instruction LI017 — Laboratory Conditions" (Anon. n.d.-g). Table 12 provides a description of the instrumentation used to collect the ambient laboratory conditions measurements during the experiments.

Experiment Photographs

Digital cameras are used within the FRL to record digital still photographs during experiments. Digital cameras used during this test series were used in accordance with the method defined in FRL "Laboratory Instruction LI003 — Digital Cameras" (Anon. n.d.-a).

Video Cameras

Video cameras were used to document the experiments. Both high definition (HD) video cameras and standard definition (SD) video cameras were used. During an experiment, up to five HD video cameras (NEX-FS100UK, Sony, Tokyo, Japan) were positioned outside of the structure and seven SD video cameras (VTC-206F03-4, Bosch, Gerlingen, Germany) were located inside of the structure. Figure 97 shows the general layout of the video cameras. The camera for the water pressure was only used during Tests 4 and 5.

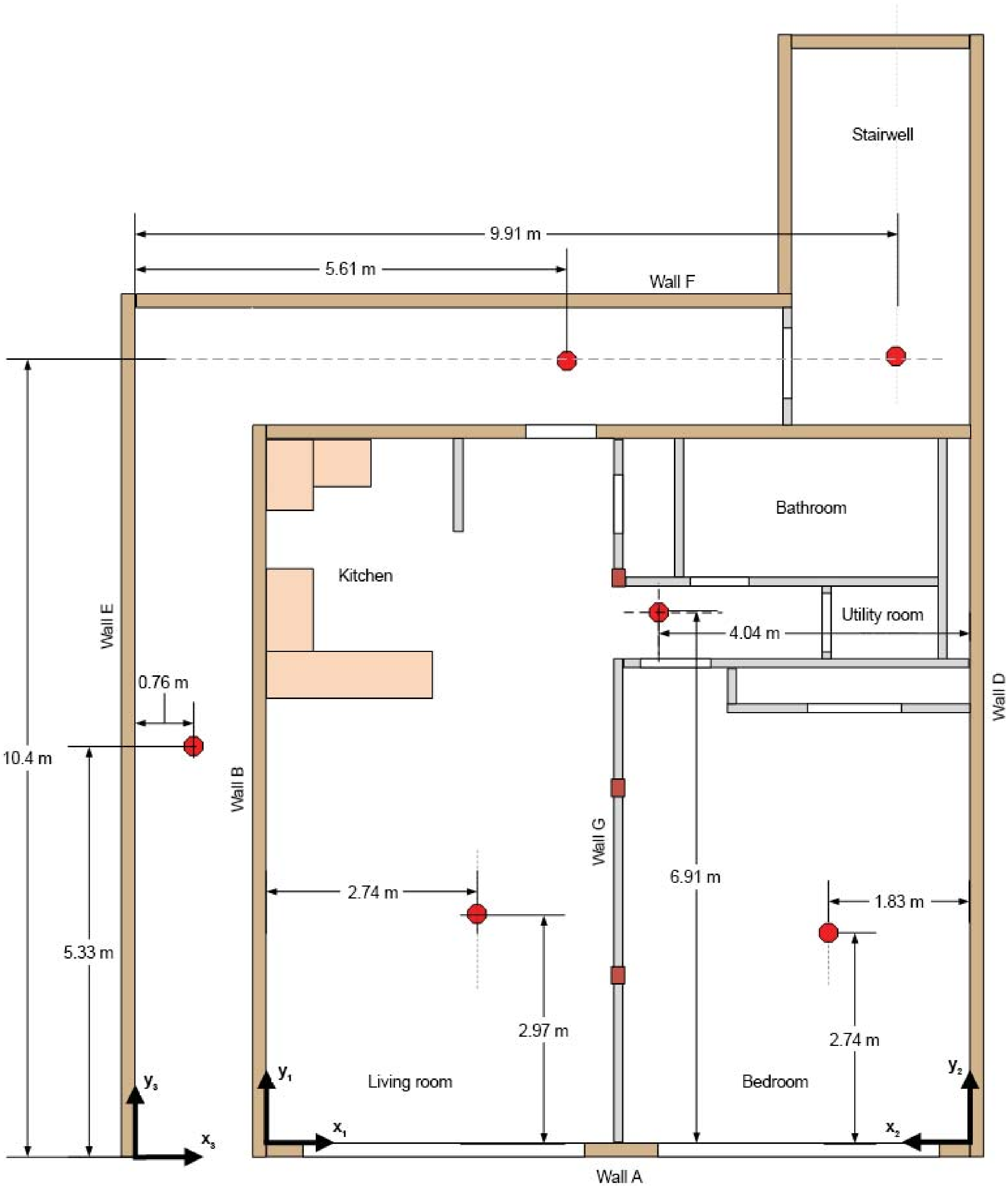


Figure 93. Location of smoke detectors (red octagons).

Table 9—Oxygen gas analyzer summary

Manufacturer	Model	Detector type	Range (%)
Siemens[a]	Oxymat 61	Paramagnetic	0–25

[a]Siemens AG, Munich, Germany.

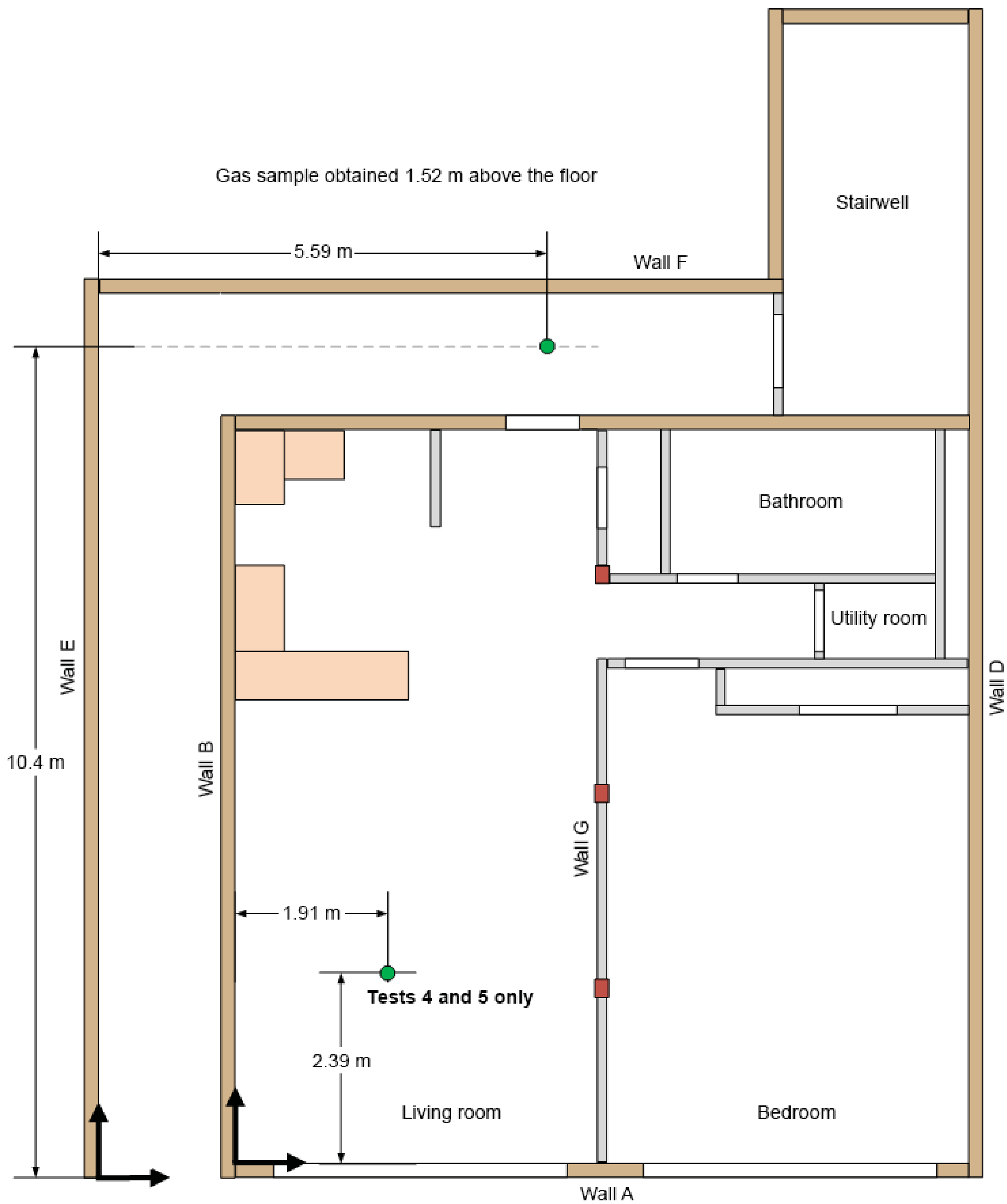


Figure 94. Gas sample locations (green octagons).

Table 10—CO–CO_2 gas analyzer summary

Manufacturer	Model	Gas	Detector type	Range (%)
Siemens[a]	Ultramat 23	CO_2	NDIR[b]	0–25
		CO	NDIR	0–5

[a]Siemens AG, Munich, Germany.
[b]NDIR, nondispersive infrared.

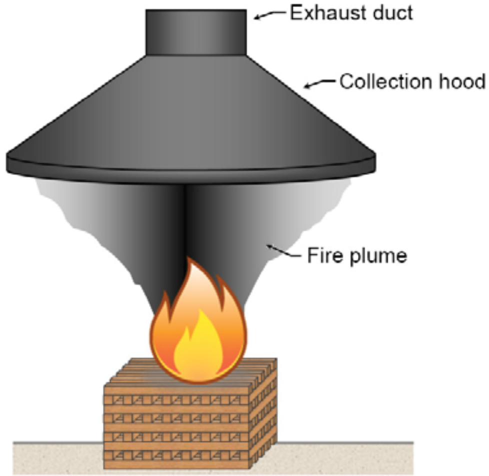


Figure 95. Schematic of a fire product collector.

Figure 96. 14-MW fire product collector at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory.

Table 11—Fire products collector description

Description	C factor	E factor (kJ/kg)
14 MW	1.128	13,100

Table 12—Laboratory conditions description

Description	Manufacturer	Model
LBR_01	Omega[a]	IBTHP-5

[a]Omega Engineering, Stamford, Connecticut, USA.

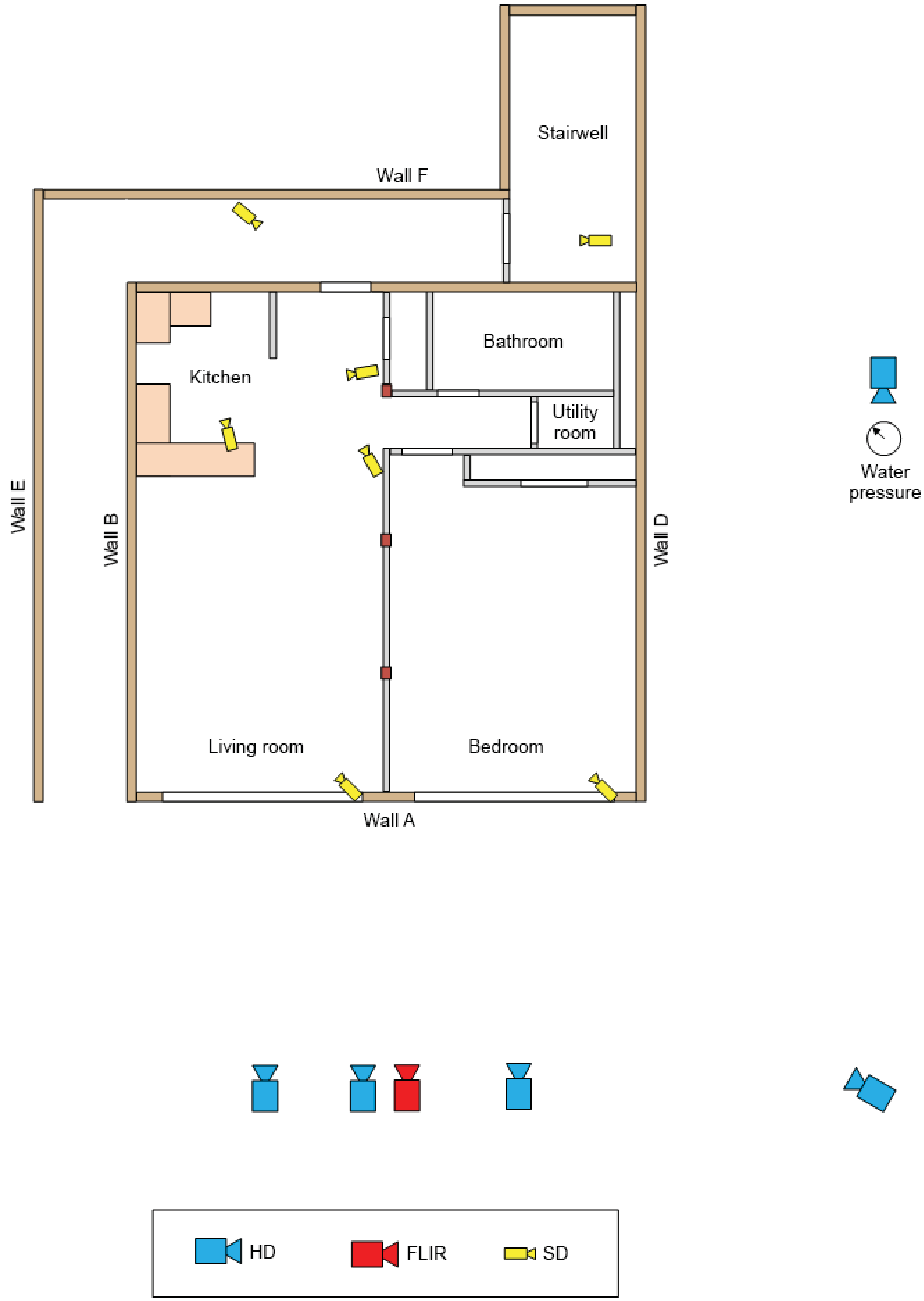


Figure 97. Layout of video cameras (HD, high definition; FLIR, forward looking infrared radiometer; SD, standard definition).

Thermal Imaging Camera

A FLIR ThermaCam SC640 thermal imaging camera (FLIR Systems, Inc., Wilsonville, Oregon, USA) was used during the test series. The infrared camera was used only to show differences in temperatures; it was not used to measure the actual temperature. The FLIR camera recorded videos in standard definition and was positioned looking toward Wall A (Fig. 97).

Summary of Results

The following is a brief summary of the results. Full results including photographs for each individual test are given in Appendices 1 through 5.

Events

Table 13 lists selected events that occurred during each experiment. These events include flashover in the living room and bedroom, visible flames in the corridor, complete failure of the apartment door, and sprinkler activation. The time (after ignition) at which each of these events occurred is given.

Flashover can be defined as “the transition from a localized fire to general conflagration within the compartment when all fuel surfaces are burning” (Drysdale 2011). Visually, it is difficult to determine the exact time when all of the fuel surfaces are burning during a test. Therefore, flashover for this test series was based on the time the two thermocouples located at a height of 1.83 m (6 ft) above the floor in a room (bedroom or living room) reached at least 600°C (1,110°F). The times were then averaged for the two thermocouple readings, and this time was taken as the time flashover occurred. Based on this definition of flashover, flashover occurred in the first three tests. The time to flashover was relatively consistent for a given room, within ±13 s from the average of 17:13 mm:ss in the bedroom and within ±1 min from the average of 12:35 mm:ss in the living room. In Test 5, although flashover conditions were not reached in the bedroom and living room, based on this definition, the thermocouples at Location B in both the bedroom and living room (see Fig. 66) exceeded the 600°C (1,100°F) threshold for a brief time prior to manual sprinkler activation. Also, flashover conditions were reached in the kitchen at approximately 17 min after ignition and were sustained until manual activation of the sprinkler system.

The entrance door to the apartment from the corridor had a fire resistance (protection) rating of 20 min. For the first two tests, flames did not breach the entrance door until after 20 min. However, for Test 3, fire breached the apartment entrance door in approximately 13 min and the entire door failed within 30 min. Although the door was kept closed during Test 3, it failed earlier than for Tests 1 and 2. One possible reason that the fire breached the door quicker in Test 3 is that the automatic door closer was (inadvertently) not attached to the door frame during the test (Fig. 98). This was not noticed until after the test. Another possible reason for the relatively early door failure was that the door frame did not appear to be properly installed. As shown in Figure 99, large gaps were observed between the door frame and the wall. These gaps allowed the steel door frame to flex as the frame was heated. The door may have then opened automatically, if the frame rotated enough that the latch no longer kept the door closed. The fire protection rating of a fire door assembly is based on NFPA Standard 252 fire exposure, in which a door is exposed to a “standard fire” rather than the natural fire growth exposure of a compartment fire. The performance of the fire door assemblies within the compartment fires presented herein cannot be directly compared with performance under a standard fire exposure.

Table 13—Major events during the cross-laminated timber test series

	Time to event after ignition (mm:ss)				
Event	Test #1	Test #2	Test #3	Test #4	Test #5
Flashover in living room	13:27	11:42	12:37	N/A	N/A
Flashover in bedroom	17:20	17:20	17:00	N/A	N/A
Flames in corridor outside of apartment door	26:51	30:38	13:06	N/A	~9:00[a]
Failure of entire apartment door	57:46	63:59	29:42	N/A	N/A
Sprinkler activation	N/A	N/A	N/A	2:37	23:00[b]

[a]Apartment door was open at the start of the test.
[b]Sprinklers were manually activated.

Figure 98. Automatic door closer not attached for Test 3.

Figure 99. Gaps between door frame and wall.

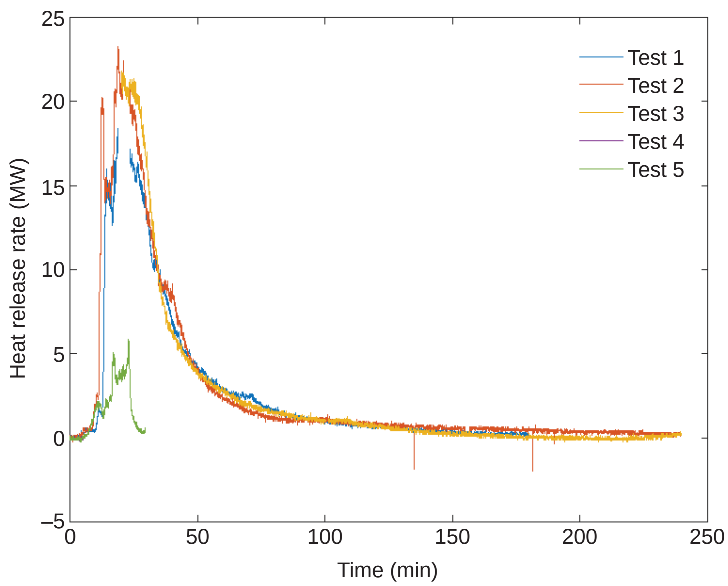


Figure 100. Heat release rate for each test.

Heat Release Rate

Figure 100 shows the heat release rate as a function of time for each test. In general, the first three tests had a similar profile. The heat release rate in Tests 4 and 5 was limited because of the use of fire sprinklers.

Table 14 provides a summary of the peak heat release rate and the total energy released for each test. These values may be less than the actual values because of several factors with the FPC. During Tests 1 and 2, the FPC was briefly taken offline to replace a gas filter. However, this occurred during a time in which the heat release rate may have been at its peak, based on the heat release rate curves shown in Figure 100. For Test 3, an issue with the FPC's gas sampling system resulted in the first 21 min of data not being collected. During Test 1, not all of the combustion products were captured by the FPC hood. This resulted in measured values of heat release rate and total energy released that were probably less than the actual values. To minimize this issue for subsequent tests, airflow through the hood was increased for Tests 2 through 5.

Temperatures

Figures 101 and 102 show the temperatures as a function of time for each test at 1.83 m (6 ft) above the finished floor at location B in the bedroom and living room, respectively. In general, the first three tests had similar temperature profiles at this location. The temperatures in Tests 4 and 5 were limited because of the use of fire sprinklers.

Figures 103 to 105 provide the temperatures of the embedded thermocouples located in the ceiling of the living room for Tests 2, 4, and 5, which all had exposed CLT. Charring, taken as a temperature of 300°C, occurred at

Table 14—Peak heat release rate (HRR) and total energy released

Test number	Peak HRR (MW)	Time of peak HRR (mm:ss)	Total energy released (MW)
1	18.5[a,b]	18:56	34,030[b]
2	23.3[a]	19:04	39,900
3	20.9[a]	20:37	29,150[c]
4	negligible	N/A	negligible
5	5.7	23:13	2,950

[a]Fire products collector (FPC) may have been offline when peak HRR occurred.
[b]Not all of the smoke was captured by the FPC hood.
[c]FPC was offline during the first 21 min of the test.

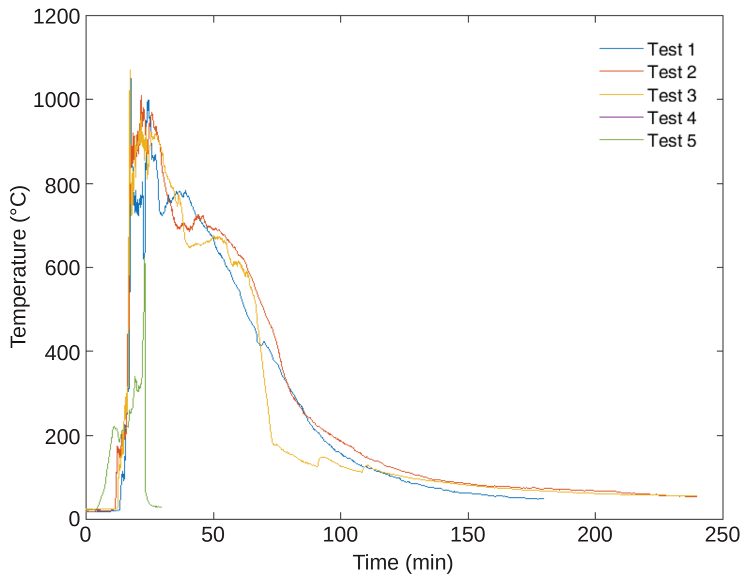


Figure 101. Bedroom air temperature at 1.83 m above finished floor at location B for each test.

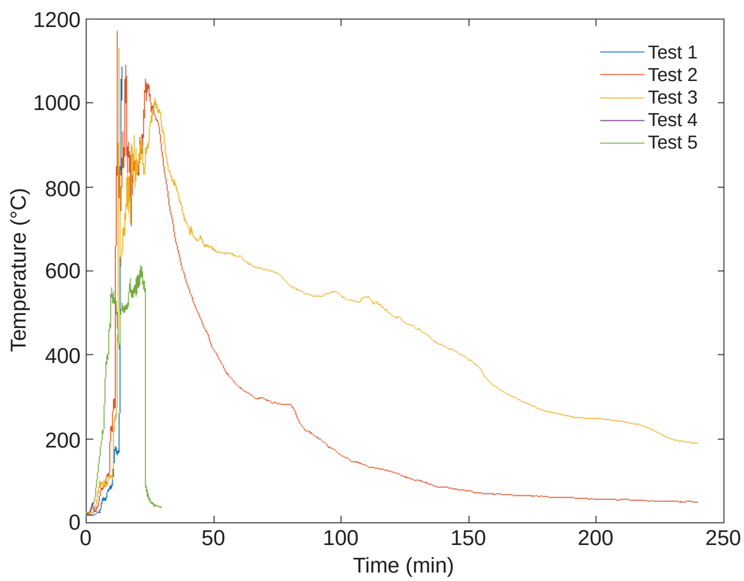


Figure 102. Living room air temperature at 1.83 m above finished floor at location B for each test.

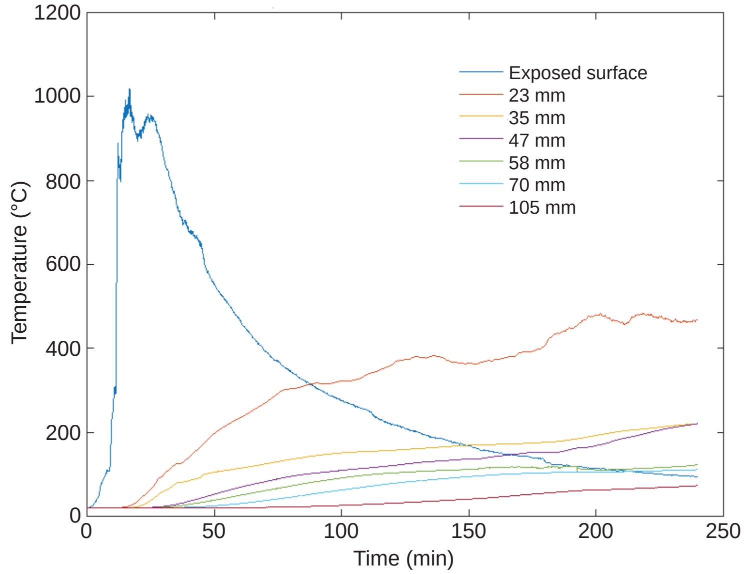


Figure 103. Embedded thermocouple temperatures in exposed cross-laminated timber portion of living room for Test 2.

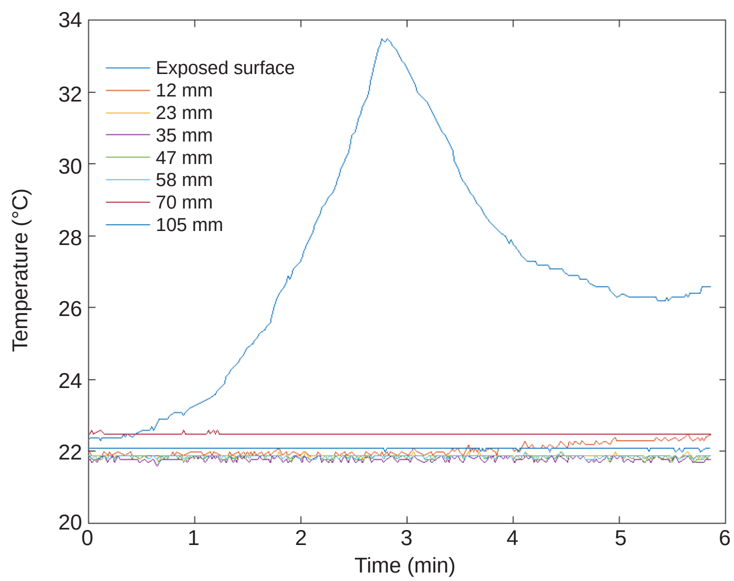


Figure 104. Embedded thermocouple temperatures in living room ceiling for Test 2.

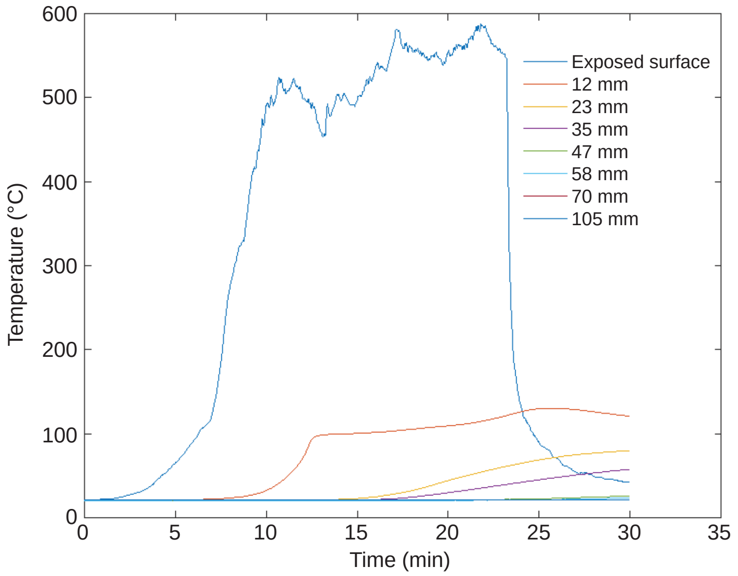


Figure 105. Embedded thermocouple temperatures in living room ceiling for Test 5.

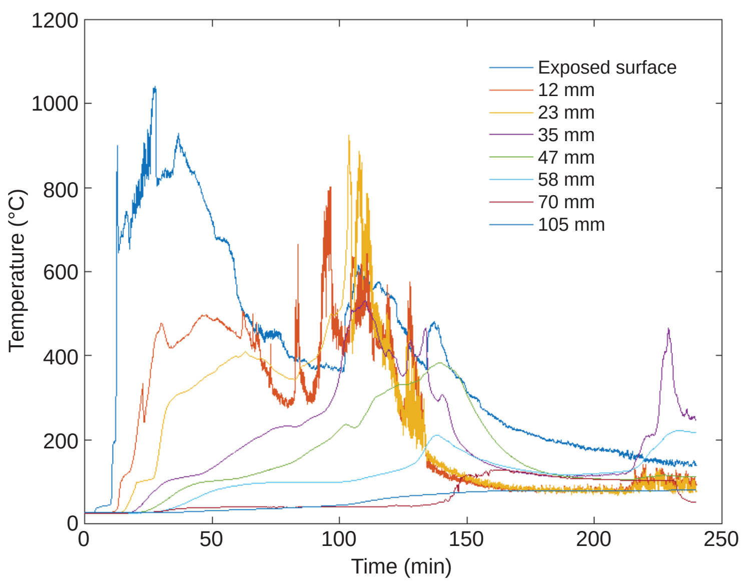


Figure 106. Embedded thermocouple temperatures in living room wall at location B for Test 3.

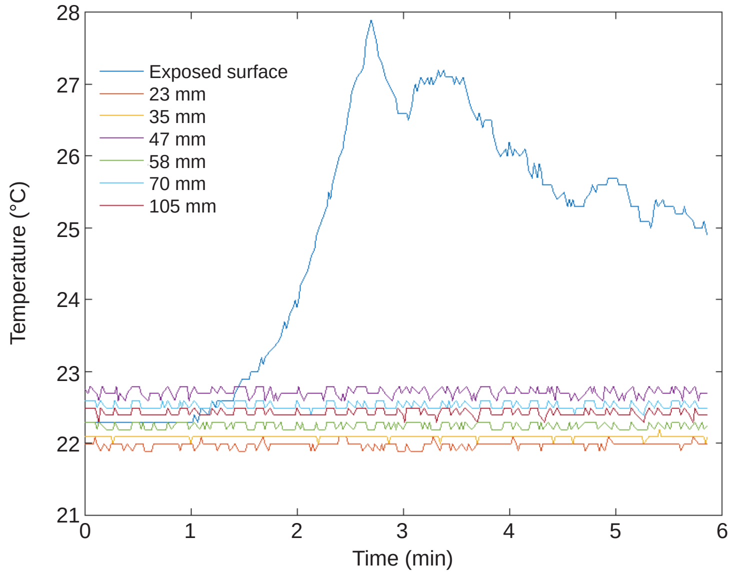


Figure 107. Embedded thermocouple temperatures in living room wall at Location B for Test 4.

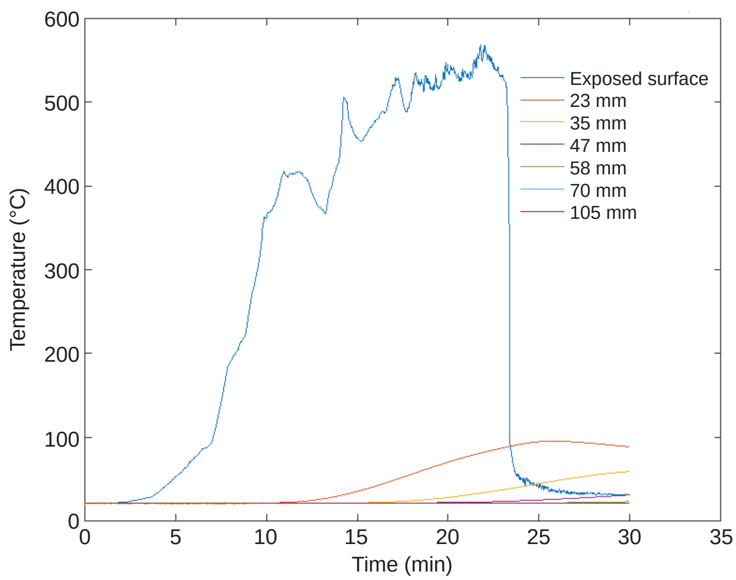


Figure 108. Embedded thermocouple temperatures in living room wall at Location B for Test 5.

depths 23 mm and less into the CLT for Test 2 and less than 12 mm for Test 5. Because of the rapid sprinkler activation in Test 4, charring did not occur in the living room ceiling.

Tests 3, 4, and 5 had exposed CLT on Wall B near the living room–dining area. The embedded thermocouple temperatures for these tests at Location B are provided in Figures 106 to 108. For Test 3, the surface temperature began to increase again around 100 min. Additionally, embedded thermocouple temperatures increased around the same time, with some noise occurring for the thermocouple at 12 mm (0.47 in.). This increase and noise were caused by localized delamination of the first layer of CLT near Location B.

Heat Flux

The heat flux meter in Wall F was positioned in the corridor across from the apartment door and was mounted 0.914 m (3 ft) above the finished floor. The heat flux for each test at this location is provided in Figure 109. The maximum heat flux at this location occurred in Tests 3 and 5, reaching 67 and 38 kW/m^2, respectively. In Test 3, the apartment door was improperly installed and failed earlier than it did in other tests. In Test 5, the apartment door remained open for the duration of the test. The heat flux for Tests 1, 2, and 4 all remained below 10 kW/m^2.

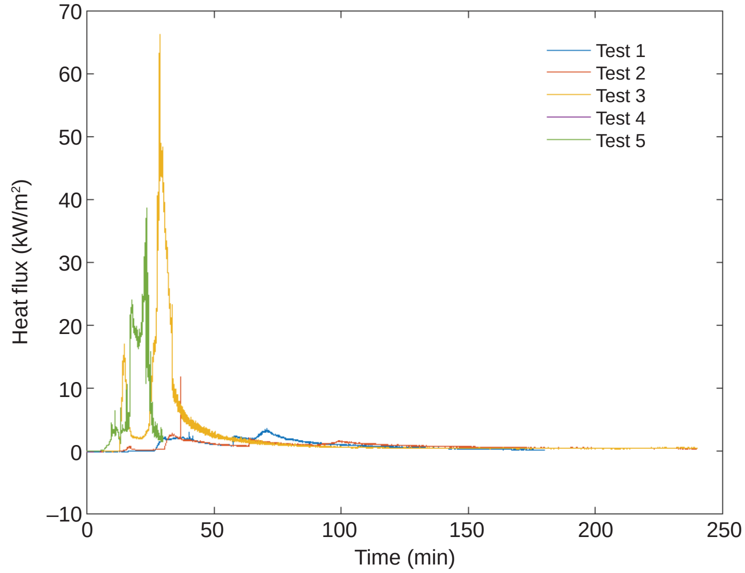


Figure 109. Heat flux in Wall F across from apartment door for each test.

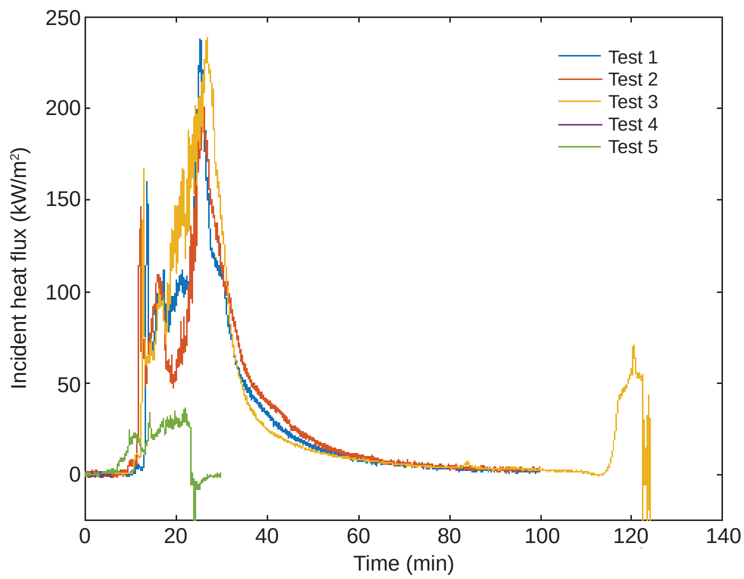


Figure 110. Directional flame thermometer incident heat flux estimates in Wall B, location B, for each test.

The heat flux was also measured throughout the apartment using DFTs. Figure 110 shows the incident heat fluxes to Wall B at Location B, which were estimated from the net heat flux measured by the DFT. The downward spike in Test 5 was most likely caused by water hitting the DFT.

The second spike in Test 3 around 115 min was from localized delamination and increased flaming in the immediate vicinity of the DFT. The DFT data for Test 3 then became noisy and was cut off; this occurred when the DFT fell off the wall.

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Literature Cited

Anon. 2000. The temperature handbook. Stamford, CT: Omega Engineering.

Anon. n.d.-a. Laboratory instruction LI003 – digital cameras. Beltsville, MD: Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory.

Anon. n.d.-b. Laboratory instruction LI001 – thermocouple. Beltsville, MD: Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory.

Anon. n.d.-c. Laboratory instruction LI002 – heat flux transducer. Beltsville, MD: Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory.

Anon. n.d.-d. Laboratory instruction LI009 – external velocity differential pressure probes. Beltsville, MD: Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory.

Anon. n.d.-e. Laboratory instruction LI011 – fire products collectors. Beltsville, MD: Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory.

Anon. n.d.-f. Laboratory instruction LI016 – point source gas analysis. Beltsville, MD: Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory.

Anon. n.d.-g. Laboratory instruction LI017 – laboratory conditions. Beltsville, MD: Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory.

ASTM. 2016. ASTM E3057-16. Standard test method for measuring heat flux using directional flame thermometers with advanced data analysis techniques. West Conshohocken, PA: American Society for Testing and Materials.

Avallone, E.A.; Baumeister III, T. 1996. Marks' standard handbook for mechanical engineers, 10th edition. New York: McGraw Hill: 16:13-16:14.

Babrauskas, V.; Peacock, R.D. 1992. Heat release rate: the single most important variable in fire hazard. Fire Safety Journal. 18(3): 255-272.

Barnes, A. 1999. Heat flux sensors part 1: theory. Sensors — The Journal of Applied Sensing Technology. 16(1): 38-43.

Brandon, D.; Östman, B. 2016. Fire safety challenges of tall wood buildings – phase 2: task 1 — literature review. Quincy, MA: Fire Protection Research Foundation. 39 p.

Clauβ, S.; Dijkstra, D.J.; Gabriel, J.; Kläusler, O.; Matner, M.; Meckel, W.; Niemz, P. 2011a. Influence of the chemical structure of PUR prepolymers on thermal stability. International Journal of Adhesion and Adhesives. 31(6): 513-523.

Clauß, S.; Joscak, M.; Niemz, P. 2011b. Thermal stability of glued wood joints measured by shear tests. European Journal of Wood and Wood Products. 69(1): 101-111.

Craft, S.T.; Desjardins, R.; Richardson, L.R. 2008. Development of small-scale evaluation methods for wood adhesives at elevated temperatures. In: 10th world conference on timber engineering. June 2–5, 2008. Miyazaki, Japan. Madison, WI: Engineered Wood Products Association: Vol. 2: 583-590.

Drysdale, D. 2011. An introduction to fire dynamics, 3rd ed. United Kingdom: John Wiley & Sons, Ltd. 354 p.

Frangi, A.; Fontana, M.; Mischler, A. 2004. Shear behaviour of bond lines in glued laminated timber beams at high temperatures. Wood Science and Technology. 38(2): 119-126.

Frangi, A.; Bertocchi, M.; Clauß, S.; Niemz, P. 2012. Mechanical behaviour of finger joints at elevated temperatures. Wood Science and Technology. 46(5): 793-812.

Gerard, R.; Barber, D.; Wolski, A. 2013. Fire safety challenges of tall wood buildings. Quincy, Massachusetts: National Fire Protection Research Foundation.

Green, M.; Karsh, J. 2012. Tall wood: the case for tall wood buildings. Report prepared for the Canadian Wood Council on behalf of the Wood Enterprise Coalition and Forest Innovation Investment. 240 p.

ICC. 2014. 2015 international building code. Washington, DC: International Code Council.

Klippel, M.; Frangi, A.; Hugi, E. 2013. Experimental analysis of the fire behavior of finger-jointed timber members. Journal of Structural Engineering. 140(3): 04013063.

König, J.; Norén, J.; Sterley, M. 2008. Effect of adhesives on finger joint performance in fire. In: CIB-W18, Meeting 41. Working Commission W18—Timber Structures. Saint Andrews, Canada, August 25-28, 2008. Delft, the

Netherlands: International Council for Research and Innovation in Building and Construction.

Lehmann, S. 2012. Sustainable construction for urban infill development using engineered massive wood panel systems. Sustainability. 4(10): 2707-2742.

Lehringer, C.; Gabriel, J. 2014. Review of recent research activities on one-component PUR-adhesives for engineered wood products. In: Aicher, S.; Reinhardt, H.W.; Garrecht, H., eds. Materials and joints in timber structures. RILEM book series, Vol. 9. Dordrecht: Springer: 405-420.

Li, X.; Zhang, X.; Hadjisophocleous, G.; McGregor, C. 2015. Experimental study of combustible and non-combustible construction in a natural fire. Fire Technology. 51(6): 1447-1474.

McGregor, C.J. 2014. Contributions of cross-laminated timber panels to room fires. Ottawa, Ontario, Canada: Carleton Institute of Civil and Environmental Engineering. M.S. thesis.

Medina Hevia, A.R. 2014. Fire resistance of cross-laminated timber rooms. Ottawa, Ontario, Canada: Carleton Institute of Civil and Environmental Engineering. M.S. thesis.

Mohammad, M.; Gagnon, S.; Douglas, B.K.; Podesto, L. 2012. Introduction to cross laminated timber. Wood Design Focus. 22(2): 3-12.

Munson, B.R.; Young, D.F.; Okiishi, T.H. 2006. Fundamentals of fluid mechanics. 5th ed. New York: John Wiley & Sons. 109 p.

Osborne, L.; Dagenais, C.; Bénichou, N. 2012. Preliminary CLT fire resistance testing report. Project No. 301006155. Final Report. Pointe-Claire, Quebec: FPInnovations. 124 p.

Su, J.; Lougheed, G. 2014. Report to research consortium for wood and wood hybrid mid-rise buildings–fire safety summary. NRCC Report No. A1-004377.1. Ottawa, Ontario, Canada: National Research Council Canada.

Tannert, T.; Vallee, T.; Hehl, S. 2009. Temperature dependent strength of adhesively bonded timber joints. In: Frihart, C.R.; Hunt, C.G.; Moon, R.J., eds. Proceedings of the international conference on wood adhesives. Lake Tahoe, NV. Madison, WI: Forest Products Society: 76-81.

Appendices

Appendices are available in full version of report at
www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr247.pdf.