Fire safety summary: Fire research conducted for the project on mid-rise wood construction: report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings

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REPORT TO RESEARCH CONSORTIUM FOR WOOD AND WOOD-HYBRID MID-RISE BUILDINGS

Fire Safety Summary – Fire Research Conducted for the Project on Mid-Rise Wood Construction

CLIENT REPORT: A1-004377.1

December 31, 2014

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1 BACKGROUND AND CONTEXT

1.1 Trends on Construction of Tall Wood Buildings outside Canada

Wood, a traditional construction material, has gained renewed interest from building sector stakeholders. Different affected parties around the world are looking for the means to accommodate an increasing population to live and work, while contributing to sustainability and sustainable development through healthy and economical building construction with reduced energy consumption and environmental impacts throughout the life cycles of the built environment. Wood is a naturally renewable building material that sequesters carbon dioxide, which helps to reduce the carbon footprint of the built environment. Designers and developers around the world are expanding the use of wood-based structures in higher and larger buildings. Demands for mid-rise wood buildings are increasing with urban building densification and in-fill projects, which increase the demand for use of wood materials, as they have been shown to reduce adverse impacts on the environment, compared to other construction materials.

Most European countries now allow the construction of timber buildings for five or more storeys even without sprinklers; by 2020 all remaining European Union member countries are expected to permit mid-rise or higher wood buildings [1]. In the western US, five-storey wood buildings have been built over one- or two-storey concrete construction with ground retail floor and/or underground parking spaces [2]. The restriction on the number of storeys that can be built with timber structures was removed in the New Zealand Building Codes in 1992 and mid-rise wood buildings have been built within New Zealand since then [3]. In recent years, a large number of mid-rise and tall wood buildings have been constructed around the world [4].

1.2 Trends on Construction of Tall Wood Buildings within Canada

1.2.1 Changes to Provincial Building Codes for Mid-rise Wood Construction

In Canada, building codes are under the jurisdiction of the provinces and territories. All buildings must satisfy, at a minimum, building code requirements enforced by local jurisdictions. Most jurisdictions only permit construction of wood buildings up to four storeys in building height (above grade), as does the model National Building Code of Canada 2010.

In 2009, British Columbia amended its building code to allow mid-rise residential buildings of wood construction up to six storeys. Since then, many mid-rise wood buildings have been constructed across the province.

Quebec Building Regulations were first amended in the fall of 2013 to establish rules under the ‘alternative solution’ path to allow up to six storey residential wood buildings. Later, in September 2014, Quebec published detailed proposed changes for public consultation to the Quebec Construction Code that would adopt prescriptive ‘acceptable solutions’ to permit 5- and 6-storey wood construction for both residential and business occupancies. Approval of the changes is expected in 2015.

Similarly, in March 2014, amendments to Ontario Regulation 332/12 (Building Code) were proposed to permit the construction of residential buildings and office buildings of wood construction for up to six storeys, with mixed use occupancies including restaurants, stores, and medical offices permitted on the first and second storeys. These changes have subsequently been confirmed and will come into effect January 1st, 2015.

1.2.2 Context and Limitation of 2010 NBC

The National Building Code (NBC) of Canada is a model construction code that is adopted in its entirety, or adapted for regional variances, by the individual Provinces and Territories in Canada who have jurisdiction over building regulations. The NBC provides minimum requirements for safety, health, accessibility, fire and structural protection in the design and construction of new buildings. It also applies to the substantial renovation and the demolition or relocation of existing buildings.

The Canadian Commission on Building and Fire Codes (CCBFC) and its standing committees are responsible for the development and maintenance of the NBC using a broad-based consensus process. A new version of the Code is published approximately every five years.

The current 2010 NBC is an objective-based code [5]. Compliance with the Code is achieved by directly applying the *acceptable solutions* in Division B or by using *alternative solutions* according to Division A. The acceptable solutions are prescriptive requirements. The alternative solutions are performance based compliance approaches related to the functional statements and code objectives associated with the minimum level of performance deemed afforded by the acceptable solutions.

Depending on the occupancy classification, most buildings of four storeys or less in height are permitted to be of combustible and/or non-combustible construction under the prescriptive acceptable solutions in Division B. For buildings greater than four storeys in height, the prescriptive provisions require that the main structural elements in the building be of noncombustible construction.

For designers and builders wishing to use structural building materials that are combustible in higher buildings, they can use the alternative solutions approach allowed under Division A. However, they must clearly demonstrate to the Authority Having Jurisdiction (AHJ) that compliance to the Code is achieved, i.e., the alternative solutions meet the minimum level of performance required by Division B in the areas defined by the objectives and functional statements attributed to the applicable acceptable solutions. The burden of proof is placed on the designers and builders. This can be an onerous process. From one jurisdiction to another, there is no harmonization in the approach used to demonstrate the compliance.

1.2.3 Development of Proposed Changes to 2010 NBC

The Province of British Columbia and the Canadian Wood Council made independent submissions in October 2010 and March 2011, respectively, to the CCBFC to request changes to the 2010 NBC Division B to allow the use of wood structural elements in mid-rise buildings. The 2010 NBC required the use of noncombustible structural systems for such buildings. A Joint Task Group (JTG) on Mid-rise Combustible Construction was established in June 2011 by the CCBFC that involved input from five CCBFC Standing Committees (Fire Protection, Use and Egress, Structural Design, Earthquake Design, Environmental Separation). In the first phase of their work, the JTG mandate was to review the code change requests, existing requirements and relevant information and to develop code change proposals for the 2015 NBC, if appropriate. The JTG's mandate for its second phase of work includes the development of performance based requirements for future editions of the code.

2 R&D NEEDS AND INITIATION OF THE PROJECT

Comprehensive research on the use of wood structural elements in mid-rise buildings is required in order to develop additional sound science and technological data for use in the code development process and for the design and construction of such buildings, while meeting the health and safety objectives for the building occupants.

The Canadian Wood Council requested that the National Research Council (NRC) undertake a research project to develop data that could be used to support the evaluation of the code change requests for incorporating requirements into the 2015 NBC to permit the use of wood structural products in mid-rise buildings, and to also facilitate the implementation of future demonstration projects.

Working in collaboration with the Canadian Wood Council and FPInnovations and in partnership with Natural Resources Canada and the governments of Ontario, Quebec and British Columbia, the National Research Council conducted a comprehensive research project, *Research Consortium for Wood and Wood-Hybrid Mid-rise Buildings*. This consortium project aimed to develop technical information that could be used to support acceptable solutions that meet the NBC's objectives for fire safety, acoustics, and building envelope performance, in order to facilitate the use of wood-based structural materials in mid-rise buildings.

A Consultation Group of key industry stakeholders and regulatory bodies was established by NRC to provide advice for the research project and to help disseminate the information developed by the project as widely as possible. Members of the Consultation Group represented building scientists, architects, engineers, regulators, fire services, users, product suppliers and various industries. The Consultation Group held five meetings during the project. Frequent research updates were provided to the CCBFC and the Provincial Territorial Policy Advisory Committee on Codes (PTPACC) through the Canadian Codes Centre and the JTG for their informed decision making.

The research project was coordinated with other research initiatives in Canada, including NEWBuildS (**N**etwork for **E**ngineered **W**ood-based **Build**ing **S**ystems, a multi-disciplinary NSERC strategic research network) and the Canadian tall wood building initiative. The latter involved the development of technical guide for the design and construction of tall wood buildings [6] and also involved demonstration projects for the construction of tall wood buildings in Canada.

3 OBJECTIVES OF THE PROJECT

The objectives of the Wood and Wood-Hybrid Midrise Buildings research project were to develop performance data and technical solutions in the areas of fire safety, acoustics and building envelope pertinent to the use of wood-based structural materials in mid-rise buildings, i.e. to develop an alternative solution to meet the 2010 NBC requirements for non-combustible construction for 5-6 storey (and taller) buildings.

This consortium project aimed to inform the technical discussions by the different CCBFC Standing Committees during the code development process for the 2015 NBC and facilitate the design and construction of mid-rise wood buildings. The research also aimed to provide initial technical data to help address long term needs for establishing performance based criteria/solutions to provide a "level" playing field for the use of various materials as structural loadbearing elements in mid-rise buildings as well as other buildings. It also aimed to provide technical data to be used to develop design standards and guides.

4 SCOPE OF THE PROJECT

In a scoping study [7], NRC had identified a range of issues and/or gaps pertaining to the use of wood as structural loadbearing elements in buildings higher and larger than the current limits set by the 2010 NBC. This project was intended to address the immediate needs for technical solutions for mid-rise wood buildings that do not compromise the minimum levels of safety and performance required by the 2010 NBC in the areas of fire safety and fire protection, acoustics, and building envelope performance.

Research was conducted in the following interdependent critical thrusts:

1) Investigation of the ‘encapsulation’ approach to limit fire severity and fire effects by protecting combustible wood-based structural assemblies with encapsulation materials;
2) Development of solutions to limit exterior fire spread by protecting combustible wood exterior wall systems with noncombustible or low-combustible materials and/or fire retardant panels;
3) Development of fire-resistance rated wood-based structural wall assemblies for applications on lower storeys of mid-rise wood buildings, which also meet acoustic performance required by the NBC (The requirements in NBC 2010 are deemed to deal adequately with the objectives and performance for up to 4 storeys. Therefore, the focus of the fire resistant part of the research was on the wall performance of the lower storeys that would support additional loads in mid-rise wood buildings);
4) Development of acoustic solutions that meet current and potential new NBC provisions for airborne sound insulation and also address the impact sound insulation of building systems; and
5) Assessment of the building envelope performance of the wood-based exterior wall systems that are also shown to meet the fire requirements for limiting exterior fire spread.

It is recognized that there are other issues and risks potentially associated with the mid-rise wood buildings that are beyond the scope of this study and therefore were not addressed in this project. These include risks associated with the actual construction process (workmanship, quality control, supervision and inspection), fire-fighting activities and related issues.

5 CONTENT OF THIS REPORT

This consortium research project produced a large amount of technical information and data in the areas of fire safety, acoustics and building envelope performance for use in mid-rise (and taller) wood buildings. The results of the acoustics and building envelope performance are summarized in separate reports [8, 9].

This report consolidates the results of fire research activities (thrusts 1-3) conducted under the project. These include investigation of the encapsulation approach to protect the combustible structural elements, development of wood-based generic exterior wall assemblies to limit exterior fire spread, and development of generic fire resistant light-weight wood-frame wall assemblies for applications in lower storeys of mid-rise wood buildings.

Among others, the minimum fire protection requirements included in the current NBC mid-rise code change proposals include the mandatory use of automatic sprinkler systems throughout the building. The designs of the fire experiments conducted under this research project do not take into account the impact of water that may be discharged from sprinklers during a fire. Sprinklers are highly effective in controlling or suppressing fires where fires are large enough to activate the sprinklers. Therefore, the NRC research documented in this report is only related to the cases where sprinklers are assumed to have failed to operate and/or control the fire in these mid-rise structures.

6 PERFORMANCE EFFECTIVENESS AND IMPACT OF SPRINKLER SYSTEM

6.1 Sprinkler System Performance Effectiveness

In the research to develop information to support an alternative solution for mid-rise wood construction, all the fire tests involving the full-scale apartment tests were conducted without sprinklers. The primary objective of the investigations was to determine the effectiveness of the encapsulation materials in protecting the combustible structural materials to delay the effects of the fire on the combustible structural elements and, as a result, delay the contribution of the combustible structural elements to the fire severity. (i.e., the research investigated the effectiveness of the encapsulation system in a mid-rise fire scenario in which the sprinkler system did not operate or was ineffective in controlling the fire.)

For mid-rise (5- and 6-stories) and taller buildings, the NBC requires that the buildings be fully sprinklered in accordance with NFPA 13 [10]. In this section, the effectiveness of sprinkler systems is analyzed to establish how likely the encapsulation system would be challenged by a fire in actual practice.

6.1.1 Sprinkler Effectiveness

Bukowski et al. [11] discuss different elements of reliability of fire protection systems. They defined a term called "operational reliability", which is a measure of the probability that a fire protection system will operate as intended when needed. The operational reliability is a measure of component or system operability and it does not take into account the possibility that the system design does not match the fire hazard(s) in the building. Therefore, there is a need to provide additional information on the likelihood that the fire development is within the system's design boundaries. Such a measure of reliability is defined by Bukowski et al. [11] as the "performance reliability", i.e. a measure of the adequacy of the system design.

In fire safety design, it is the combination of operational reliability and performance reliability that is of most interest. It is not possible to only study how often a sprinkler system operates as designed, as information on the system performance in an actual fire is crucial to decide if the system has been successful, or not.

For automatic sprinklers, Hall [12] has combined measures of operational reliability (percent where equipment operated) with measures of performance reliability (percent effective of those that operated) to an overall measure of effectiveness (percent where equipment operated effectively).

Fire statistics have been used in a number of studies to determine the operational reliability of sprinklers since the seminal study by Marryatt in 1988 [13]. The most recent studies are by Hall [12], based on U.S. statistics and Frank et al. based on New Zealand fire statistics [14].

A literature survey by Malm and Pettersson [15] determined that there was a wide range in sprinkler reliability (38 to 99.5%) in the available studies. A number of factors need to be taken into consideration when analyzing statistical data to determine sprinkler reliability. This includes whether the fire was confined or unconfined, whether it was large enough to activate the sprinklers and whether the sprinkler system was in the fire area. For example, in Table 1 extracted from Reference [12], there was an estimated total of 48,460 structure fires/year in buildings with sprinklers present in the U.S. during the period of 2007 – 2011. Of these fires, 6,440 (13.2%) were unconfined but too small to activate the sprinklers and 34,000 (70%) were coded as confined fires, which were treated as fires too small to activate operating equipment. Other factors used to exclude fires from the analysis included buildings under construction and lack of sprinklers in the fire area. Based on the analysis of the statistical data, the number of qualifying fires/year was 3,020 (6.2%).

The term "effective" is subjective and open to ambiguity in the analysis of fire statistics to determine the performance effectiveness of sprinklers [15]. Hall, in his studies, has suggested that the sprinkler effectiveness should be measured relative to the design objective of the system, which is typically to confine the fire to the room of fire origin or in the case of large rooms to the sprinkler 'design area' [12]. The guideline on the probabilistic risk assessment for fire safety design of buildings published by the British Standards Institution [16] recommends using four activated sprinklers as the cutoff for effective sprinkler operation. Marryatt [13], in his study, used 20% destruction of the protected property as the criteria for effective sprinkler operation.

Table 1 extracted from Reference [12] shows the reliability of sprinklers (ability to respond and provide water), their efficacy (effectiveness when operated) and total effectiveness (product of reliability and efficacy) for various property uses based on U.S. fire statistics. The results indicate that sprinkler reliability varied widely depending on the occupancy, with the lowest (79%) for storage applications and the highest (94%) for residential applications. There was less variation in sprinkler efficacy with the lowest (93%) for public assembly applications and the highest (98%) for health care properties.

The two highest values for total sprinkler effectiveness were 91% for residential and 87% for store or office applications. These two categories are the areas of primary interest for mid- and tall-wood building construction.

The data provided in Table 1 is for all sprinklers. Reference [12] also provided results for wet and dry pipe sprinkler systems. A wet pipe sprinkler system has sprinklers attached to a piping system containing water so that water discharges immediately from sprinkler heads opened by heat from a fire, while a dry pipe sprinkler system has sprinklers attached to a piping system containing air or nitrogen under pressure so that sprinkler activation releases the air or nitrogen, allowing water pressure to open a valve and water to flow into the piping system and out the opened sprinklers. Table 2, which is based on data extracted from Reference [12], shows the reliability of sprinklers (ability to respond and provide water), their efficacy (effectiveness when operated) and total effectiveness (product of reliability and efficacy) for wet and dry pipe systems based on U.S. fire statistics for all structures. The dry pipe systems represent approximately 10% of the sprinkler systems. This type of system had a lower reliability (81%) than the wet pipe system (92%). The efficacy of the two types of systems was comparable and overall the dry pipe system had a lower total effectiveness (76%) than the wet pipe system (89%).

Frank et al. [14] analyzed New Zealand fire statistics for 2001 – 2010 and, based on this analysis, the reliability of sprinklers was 95%, the efficacy was 90% and the total effectiveness was 86%, with a standard deviation of uncertainty of 4.6%. The sprinkler reliability based on the New Zealand fire statistics is higher than that determined by Hall [12] and the sprinkler efficacy was lower in the New Zealand study. Overall, the total sprinkler effectiveness determined in the two studies was comparable with 86% and 87% based New Zealand and U.S. fire statistics, respectively.

Table 1. Automatic extinguishing equipment reliability and effectiveness when fire coded as non-confined and large enough to activate equipment and equipment was present in area of fire, by property use 2007-2011 U.S. structure fires, all sprinklers [12].

Property Use	Number of fires per year where sprinklers were present	Non-confined fires too small to activate equipment	Fires coded as confined fires	Number of qualifying fires per year	Percent where equipment operated (A)	Percent effective of those that operated (B)	Percent where equipment operated effectively (A x B)
All public assembly	3,410	560	2,210	640	91%	93%	84%
Eating or drinking establishment	1,680	300	990	390	91%	91%	83%
Educational property	2,020	440	1,400	180	87%	97%	84%
Health care property*	3,360	670	2,350	340	86%	98%	84%
All residential	29,430	2,500	23,010	3,920	94%	97%	91%
Home (including apartment)	23,650	1,630	18,890	3,120	95%	97%	91%
Hotel or motel	1,870	370	1,210	300	90%	97%	88%
Store or office	4,230	1,090	2,040	1,100	90%	97%	87%
Grocery or convenience store	880	250	430	190	90%	95%	85%
Department store	470	180	170	120	87%	98%	85%
Office	1,100	240	680	180	89%	97%	87%
Manufacturing facility	2,530	660	760	1,110	90%	94%	84%
All storage	770	150	280	340	79%	97%	76%
Warehouse excluding cold storage	400	80	110	200	84%	97%	82%
All structures**	48,460	6,440	34,000	3,020	91%	96%	87%

* Nursing home, hospital, clinic, doctor's office, or other medical facility.
** Includes some properties not listed separately above.

Table 2. Automatic extinguishing equipment reliability and effectiveness when fire coded as non-confined and large enough to activate equipment and equipment was present in area of fire by sprinkler system 2007-2011 U.S. structure fires, all structures [12].

Sprinkler System	Number of fires per year where sprinklers were present	Non-confined fires too small to activate equipment	Fires coded as confined fires	Number of qualifying fires per year	Percent where equipment operated (A)	Percent effective of those that operated (B)	Percent where equipment operated effectively (A x B)
Wet pipe sprinklers	42,520	5,680	29,690	2,150	92%	96%	89%
Dry pipe sprinklers	4,530	620	3,250	660	81%	94%	76%
All sprinklers	48,460	6,440	34,000	3,020	91%	96%	87%

6.1.2 Reasons for Failure to Operate

Reference [12] provides results for the primary reasons that the sprinkler system failed to operate. Table 3, extracted from Reference [12], provides the percentages for each reason for failure for all sprinklers by property use in 2007-2011. The results are also illustrated in Figure 1 based on the 9% of the fires in which the sprinklers failed to operate in all structures.

Nearly two-thirds (64%) of sprinkler failures occurred because the system was shut off. The other reasons for failure to operate were manual intervention defeated the equipment (17%), component was damaged (7%), lack of maintenance (6%) and equipment inappropriate for the type of fire (5%).

Only 7% of the failures were because of a failing of the equipment rather than a failing of the people who designed, selected, maintained, and operated the equipment. If these human failings could be eliminated, the overall sprinkler failure rate would drop from the estimated 9% of reported fires to 0.6% [12]. That is close to the sprinkler failure rate reported in the mid-1980s by Marryatt [13] for Australia and New Zealand, where high standards of maintenance were reportedly commonplace. The difference in maintenance standards may also account for the higher reliability in the recent New Zealand study [14].

Table 3. Reasons for failure to operate when fire was coded as not confined and large enough to activate equipment and equipment was present in area of fire, by property use based on estimated number of 2007-2011 structure fires per year [12].

Property Use	System shut-off	Manual intervention defeated system	System component damaged	Lack of maintenance	Inappropriate system for type of fire	Total fires per year
All public assembly	51%	13%	7%	13%	15%	61
Eating or drinking establishment	43%	11%	10%	21%	15%	34
All residential	59%	21%	8%	7%	4%	233
Home (including apartment)	64%	16%	9%	6%	5%	168
Store or office	62%	16%	11%	5%	6%	112
Manufacturing facility	65%	17%	7%	5%	5%	111
All structures**	64%	17%	7%	6%	5%	711

** Includes some properties not listed separately above.

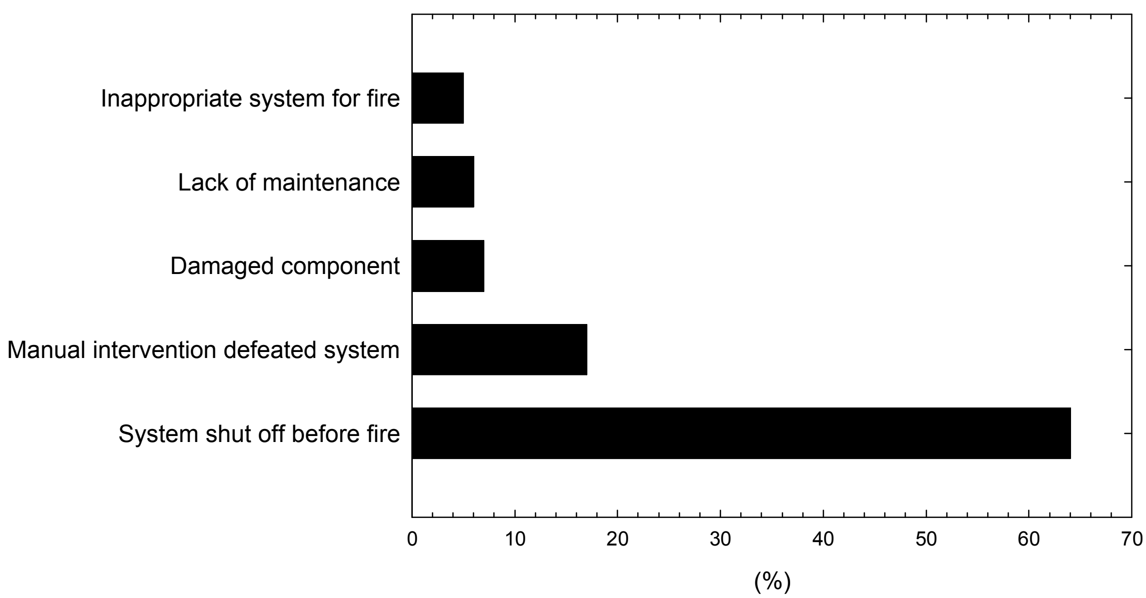

Figure 1. Reason when sprinklers fail to operate 2007-2011 (all sprinklers and all structures).

6.1.3 Reasons for Sprinkler Ineffectiveness

Reference [12] provides results for the primary reasons that the sprinkler system was ineffective when activated by a fire. Table 4, extracted from Reference [12], provides the percentages for each reason automatic sprinklers were ineffective by property use in 2007-2011. The results are also illustrated in Figure 2 based on the 4% of the fires in which the sprinklers operated in all structures but were ineffective.

Sprinkler ineffectiveness in non-confined fires was primarily because the water did not reach the fire (44%) or because not enough water was released (30%). Other reasons included damage to a system component (8%), manual intervention (7%), lack of maintenance (7%) and inappropriate equipment for the type of fire (5%).

Insufficient (not enough) water can be released if there are problems with the system's water supply. This reason for ineffectiveness also overlaps with other reasons:

1. Inappropriate equipment. For example, the occupancy hazard has changed requiring a higher water flow density than is provided by the now inappropriate equipment,
2. Manual intervention. The system is turned off before sufficient water has reached the fire,
3. Flash fire, fire with multiple origins and explosions.

There are a number of different ways in which *water may not reach the fire*.

1. Shielded fires,
2. Deep-seated fires in bulk storage,
3. Fire spread above exposed sprinklers, through unsprinklered concealed spaces, or via exterior surfaces.
4. Droplet sizes that are too small to penetrate the buoyant fire plume and reach the seat of the fire.

The discussion in Reference [12] on sprinkler effectiveness when operated was based on whether or not the system met the design objective (whether or not the fire was confined to the room of fire origin or to the design area, in the case of large rooms/un-compartmented spaces).

Table 4. Reasons for ineffectiveness when fire was coded as not confined and large enough to activate equipment and equipment was present in area of fire, by property use based on estimated number of 2007-2011 structure fires per year [12].

Property Use	Water did not reach fire	Not enough water released	System component damaged	Manual intervention defeated system	Lack of maintenance	Inappropriate system for type of fire	Fires per year
All public assembly	69%	21%	0%	0%	5%	5%	41
Eating or drinking establishment	69%	25%	0%	0%	6%	0%	33
All residential	39%	40%	7%	3%	5%	7%	119
Home (including apartment)	40%	35%	8%	3%	6%	9%	102
Store or office	39%	32%	8%	13%	4%	4%	34
Manufacturing facility	39%	26%	9%	9%	13%	6%	62
All structures**	44%	30%	8%	7%	7%	5%	300

** Includes some properties not listed separately above.

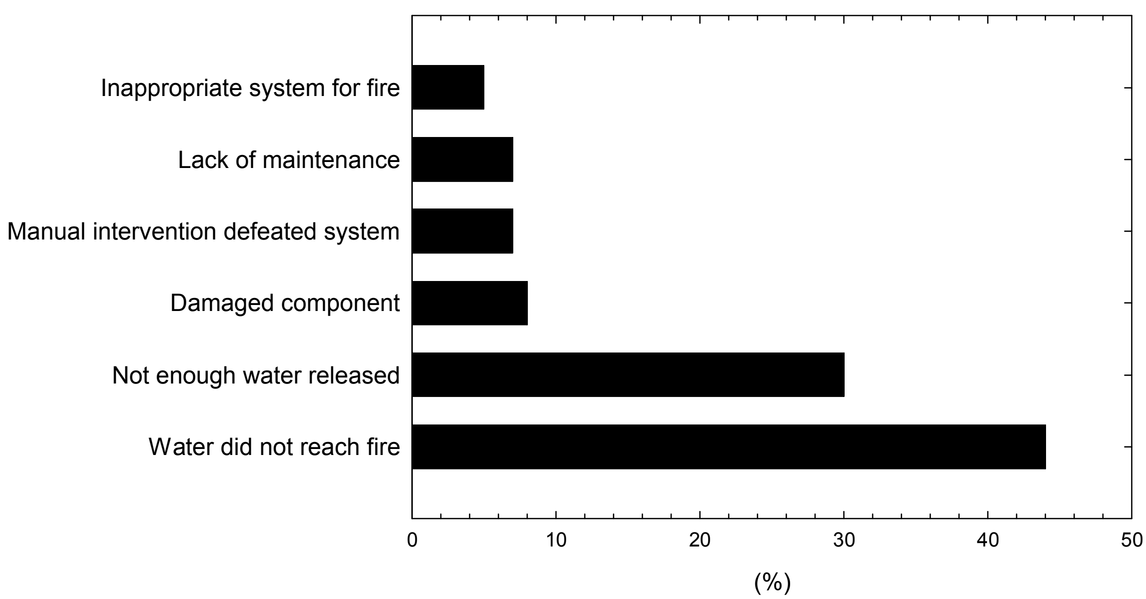

Figure 2. Reason when sprinklers are ineffective 2007-2011 (all sprinklers and all structures).

6.2 Sprinkler Impact on Extent of Flame Damage and Loss of Life

The discussion in Reference [12] on sprinkler effectiveness when operated was based on whether or not the system met the design objective (i.e., whether or not the fire was confined to the room of fire origin or to the design area in the case of large rooms/un-compartmented spaces). Therefore, the benefits of sprinklers will tend to come in the following scenarios [12]:

- A fire that would otherwise have spread beyond the room of fire origin will be confined to the room of origin, resulting in a smaller fire-damaged area and less property damage.
- A fire that would otherwise have grown larger than the design fire area in a room larger than that area will be confined to the design fire area, resulting in a smaller fire-damaged area and less property damage.
- A fire will be confined to an area smaller than the room or the design fire area, even though that degree of success goes beyond the performance assured by the design, resulting in a smaller fire-damaged area and less property damage.

Table 5 provides direct measurement of sprinkler effect involving the first bulleted scenario above. For all structures combined, 51% have flame damage confined to room of origin when there is no automatic extinguishing equipment present. This rises to 86% of fires with flame damage confined to room of origin when any type of sprinkler is present.

The extent of fire spread for residential buildings was investigated in Reference [17] using the Province of British Columbia's fire statistics for the period between October 2006 an October 2011. The extent of fire spread in residential properties with the fire controlled by the sprinkler system is shown in Figure 3. Figure 4 shows the extent of fire spread in residential properties without sprinkler protection.

The extent of fire spread based on the Province of British Columbia fire statistics show a similar trend to Reference [12] with 96.7% of the fires controlled by sprinklers confined to the room of fire origin compared to 62.6% in buildings without sprinkler protection for all residential properties. The difference in the fire spread was less for apartment buildings with 95.2% of fires confined within the room of fire origin for buildings with sprinkler protection and 84.7% in buildings without sprinklers.

Fires controlled by sprinklers were as likely to extend as far as the floor of origin in apartment buildings as fires in apartment buildings without sprinklers. However, in the apartment buildings without sprinkler protection, there was an increased likelihood of the fire spreading to the building and beyond the building.

Overall, the results indicate that, with sprinkler protection, it is less likely that a fire will spread beyond the room of fire origin with a resulting reduction in property damage. Also, with sprinklered buildings, it is less likely that fire service personnel will be faced with a large fire situation.

A second approach to determine the impact of sprinklers is the reduction in life loss per fire. Table 6 extracted from Reference [12] shows fire death rate reductions for various property use groups. Table 7 shows fire death rate reductions for residential properties based on Reference [17].

For properties other than homes, deaths tend to be extremely rare, with or without sprinklers. The associated rates of deaths per thousand fires will therefore be very sensitive to individual fires with large death tolls, fatal fires with unusual circumstances, the variability associated with analysis of confined fires, and fires with fatalities or other characteristics misreported.

For 2007-2011 home fires, Reference [12] indicates the death rate per 1,000 fires was 82% lower with wet pipe sprinklers than with no automatic extinguishing equipment. Based on the Province of British Columbia fire statistics in Reference [17], the death rate per 1,000 fires was 92% lower in all residential properties with sprinkler protection.

Table 5. Extent of Flame Damage for Sprinklers Present vs. Automatic Extinguishing Equipment Absent 2007-2011 Structure Fires [12].

Property Use	Percentage of fires confined to room of origin excluding structures under construction, fires coded as confined fires, and sprinklers not in fire area		
	With no automatic extinguishing equipment (%)(%)	With sprinklers of any type (%)	Difference (in percentage points)
All public assembly	58	82	24
Variable-use amusement or recreation place	65	88	23
Religious property	54	83	30
Library or Museum	67	87	20
Eating or drinking establishment	58	79	21
Educational property	77	92	15
Health care property*	79	94	15
All residential	54	89	35
Home (including apartment)	54	88	34
Hotel or motel	74	93	19
Dormitory or barracks	76	94	18
Store or office	56	84	27
Grocery or convenience store	59	86	27
Department store	56	85	29
Office	60	88	27
Manufacturing facility	55	85	24
All storage	24	68	44
Warehouse excluding cold storage	39	71	32
All structures**	51	86	35

* Nursing home, hospital, clinic, doctor’s office, or other medical facility.
** Includes some properties not listed separately above.

Table 6. Estimated Reduction in Civilian Deaths per Thousand Fires Associated With Wet Pipe Sprinklers, by Property Use 2007-2011 Structure Fires [12].

Property Use	Without automatic extinguishing equipment	With wet pipe sprinklers of any type	Percent reduction (%)
All public assembly	0.6	0.0	100
All residential	7.4	1.1	85
Home (including apartment)	7.4	1.3	82
Boarding or rooming house	9.6	1.5	84
Hotel or motel	7.3	0.0	100
Residential board and care home	5.7	0.7	88
Dormitory or barracks	1.1	0.0	100
Store or office	1.5	0.6	62
Manufacturing facility	2.3	0.6	88
Warehouse excluding cold storage	3.5	1.4	61
All structures	6.3	0.8	86

Table 7. Estimated Reduction in Civilian Deaths per Thousand Fires Associated With Sprinklers, by Property Use 2006-2011 Structure Fires [17].

Property Use	Without automatic extinguishing equipment	With sprinkler protection	Percent reduction (%)
All residential	15.9	1.2	92
Apartment	23.1	2.1	91
Single detached	12.4	0.0	100

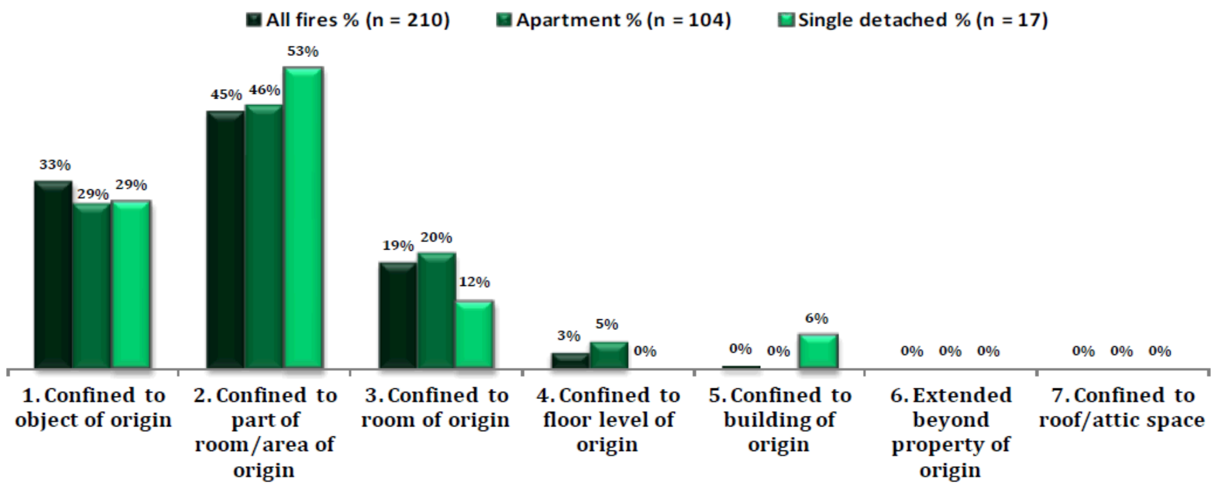

Figure 3. Extent of fire spread for sprinkler protected buildings (where the method of fire control was by the sprinkler system) by property classification [17].

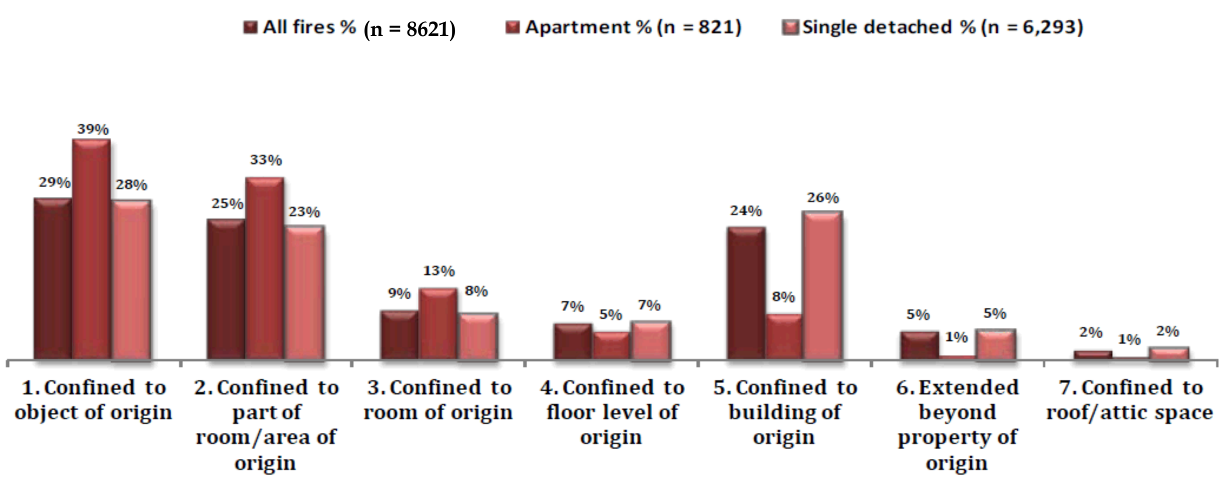

Figure 4. Extent of fire spread for buildings without sprinkler protection, by property classification [17].

6.3 Summary of Sprinkler Effectiveness and Impact

In the research to develop an alternative solution for mid-rise wood construction, the primary objective of the investigations was to determine the effectiveness of the encapsulation materials in protecting the combustible structural materials to delay the effects of the fire on the combustible structural elements and, as a result, delay the contribution of the combustible structural elements to the fire severity. However, for mid-rise (5- and 6-stories) and taller buildings, the NBC requires that the buildings be fully sprinklered in accordance with NFPA 13. In this section, the effectiveness of sprinkler systems was analyzed to establish how frequently the encapsulation system would be challenged by a fire in actual practice.

There are two primary parameters impacting the performance effectiveness of a sprinkler system in the event of a fire:

1. Sprinkler reliability. Sprinkler reliability indicates whether or not the sprinkler responds and delivers water to the fire when required. In most cases (91% in Reference [12]), the failure of the sprinkler system was due to human factors. If these factors were reduced through better maintenance and operating practices, the reliability of sprinklers could be significantly improved [12].
2. Sprinkler efficacy. Sprinkler efficacy is a measure of whether or not the sprinkler system was effective when operated. There is considerable subjectivity in assessing the efficacy of a sprinkler system including the parameter used to assess whether or not the system was "effective". Hall [12] based his analysis on whether not the system met its design objective by confining the fire to the room fire origin or, in the case of large rooms/un-compartmented spaces, to the design area.

The product of the two parameters (sprinkler reliability and efficacy) gives the overall performance effectiveness of the sprinkler system.

The analysis in Reference [12] based on US experience for 2007-2011 and in Reference [14] based on New Zealand fire statistics for 2001 – 2010 indicate that the performance effectiveness of sprinklers is 87% and 86%, respectively, for fires in all occupancies. It should be noted that the percentages are based on only those fires for which the sprinkler system should have operated.

The performance effectiveness of sprinklers is dependent on property use with the highest values 91% and 87% for residential and for store or office applications, respectively. These two categories are the areas of primary interest for mid- and tall-wood building construction.

The primary benefits of sprinkler systems are a reduction in the extent of fire spread resulting in reduced losses and a reduction in the loss life. The impact of sprinklers on the extent of fire spread and life loss were investigated in References [12] and [17]. Overall, the results indicate that, with sprinkler protection, it is less likely that a fire will spread beyond the room of fire origin with a resulting reduction in property damage. Also, with sprinklered buildings, it is less likely that fire service personnel will be faced with a large fire situation. Both studies also indicate a significant reduction in life loss per 1,000 fires with a 82% reduction based on the US fire experience and a 92% reduction in residential occupancies based on the Province of British Columbia fire statistics.

7 FIRE RESISTANCE TESTS OF WALL ASSEMBLIES FOR USE IN LOWER STOREYS

One of the major differences between structural lightweight wood-frame (LWF) assemblies used in mid-rise wood buildings and low-rise wood buildings (≤ 4 stories) are the loadbearing wall assemblies for the lower storeys. For mid-rise wood buildings, loadbearing wall assemblies utilized on the lower storeys have to be designed to resist higher gravity loads due to higher gravityloads from the additional upper storeys, and higher lateral loads in case of seismic events or wind loads. These wall assemblies need to meet standard fire resistance and acoustic requirements, and therefore, information regarding their standard fire resistance and Sound Transmission Class (STC) ratings are required. The NBC currently requires the wall assemblies that separate a dwelling unit from other spaces in a building to meet a STC rating of 50 or higher for direct airborne sound insulation. Extensive acoustic experiments were conducted to determine STC ratings for 49 LWF wall assemblies with various stud sizes and configurations (staggered-stud; single-, double- or triple-stud; different stud spacing; built-up end columns; etc.) and with or without a shear membrane [8]. A number of the assemblies that met an STC rating of 50 or higher were selected for standard fire resistance testing. The fire resistance tests of the lightweight wood frame wall assemblies for use in mid-rise applications are fully documented in a series of reports [18, 19]. A brief summary is provided below.

7.1 Wall Assemblies for Fire Resistance Tests

Standard full-scale furnace tests were conducted to determine the fire endurance period for 6 encapsulated lightweight wood frame wall assemblies. The tests were conducted in conformance with CAN/ULC-S101 [20].

Table 8 shows the six wall assemblies with staggered-stud configurations developed and tested. The basic wood-stud framing included single or built-up (tripled) staggered studs on a single common bottom plate, with a double top plate and single end studs. For Wall Assemblies #1, 5 and 6, a shear membrane layer of 11.1 mm thick OSB wood structural panel was attached to the unexposed side of the framing (the side of the assembly facing away from the furnace). For Wall Assemblies 2 and 3, horizontal resilient metal channels were installed on the fire-exposed side of the framing (the side of the wall assembly facing into the furnace). Glass fibre insulation was installed in the wall cavities in all tests; for Wall Assemblies #5 and 6, the insulation on each cavity side was installed with its back side (side facing the centre staggered studs) partially scored so that it wrapped around the centre staggered stud. This was done to ensure that the gypsum board was not put under excessive stress. The wall assemblies were protected with a double layer of 12.7 mm thick Type X gypsum board on both sides applied with or without the shear membrane layer and with or without resilient metal channels.

The total superimposed load was applied along the width of the assembly, satisfying the full specified load conditions as per CAN/ULC-S101 [20].

Wall Assembly #4 was the same as Wall Assembly #1 but without the shear membrane layer. Wall Assembly #6 was the same as Wall Assembly #5 in the basic framing but horizontal blocking was added at the mid-height of Wall Assembly #6 to limit the deformation of the studs in the plane of the wall assembly.

In addition to the measurements required by the CAN/ULC-S101 test standard to determine the fire endurance period (FEP) for each test assembly, temperatures at the interface between the gypsum board used to protect the structural elements, on the studs and in the wall cavity were also measured. This provides data to determine the protection (encapsulation) time for the structural elements provided by two layers of 12.7 mm thick Type X (fire-resistant) gypsum board under standard fire exposure. These results are discussed and summarized in Section 9.5 of this report.

Table 8. Fire Resistance Tests of Wall Assemblies with Staggered Studs and 2 Layers of 12.7 mm Thick Type X Gypsum Board on Both Sides of Framing

Wall	Stud size	Stud spacing (mm o.c.)	Size of top plate,* bottom plate, end studs	Glass fibre thickness (mm)	OSB shear membrane layer (11.1 mm thick)	Resilient metal channels (600 mm o.c)	Applied load (kN)	Fire endurance period (FEP) (min)
# 1	38 mm x 89 mm	400	38 mm x 140 mm	90	unexposed side†	-	170	92
# 2	38 mm x 89 mm[Tri]	400	38 mm x 140 mm	90	-	exposed side‡ only	456	90
# 3	38 mm x 89 mm	100	38 mm x 140 mm	90	-	exposed side‡ only	624	75
# 4	38 mm x 89 mm	400	38 mm x 140 mm	90	-	-	170	87
# 5	38 mm x 140 mm	400	38 mm x 190 mm	140	unexposed side†	-	506	81
# 6§	38 mm x 140 mm	400	38 mm x 190 mm	140	unexposed side†	-	506	98

* A double top plate was used.
[Tri] – built-up tripled studs
† "unexposed side" refers to the side of the assembly facing away from the furnace.
‡ "exposed side" refers to the side of the wall assembly facing into the furnace.
§ Assembly #6 with horizontal blocking (38 mm x 89 mm) at mid-height to limit deformation of the studs in the plane of the wall assembly.

7.2 Results and Summary of Fire Resistance Tests

Table 8 shows the results of the full-scale standard furnace tests for the six light-weight wood-frame wall assemblies with staggered studs protected by two layers of 12.7 mm thick Type X (fire-resistant) gypsum board. The fire endurance period of each of the assemblies provided in the table is assigned based on the time at which the test assembly failed to sustain the applied load. All of the assemblies failed structurally prior to either the temperatures on the unexposed side of the assembly exceeding the temperature criteria due to transmission of heat through the test assembly or any passage of flame or hot gases to the unexposed side, as defined in CAN/ULC-S101. The wall assemblies provided fire endurance periods of 75 min or higher. Three wall assemblies (#1, #2 and #6) had fire endurance periods of 90 min or longer.

Wall Assembly #2, with tripled built-up studs, and Wall Assembly #3 with 100 mm stud spacing investigated two different methods of increasing the loadbearing capacity of a wall assembly. The close stud spacing assembly (#3) had a higher loadbearing capacity but a lower fire endurance period.

Wall Assembly #4 was essentially the same as Wall Assembly #1 but without the shear membrane layer. Results from the tests of these two assemblies show that the OSB shear membrane layer contributed extra 4-5 min to the fire endurance period.

The structural failure of Wall Assembly #5 occurred at 81 min. After the test, it was observed that many of the studs, particularly those on the exposed side of the assembly, buckled within the plane of the wall rather than perpendicular to the wall plane. For Wall Assembly #6, the assembly was modified by adding horizontal blocking at the mid-height. With the blocking, the deformation of the studs within the plane of the wall assembly (the weak-axis buckling) was limited and structural failure occurred at 98 min with the studs deforming perpendicular to the plane of the wall resulting in a 17 min increase in the fire endurance period. The results suggest that limiting the lateral deflection of the studs in the plane of the wall (in-plane buckling) could be an important factor in improving the fire performance of staggered stud wall assemblies with high imposed loads.

The deflection of the test assemblies were measured using nine deflection gauges attached to each test assembly. The average deflection of the test assemblies is shown in Figure 5. Initially, there was a small positive deflection (into the furnace) of the test assemblies. After approximately 55 min, the wall assemblies began to deflect away from the furnace. This time corresponds to the time at which the temperatures at the interface (space) between the studs and the back side of the base layer of gypsum board on the exposed (fire) side of the test assembly exceeded 300°C and the studs began to char. This is discussed further in Section 9.5.

The average deflection was small (< -10 mm) until the last 3 – 8 min of the test except for Assembly #4, for which the wall deflection exceeded -10 mm at 14 min before structural failure. Assembly #4 was the same as Assembly #1 except an OSB shear membrane was attached to the studs on the unexposed side of Assembly #1. The results indicate that the OSB shear membrane on the unexposed side of the assembly decreased the initial rate at which the wall assembly deflects. Subsequently, there was a rapid deflection at the end of the tests. This observation is consistent with the average deflections for Assemblies #5 and #6, which also included an OSB shear membrane on the unexposed side of the assembly.

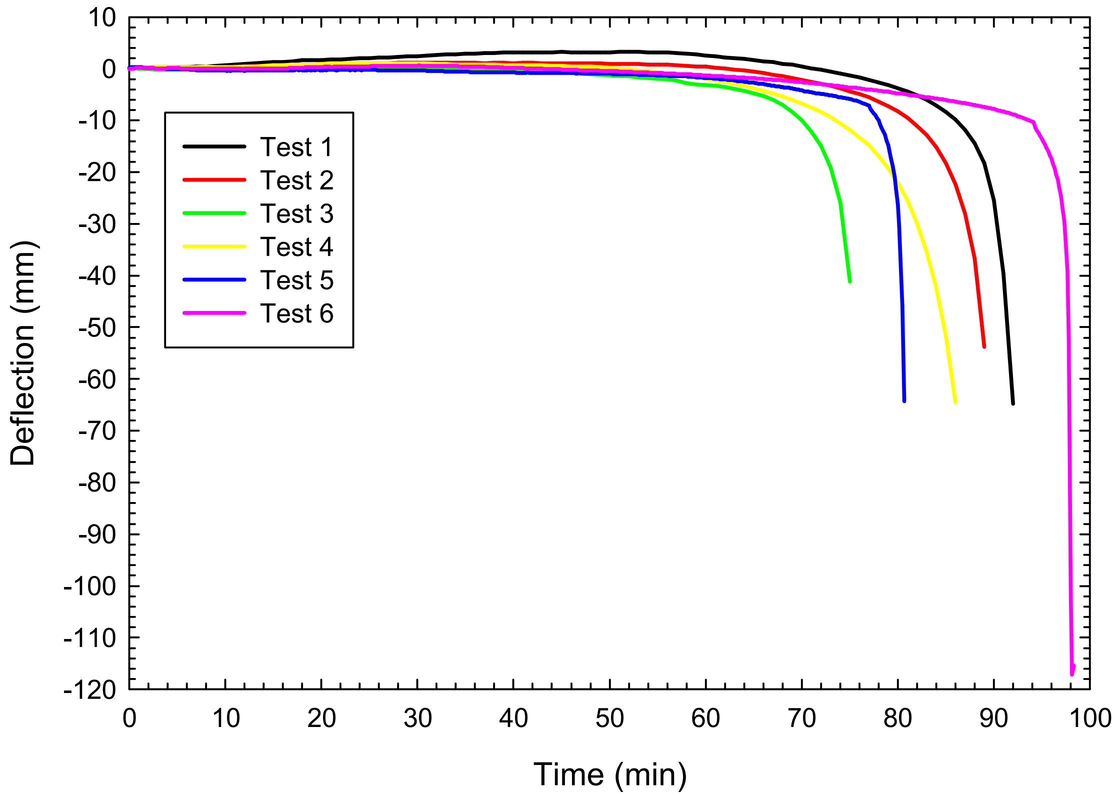

Figure 5. Average deflections.

8 WOOD-BASED EXTERIOR WALLS FOR LIMITING FIRE SPREAD

In Article 3.1.5.5, the NBC [5] allows the use of combustible components for non-loadbearing exterior walls to be used in a building required to be of noncombustible construction provided:

a) the building is
   i. not more than 3 storeys in height, or
   ii. sprinklered throughout,
b) the interior surfaces of the wall assembly are protected by a thermal barrier conforming to Sentence 3.1.5.12.(3), and
c) the wall assembly satisfies the criteria of Sentence 3.1.5.5.(3) and 3.1.5.5.(4) when subjected to testing in conformance with CAN/ULC-S134 *Fire Test of Exterior Wall Assemblies* [21].

Lightweight wood-frame assemblies were developed in the 1990's during the development of the CAN/ULC-S134 test method that met the criteria in the NBC for nonloadbearing exterior walls [22]. However, proprietary alternative solutions based on these tests would be limited to the materials used in the original tests, such as the glass-fibre and phenolic foam insulation.

One of the tasks in this current project was to develop further information and data for use in developing generic exterior wall systems for use in mid-rise wood buildings. A series of

CAN/ULC-S134 standard fire tests were conducted for exterior wall systems constructed with lightweight wood-frame (LWF) and cross-laminated timber (CLT) structural assemblies.

Test results show that a wider range of generic exterior wall systems constructed with LWF and CLT can be built to meet the requirements of limiting fire spread on the exterior surface, based on the criteria stipulated in Sentences 3.1.5.5.(3) and 3.1.5.5.(4) in Division B of the 2010 NBC. The details of the tests are described in several reports [23, 24, 25, 26, 27].

8.1 Test Facility and Exterior Wall Assemblies

The tests were conducted in accordance with CAN/ULC-S134 [21] in the NRC large scale fire laboratory. Figure 6 shows the exterior wall fire test facility.

The generic exterior wall systems that were investigated included:

1) A LWF wall with spray-applied medium density polyurethane foam insulation filling the stud cavities protected by 12.7 mm thick regular gypsum sheathing;
2) A LWF wall with spray-applied medium density polyurethane foam insulation filling the stud cavities protected by 15.9 mm thick interior fire-retardant-treated (FRT) plywood sheathing;
3) A simulated CLT wall with an outboard nonloadbearing LWF wall 38 mm x 140 mm studs and rigid polystyrene foam insulation filling the stud cavities protected by 12.7 mm thick regular gypsum sheathing; and,
4) A simulated CLT wall with an outboard nonloadbearing LWF wall 38 mm x 140 mm studs and rigid polystyrene foam insulation filling the stud cavities protected by 15.9 mm thick interior FRT plywood sheathing.
5) A rain screen test assembly included OSB sheathing (15.9 mm thick) with a 12.7 mm gap between the sheathing and a single layer of generic fibre-cement board, which was used to simulate the exterior cladding (6 mm thick) and was attached with vertical plywood strips used as strapping.

Cone calorimeter tests [28] were conducted to help select the sheathing and foamed plastic insulation materials for use in the construction of the full-scale exterior wall assemblies [29]. The materials that gave the highest heat output were selected for use in the exterior test assemblies.

Each wall assembly was three-storey high (5.0 m width and 9.9 m height) with simulated floors between storeys. The base storey wall section included an opening (2.5 m wide and 1.45 m high) to the burn room of the test facility. The wall assembly extended 7.0 m above the opening.

8.1.1 Lightweight Wood-Frame (LWF) Assemblies and Insulation

The two LWF wall assemblies simulated platform construction. Wall sections for each storey were constructed using 38 mm x 140 mm x 2286 mm long wood studs spaced at 400 mm on center (o.c.) with a double top plate and single bottom plate. The height of the wall sections for each storey was 2.4 m. Floor sections framed within the test specimen were simulated using a 38 mm x 286 mm rim board with short pieces of 286 mm wood I-joists spaced 400 mm o.c. and 15.9 mm thick plywood subfloor.

A spray-applied medium-density polyurethane foam (SPF) was applied on site to fill the 140 mm depth of the stud wall cavities. The medium density SPF insulation was selected based on cone calorimeter tests that showed that it had a higher potential heat output than a light density SPF [29].

Although medium density SPF insulation was used in the test assembly, it was assumed that, if the assembly using the medium density SPF insulation met the requirements in 3.1.5.5. of the 2010 NBC for exterior wall systems, exterior wall assemblies insulated using light density SPF insulation or non-combustible mineral fibre insulation would also meet the requirements.

8.1.2 Cross-Laminated Timber (CLT) Assemblies and Insulation

The two CLT wall assemblies were simulated using 38 mm x 235 mm lumber laid flat and attached horizontally to the test facility. CLT wall systems can be much thicker than the simulated system. However, a thickness of 38 mm was considered adequate for this testing because if, during the test, there was sufficient burning of the lumber to char through the 38 mm thickness, it is very likely that the wall system would not meet the requirements in 3.1.5.5. of the 2010 NBC anyway, and therefore any additional thickness of wood would be redundant.

A water resistant barrier (WRB) was attached to the exterior surface of the simulated CLT wall. This material was paper impregnated with asphalt and selected for use in the full-scale exterior wall assembly tests based on the results of cone calorimeter tests, which indicated that it ignited earlier and had a higher peak heat release rate and total heat output than a thermoplastic polyolefin (TPO) WRB.

Insulated wall sections were attached to the simulated CLT wall. The wall sections were constructed using 38 mm x 140 mm x 2400 mm long wood studs spaced at 600 mm on center (o.c.). The wall sections included a single base plate and a single top plate constructed using 38 mm x 140 mm x 2400 mm lumber.

Rigid polystyrene foam insulation was used to fill the stud cavities in the lightweight wood frame attached to the simulated CLT wall. The foam insulation was extruded polystyrene (XPS) with a thickness of 140 mm. The XPS foam insulation used in the test assemblies was selected based on cone calorimeter tests that showed that XPS rigid foam insulation had higher heat output than expanded polystyrene (EPS) rigid foam insulation [29]. Of the three different XPS rigid foam insulation products tested, the product with the highest heat output was used in the CLT assemblies.

Although an XPS foam insulation was used in the test assembly, it was assumed that, if the assembly using an XPS foam insulation met the requirements in 3.1.5.5. of the 2010 NBC for exterior wall systems, exterior wall assemblies insulated using EPS rigid foam insulation panels or non-combustible mineral fibre insulation would also meet the requirements.

8.1.3 Sheathing and Cladding

Regular gypsum sheathing (12.7 mm x 1.2 m x 2.4 m panels) was used as the exterior surface of two wall assemblies (one LWF and the other CLT). The gypsum sheathing complied with

CAN/CSA-A82.27-M91 [30]. The material was combustible with a surface flame-spread rating of 20, and a smoke developed classification of 0.

Although the regular gypsum sheathing was used in the two test assemblies, it was assumed that, if the assembly using the regular gypsum sheathing met the requirements in 3.1.5.5. of the 2010 NBC for exterior wall systems, exterior wall assemblies with other gypsum sheathing with better fire performance would also meet the requirements.

Interior FRT plywood (15.9 mm x 1.2 m x 2.4 m panels) was used as the exterior sheathing of another two assemblies (one LWF and the other CLT). The FRT plywood sheathing complied with CAN/CSA-O80 Series-08 [31]. The material was combustible and had a surface flame-spread rating of 25, and a smoke developed classification of 25. The FRT plywood used for the tests was selected based on the results of cone calorimeter tests, which indicated that it ignited earlier and had a higher peak heat release rate and total heat output than a second FRT plywood produced in Canada.

A horizontal joint between sheathing panels was located 3.0 m above the opening. This complies with the requirement in CAN/ULC-S134 [21] that a horizontal joint is located 2.7 ± 0.3 m above the opening in the wall assembly. There were an additional four horizontal joints for the two LWF assemblies (0.6 m, 3.4 m, 5.8 m and 6.2 m above the opening) and an additional two horizontal joints for the two CLT assemblies (0.6 m and 5.4 m above the opening). Each test assembly had a vertical joint above the window on the centerline of the assembly, and additional two vertical joints 1.2 m to either side of the centerline of the assembly.

An exterior cladding system was not included in any of the test assemblies. It was assumed that a noncombustible exterior cladding would provide additional protection for the wall assembly and, therefore, if the wall assembly met the requirements in Article 3.1.5.5. of the 2010 NBC without an exterior cladding, it would also meet the requirements with a noncombustible cladding.

8.1.4 Rain Screen Test Assembly

A CAN/ULC-S134 test was also conducted to address the fire spread potential within rain screen cavities. The rain screen test assembly included OSB sheathing (15.9 mm thick) with a 12.7 mm gap between the sheathing and a single layer of generic fibre-cement board, which was used to simulate the exterior cladding (6 mm thick) and was attached with vertical plywood strips used as strapping. Drainage openings were also incorporated into the test assembly at the 0.6 m and 3.0 m above the opening.

8.2 Procedure for Exterior Wall Fire Tests

The test procedure was in accordance with CAN/ULC-S134. The pilot burners were lit prior to the commencement of the test. The mass flow of propane supply to the propane burners in the burn room was manually adjusted to follow the prescribed heat input required by the standard, increasing to a set value in 5 min, maintaining at the steady state for 15 min and then reducing to shut off at 25 min. During the 60-min observation period from the time of ignition of the burners, the test assembly must meet the criteria stipulated in Sentences 3.1.5.5.(3) and 3.1.5.5.(4) in Division B of the 2010 NBC as follows:

- Flaming on or in the wall assembly shall not spread more than 5 m above the opening; and,
- The heat flux during the flame exposure on a wall assembly shall not be more than 35 kW/m^2 measured 3.5 m above the opening.

8.3 Results of Exterior Wall Tests

Table 9 shows the results of the full-scale fire experiments conducted for the generic exterior wall assemblies using the CAN/ULC-S134 test method.

The peak temperature of the flames issuing from the opening and the peak temperatures outside and inside each wall assembly along its vertical centre line as well as visual observations during and after the test provide evidence of the maximum height of flame spread on and in the assembly. These peak temperatures include temperatures on the exterior wall surface, behind the sheathing, inside and behind the foam insulation as well as in the rain screen gap at different heights.

The heat flux to the wall assembly at 3.5 m above the top of the opening was measured on the centre line of the wall and 0.5 m from the centre line on each side at the same height. The measured heat flux time profiles are smoothed using one-minute running average. The central location on the wall received the maximum heat flux.

The centre of the opening on the wall (the exposing surface) was at the 2.1 m height. Radiant heat emitted by the fire was also monitored at target locations 3.0 m away from the test wall opposite to its centre line at the heights of 2.1 m, 3.4 m, 4.7 m and 6.0 m, and 2.4 m away at the 4.0 m height. The heat fluxes measured at the target locations provided data relating to ignition potential of an adjacent exposed wall should the adjacent wall have been located at the target locations. Table 9 shows the maximum and average heat fluxes at each target location during the 15 min of steady state fire challenge. For comparison, 15-min averaged heat fluxes at the target locations for a noncombustible exposing wall (Marinite) are also provided in the table. (Note: Marinite is a thermal structural board insulation, which is formed from calcium silicate with inert fillers and reinforcing agents. This material was used to provide the noncombustible wall, which was used for calibration and reference purposes in the initial test series used to develop the test method [22]).

The LWF assembly with the regular gypsum sheathing, the LWF assembly with the FRT plywood sheathing and the CLT assembly with the regular gypsum sheathing met the criteria stipulated in Sentences 3.1.5.5.(3) and 3.1.5.5.(4) in Division B of the 2010 NBC. As shown in Table 9, the maximum flame spread heights and the maximum heat fluxes on these three assemblies were less than the 5 m limit for flame spread and the 35 kW/m^2 limit for heat flux, respectively. The extent of damage to the test assemblies was limited to an area above the window opening. There was limited damage to the foam/foamed plastic insulation.

The heat fluxes at the target locations were equivalent to the heat fluxes measured in testing with the noncombustible wall (Marinate), indicating these wall assemblies would not increase the ignition potential to an adjacent exposed wall (building).

The CLT assembly with the FRT plywood sheathing did not meet the code criteria for flame spread. Flames on the surface of the specimen surpassed the 5 m height along the vertical face of the wall and the 35 kW/m^2 heat flux to the wall was exceeded within 20 min from the start of the test, with flame spread eventually extending to the top of the wall and over 130 kW/m^2 heat flux being measured at the sensor location. The fire was suppressed at 25 min to avoid damage to the test facility.

During the test of the rain screen assembly, the primary area of damage was limited to the lower portion of the wall assembly between the window opening and the rain screen opening 0.6 m above. There was no fire propagation in the rain screen cavities beyond the rain screen opening located 3 m above the window opening. The test results show that fire spread potential would be very low in the rain screen cavities for assemblies with a 12.7 mm gap between the OSB sheathing and the fibre-cement based cladding. The results of this test should not be used for rain screen assemblies with larger gaps between the combustible sheathing and noncombustible cladding.

8.4 Implications of Exterior Wall Tests

The CAN/ULC-S134 test results indicate that a wide range of generic exterior wall systems can be constructed with LWF and CLT to meet the code requirements of limiting fire spread on or within the exterior wall assembly, based on the criteria stipulated in Sentences 3.1.5.5.(3) and 3.1.5.5.(4) in Division B of the 2010 NBC.

Without exterior cladding, the CLT assembly (the one with the regular gypsum sheathing) and the two LWF assemblies passed the CAN/ULC-S134 test, meeting the code requirements of limiting fire spread on the exterior of the building. It would be expected that a noncombustible exterior cladding would provide additional protection for the wall assemblies, without increasing the potential for vertical fire spread or increased heat flux to the assembly. Therefore, these wall assemblies would also be expected to meet the requirements with a noncombustible cladding. Furthermore, these generic wall assemblies would be expected to meet the code requirements if used in conjunction with existing combustible cladding systems currently permitted in noncombustible mid-rise building applications.

The sheathing and foamed plastic insulation materials that gave the highest heat output in the cone calorimeter tests were selected for use in the full-scale exterior test assemblies. If using other gypsum sheathing and insulation products with better fire performance (i.e. exhibit lower fire hazard), the generic assemblies would also be expected to meet the code requirements, without increasing the potential for vertical fire spread or increasing the heat flux to the assembly. This means that: 1) the medium-density spray polyurethane foam used in the two LWF assemblies can be replaced using light-density spray polyurethane foam, glass-fibre or mineral fibre insulation; 2) the extruded polystyrene (XPS) rigid foam used in the CLT test assembly can be replaced using an expanded polystyrene (EPS) rigid foam, glass-fibre or mineral fibre insulation; and, 3) the regular gypsum sheathing used in the LWF and CLT test assemblies can be replaced using other gypsum sheathing with better fire performance.

The test with the rain screen assembly showed no fire spread in the rain screen cavities between the OSB sheathing and generic fibre-cement based cladding attached with plywood strapping, indicating a low fire spread potential in the rain screen cavities for assemblies with a 12.7 mm gap between the sheathing and the non-combustible cladding. The results of this test should not be used for rain screen assemblies with larger gaps between the combustible sheathing and noncombustible cladding.

Each test assembly simulated a structural exterior wall system. However, no loads were applied to the wall. The objective of the test was to evaluate the performance of the assembly for exterior fire spread in conformance with CAN/ULC-S134. If, in practice, the exterior wall assembly also required a fire-resistance rating, it would need to be evaluated using CAN/ULC-S101 [20].

Figure 6. Tests of Exterior Wall Assemblies.

Table 9. Generic exterior wall assemblies and fire experiment results using CAN/ULC-S134 test method.

	Wall Assembly →	(1) LWF	(2) LWF	(3) CLT	(4) CLT	(5) Rain Screen
	Size of wall (WxH)	5.0 m x 9.9 m	5.0 m x 9.9 m	5.0 m x 9.9 m	5.0 m x 9.9 m	2.4 m x 4.9 m
	Particulars	38 mm x 140 mm studs@400 mm o.c.	38 mm x 140 mm studs@400 mm o.c.	WRB on CLT, 38 mm x 140 mm studs@600 mm o.c	WRB on CLT, 38 mm x 140 mm studs@600 mm o.c	12.7 mm gap with vertical plywood strips@600 mm o.c.
	Foamed plastic insulation 140 mm thick in stud cavities	Polyurethane	Polyurethane	Polystyrene (outboard)	Polystyrene (outboard)	-
	Sheathing (thickness)	Regular gypsum (12.7 mm)	Interior FRT plywood (15.9 mm)	Regular gypsum (12.7 mm)	Interior FRT plywood (15.9 mm)	OSB (15.9 mm) + double WRB
	Cladding (thickness)	none	none	none	none	fibre-cement board (6 mm)
	Ambient temperature and relative humidity	6°C, 53%	2.8°C, 45%	20.4°C, 81%	5.0°C, 94%	6°C, 53%
Peak temperature on and in wall above opening* (°C)	at opening	800	940	710	1100	947
	1.5 m above	634 / 359 / 360‡	891 / 805 / 850	542 / 34	1005 / 1019 / 930	537 / 340 / 99
	2.5 m above	560 / 182 / 119	998 / 987 / 1000	470 / <34	920 / 927 / 850	393 / 283 / 94
	3.5 m above	387 / 99 / 6	749 / 266 / 100	326 / <34	878 / na / na	307 / 159 / 59
	4.5 m above	286 / 93 / 6	260 / 91 / 64	258 / <34	840 / na / na	264 / 159 / 67
	5.5 m above	236 / 91 / 6	199 / 60 / 57	229 / <34	709 / na / na	na
	7.0 m above	167	163	154	522	na
	Max. flame spread height (m)	3.0	4.5	3.0	5.5	2.5
	Max. heat flux on wall at 3.5 m above opening (kW/m^2)	22.5	30.7	18.4	133.9	23.2
Heat flux at target (kW/m^2)§	Wall Assembly →	(1) LWF	(2) LWF	(3) CLT	(4) CLT	(6) Marinite
	3.0 m away 2.1 m high	16.6 (19.3)	17.4 (20.0)	14.4 (17.0)	15.7 (19.1)	15.9
	3.0 m away 3.4 m high	12.7 (14.9)	11.9 (14.7)	10.5 (12.8)	12.2 (20.9)	11.2
	2.4 m away 4.0 m high	9.1 (10.7)	7.8 (9.1)	7.3 (9.3)	10.2 (23.1)	8.2
	3.0 m away 4.7 m high	4.9 (5.9)	4.7 (5.7)	3.8 (4.9)	5.2 (14.0)	4.7
	3.0 m away 6.0 m high	2.6 (3.3)	2.6 (3.3)	2.0 (2.5)	3.1 (11.3)	4.7
	Remarks	Passed – Tested for 85 min	Passed	Passed	Failed – Test had to stop at 25 min	Passed (5)

*The wall peak temperatures measured at: Wall Assembly (1) exterior surface, mid-depth insulated cavity, behind foam; Wall Assembly (2) exterior surface, behind plywood, behind foam; Wall Assembly (3) exterior surface, behind foam; Wall Assembly (4) exterior surface, behind plywood, behind foam; and, Wall Assembly (5) cladding surface, rain screen gap, behind OSB. ‡ at 60 min. §Heat flux at target: 15-min average; maximum in brackets. na: not applicable.

9 ENCAPSULATION – ALTERNATIVE TO NONCOMBUSTIBLE CONSTRUCTION

9.1 Requirements for Noncombustible Construction

The acceptable solutions provided in the 2010 NBC Division B [5] limit the use of combustible (wood) construction based on building height. For example, for Group C (Residential), Group D (Business and Personal Services) and Group E (Mercantile) occupancies, combustible construction can be used up to 4 storeys and up to 2 storeys for Group A – Division 2 (Assembly) occupancies. In addition to the building height limitation, there are also building area limitations in the 2010 NBC for the use of combustible construction for these occupancies. For buildings that exceed the height and area limits for combustible construction, the prescriptive requirements in Division B of the 2010 NBC require that noncombustible construction be used for the primary structural elements.

The prescriptive construction requirements for fire safety and protection of buildings, which are dependent upon the building size and occupancy type, are provided in Subsection 3.2.2 of Division B of the 2010 NBC. This includes the identification of the buildings for which noncombustible construction is required. The intent of the prescriptive requirements for noncombustible construction, as they relate to the NBC fire safety/fire protection of building objectives is "*to limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm to persons/damage to the building*".

The 2010 NBC defines noncombustible construction as "*that type of construction in which a degree of fire safety is attained by use of noncombustible construction materials for structural members and other building assemblies*" [5]. Article 3.1.5.1 requires that a building or part of a building required to be of noncombustible construction be constructed using noncombustible materials. The intent of this requirement, as it relates to the NBC fire safety/fire protection of building objectives, is "*to limit the probability that construction materials will contribute to the growth and spread of fire, which would lead to harm to persons/damage to the building*".

The NBC does permit, as exceptions, an extensive use of combustible materials in buildings otherwise required to have their primary structural elements to be of noncombustible construction. The allowed materials and associated limitations are provided in Articles 3.1.5.2 to 3.1.5.21. Generally, the combustible elements permitted relate to interior finishes, gypsum board, combustible roofing materials, combustible plumbing fixtures, cabling, protected insulation, flooring, combustible glazing, combustible cladding systems, non-loadbearing framing elements in partitions, stairs in dwellings, and trim and millwork, among others.

Division B of the 2010 NBC (the "acceptable solutions" portion of the Code) generally does not permit combustible materials to be used for the primary structural elements in buildings required to be of noncombustible construction.

9.2 Investigation of Alternative Solution Using Encapsulation

In the Scoping Study [7] for mid-rise and hybrid buildings, it was suggested that an alternative solution using wood construction may be developed to meet the intent of the prescriptive "noncombustibility" requirement for mid-rise (and taller) buildings. As one approach, encapsulation materials could be used to protect the combustible (wood) structural materials for a period of time in order to delay the effects of the fire on the combustible structural elements, including delay of ignition. In delaying ignition, any effects of the combustion of the combustible structural elements on the fire severity can be delayed. In some cases, and depending upon the amount of encapsulating material used (e.g. number of layers), ignition of the elements might be avoided completely. This scenario would primarily depend upon the fire event and the actual fire performance of the encapsulating materials used. In Europe, the protection of combustible materials by means of encapsulation of building elements to delay the contribution of combustible building elements to a fire has proved successful [1].

The investigation of an "alternative solution" using the encapsulation approach was undertaken for mid-rise wood buildings to meet the intent of the relevant objectives and functional statements pertinent to the requirements of noncombustible construction in the 2010 NBC. Three materials were selected for evaluation as encapsulation materials for combustible structural elements: Type X gypsum board (12.7 mm thick and 15.9 mm thick), cement board (12.7 mm thick) and gypsum-concrete (25 mm thick and 38 mm thick). Bench-scale cone calorimeter tests, intermediate-scale and full-scale furnace tests, and large-scale apartment tests were conducted to investigate the performance of the encapsulation materials. Details of these tests are documented in a series of reports [32, 33, 34, 35, 36, 37, 38, 39, 40].

9.2.1 Criteria for Evaluating Performance of Encapsulation Materials

In this project, three sets of criteria were investigated for evaluating the performance of the encapsulation materials. They are based on temperature rise criteria used in CAN/ULC-S101 [20], CAN/ULC-S124 [41] and European practice [1], respectively:

1. Criteria 1 (CAN/ULC-S101). The average temperature rise value over the whole exposed surface of the protected building element is limited to 140ºC, and the maximum temperature rise value at any point on that surface does not exceed 180ºC. These temperature criteria are used in CAN/ULC-S101 [20] and CAN/ULC-S124 [41].
2. Criteria 2 (CAN/ULC-S124). The average temperature rise value over the whole exposed surface of the protected building element is limited to 195ºC, and the maximum temperature rise value at any point on that surface does not exceed 250ºC. These temperature criteria are used in CAN/ULC-S124 [41]
3. Criteria 3 (European criteria). The average temperature rise value over the whole exposed surface of the protected building element is limited to 250ºC, and the maximum temperature rise value at any point on that surface does not exceed 270ºC. These criteria are used in standard tests in Europe to evaluate the performance of encapsulation materials.

The European criteria are based on the temperature at which wood-based products begin to char (approximately 300ºC) [1, 42]. At lower temperatures, fires will not affect the structural elements and there would be no gasification or pyrolysis of the wood. It is assumed that a protective cover will be effective as long as the average temperature rise value over the exposed surface of the protected building element is limited to 250ºC, and the maximum temperature rise value at any point on that surface does not exceed 270ºC. Among the three sets of criteria investigated in this project, the set of the European criteria (Criteria 3) provides a conservative, technically-based estimate for evaluating the performance of the encapsulation materials [32, 33, 34, 35, 36].

9.2.2 Determination of Encapsulation Time

Heat transfer through the selected encapsulation materials follows a typical three-stage pattern: an initial phase with the temperatures gradually rising to approximately 100°C; a second phase with steady temperatures at approximately 100°C during the calcination of the gypsum board or water removal from the cement board or gypsum-concrete; a third phase with a more rapid temperature increase.

Temperature profiles at the interface between the encapsulation material and the protected element were used to determine the time required for the fire to penetrate the encapsulation material. The times at which the temperature rise values at the interface exceeded each of the three sets of criteria were determined for each test.

9.2.3 Dependence of Encapsulation Time on Fire Exposure Conditions

The encapsulation time provided by the three materials is dependent on the fire exposure and temperature rise criteria. Many exposure conditions or scenarios exist in real applications and it is impossible to determine the encapsulation time for every situation. In this project, encapsulation times were determined for selected standard and non-standard exposure conditions. For a given encapsulation material, the more severe the fire exposure, the shorter the encapsulation time.

9.3 Cone Calorimeter Tests of Encapsulation Materials

The cone calorimeter tests were conducted on Type X gypsum board (12.7 mm thick and 15.9 mm thick), cement board (12.7 mm thick) and gypsum-concrete (25 mm thick and 38 mm thick) for encapsulation of combustible wood material [32]. The tests were in general conformance with ISO 5660-1 [28]. The test specimen consisted of the encapsulation material attached to a 15.9 mm thick plywood substrate. The specimen (100 mm x 100 mm) was mounted in the specimen holder on a ceramic fibre substrate as shown in Figure 7.

The temperature rise values were measured using five thermocouples located at the interface between the encapsulation material and the plywood substrate at the center and quarter points of the specimen. A pyrometer and another thermocouple were used to measure the temperature at the centre of the exposed surface of the specimen.

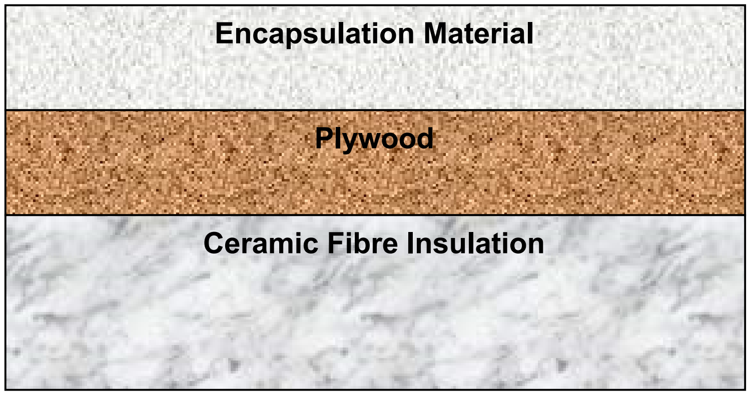

Figure 7. Test sample cross-section for cone tests with encapsulation materials.

Based on the temperature rise values at the interface between the encapsulation material and the plywood substrate, the times to reach the three sets of temperature criteria were determined. Table 10 to Table 13 show the times at which the temperature criteria were exceeded at the interface and the average interface temperature at the time of plywood ignition.

The 'encapsulation' temperature criteria were all reached prior to the ignition of the plywood substrate. The average temperature at the interface between the encapsulation material and the plywood substrate was 320 - 350°C when the plywood ignited, which is consistent with the temperatures in the literature for the piloted ignition of wood [42].

The temperature rise values at the interface had the same trend and were comparable from test-to-test with the same setup and exposure. However, changes in the test setup (such as specimen holder, number of plywood layers, with or without ceramic fibre substrate) did affect the temperature profiles. For example, the tests conducted using the large holder specified in CAN/ULC-S135 [43] had faster temperature rise than for tests with the standard specimen holder specified in ISO 5660-1 [28]. For tests with the larger holder, insulation was inserted between the specimen and the walls of the holder to minimize heat transfer at the sides of the specimen.

Table 10. Times for exceeding temperature rise criteria and average interface temperature at plywood ignition – Cone Calorimeter Tests with 12.7 mm thick Type X gypsum board.

Test	Number Gypsum Board Layers	Heat Flux Exposure (kW/m²)	Time to Exceed ΔT						Plywood Ignition		
			Average ΔT (ºC)			Single Point ΔT (ºC)			Time (min)	Avg Temp (ºC)	Temp Max Single Point (ºC)
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)			
1	1	75	13.30	14.73	16.53	13.90	16.23	16.73	20.70	363.87	393.82
2	1	75	13.33	15.03	16.97	13.87	16.13	16.83	19.18	342.32	362.38
3	2	50 Lh	39.03	43.00	46.80	40.56	44.53	46.23	51.33	329.88	348.18
4	2	50 Lh	40.19	44.09	47.67	41.77	45.97	47.44	52.72	333.76	348.76
5	1	75 Lh	13.27	14.77	16.44	13.64	15.47	16.05	18.23	326.80	335.96
6 ply2/ncf	1	50 Lh	15.80	18.03	20.57	16.27	19.27	20.20	29.11	429.49	500.08
7 ply2/ncf	1	75 Lh	12.03	13.30	14.83	12.33	13.73	14.23	17.87	333.67	376.46

Avg Temp – Average temperature at interface at plywood ignition
Temp Max Single Point – Maximum single point temperature at interface at plywood ignition
ply2 – double plywood layers ncf – no ceramic fibre Lh – Large specimen holder

Table 11. Times for exceeding temperature rise criteria and average interface temperature at plywood ignition – Cone Calorimeter Tests with 15.9 mm thick Type X gypsum board.

Test	Number Gypsum Board Layers	Heat Flux Exposure (kW/m²)	Time to Exceed ΔT						Plywood Ignition		
			Average ΔT (ºC)			Single Point ΔT (ºC)			Time (min)	Avg Temp (ºC)	Temp Max Single Point (ºC)
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)			
1	1	75	16.17	17.86	21.73	17.10	19.60	20.40	21.73	321.59	358.58
2	1	75	16.33	18.13	22.08	16.70	19.03	19.77	22.08	328.38	355.69
3	2	50 Lh	46.47	51.9	57.13	46.60	51.63	53.67	61.70	322.11	365.44
4	2	50 Lh	46.43	51.63	56.57	47.17	52.23	54.33	62.25	332.91	363.32

Table 12. Times for exceeding temperature rise criteria and average interface temperature at plywood ignition – Cone Calorimeter Tests with 12.7 mm thick cement board.

Test	Number Cement Board Layers	Heat Flux Exposure (kW/m²)	Time to Exceed ΔT						Plywood Ignition		
			Average ΔT (ºC)			Single Point ΔT (ºC)			Time	Avg Temp	Temp Max Single Point
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)	(min)	(ºC)	(ºC)
1	1	75	7.60	9.20	13.83	8.33	10.30	11.00	13.83	362.70	374.65
2	1	75	8.10	9.93	14.32	8.83	10.80	11.37	14.32	353.15	383.16
3	2	50 Lh	22.87	28.60	34.17	24.73	32.03	34.30	40.80	331.40	347.37
4	2	50 Lh	23.03	29.00	35.10	25.73	32.50	35.10	41.68	331.72	351.00

Avg Temp – Average temperature at interface at plywood ignition.
Temp Max Single Point – Maximum single point temperature at the interface at plywood ignition.

Table 13. Times for exceeding temperature rise criteria and average interface temperature at plywood ignition – Cone Calorimeter Tests with gypsum-concrete.

Test	Thickness (mm)	Heat Flux (kW/m²)	Time Exceed ΔT						Plywood Ignition		
			Average ΔT (ºC)			Single Point ΔT (ºC)			Time	Avg Temp	Temp Max Single Point
			140 (min)	195 (min)	250 (min)	180 (min)	250 (min)	270 (min)	(min)	(ºC)	(ºC)
1	25	50 Lh	20.90	25.53	29.27	23.37	28.07	29.07	36.45	350.06	357.12
2	25	50 Lh	21.60	26.27	30.33	24.60	29.10	31.20	37.35	347.98	359.37
3	39	50 Lh	34.77	41.90	48.70	37.33	45.53	48.30	58.32	346.38	366.59
4	39	50 Lh	32.63	39.63	46.17	35.83	43.67	46.33	55.33	341.44	357.90

9.4 Intermediate-Scale Furnace Tests of Encapsulation Materials

Intermediate-scale furnace tests were conducted using a 1.33 m by 1.94 m horizontal furnace to evaluate each encapsulation material [34, 35]. A full description of the intermediate-scale furnace facility is provided by Sultan *et al.* [44].

9.4.1 Test Method and Assembly

The test method and arrangement used for these tests were based on CAN/ULC-S124 [41], which is used to evaluate protective covers for use with foamed plastic insulation.

Each test assembly consisted of a wood frame constructed using 38 mm x 89 mm wood studs. Gypsum board (12.7 mm thick Type X) was mounted on the unexposed side of the test assembly. Two layers of 15.9 mm thick plywood were mounted on the exposed side of the test frame as a substrate for the encapsulation material in all tests except one test, where a single layer of the plywood was used as the substrate. The encapsulation material was then mounted on top of the plywood on the exposed side of the test frame.

Thermocouples were installed at various locations throughout the test assembly, including the interface between the encapsulation material and the plywood substrate and, where applicable, the interface between layers of the encapsulation materials.

The times at which the temperature rise values at the interface between the encapsulation material and the plywood substrate exceeded each of the three sets of criteria were determined under both standard and non-standard fire exposures. In addition, the times at which the three sets of temperature rise criteria were met or exceeded at other interfaces in the assembly were also determined, including the times at the interface between layers of the encapsulation materials.

9.4.2 Fire Exposures with Standard and Non-standard Time-Temperature Curves

For the majority of the intermediate-scale experiments, the temperature in the furnace followed the standard time-temperature curve given in CAN/ULC-S101 [20]. Two additional tests were conducted using a non-standard time-temperature curve based on temperatures measured in a full-scale fully furnished bedroom fire test (PRF-03) [45].

Figure 8 shows the standard time-temperature curve prescribed for standard fire-resistance tests (CAN/ULC-S101 [20]) and the non-standard time-temperature curve derived from the full-scale fully furnished bedroom fire test (PRF-03 [45]). The non-standard time-temperature curve is higher than the standard time-temperature curve until 40 min. As such, the intermediate-scale furnace tests using the non-standard time-temperature curve based on the room fire test imposed a more severe exposure than using the standard curve to the test assembly during the initial 40 min of the tests.

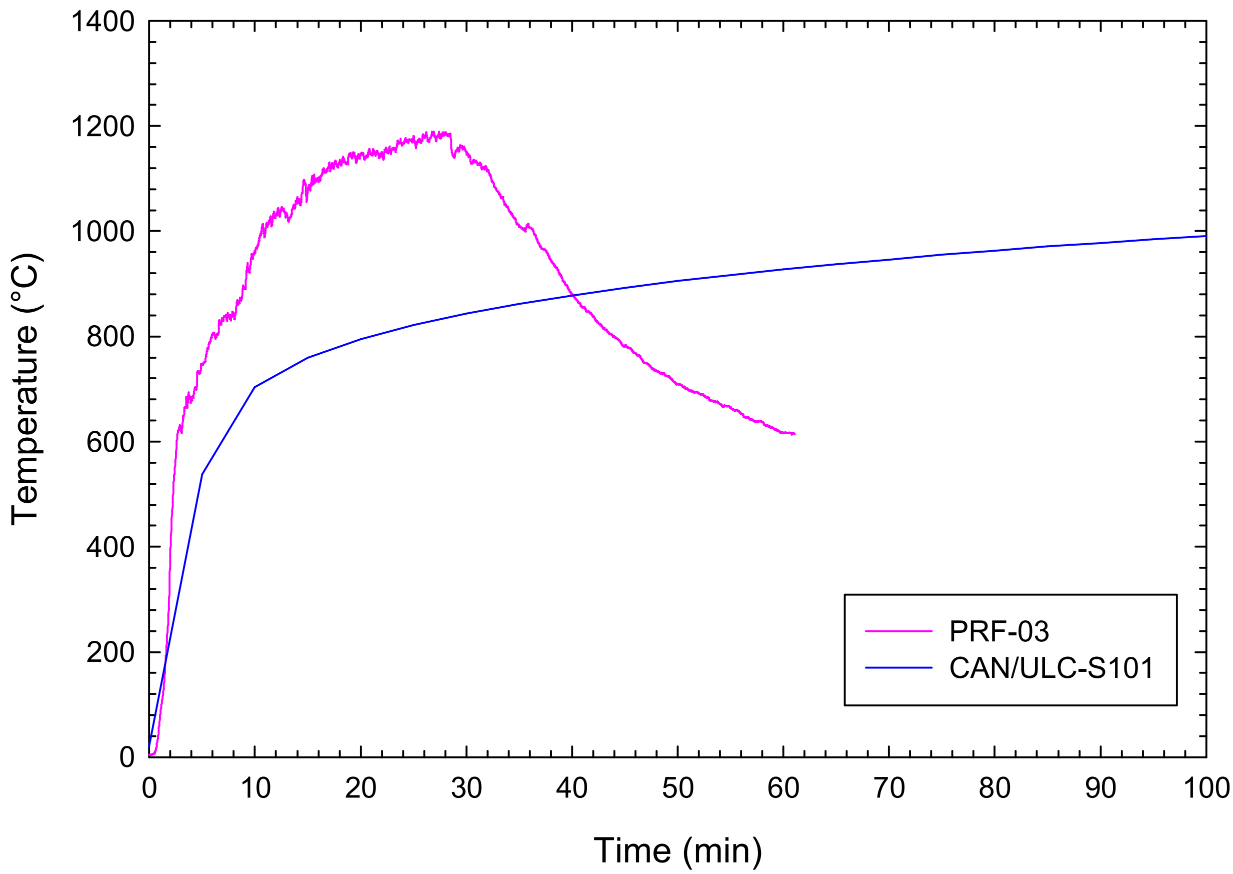

Figure 8. Standard and non-standard time-temperature curves used in the intermediate-scale furnace tests.

9.4.3 Results and Discussion for the Intermediate-scale Tests

Table 14 shows the results of the intermediate-scale furnace tests conducted to investigate the performance of the encapsulation materials, including nine tests using the standard time-temperature curve and two tests using the non-standard time-temperature curve. The times at which the three sets of criteria were exceeded in each test are provided in the table. These times are based on either the single-point or average temperature rise value at the interface, whichever was exceeded first. Figure 9 shows exemplar temperature rise profiles measured at the interface between the encapsulation material and the plywood substrate.

Table 14. Summary of results for tests on encapsulation materials with intermediate-scale furnace.

Encapsulation Material	Thickness (mm)	Number of Layers	Test Number	Layer Position	Time at which Criteria Reached (Average Temperature Rise or Single-point Temperature Rise) (min)			Fall-off Time (min)
					Criteria 1	Criteria 2	Criteria 3	
Type X Gypsum Board	12.7	1	1	face	17.9	19.8	21.6	38
	12.7	1	2*	face	18.6	21.7	24.1	41
	12.7	2	5	face	18.7	20.7	21.9	68
				base	50.7	55.3	58.8	71
	12.7	2	11**	face	15.2	16.1	16.3	27
				base	33.4	34.6	35.2	67
Type X Gypsum Board	15.9	1	4	face	21.3	23.4	25.5	59
	15.9	2	9	face	23.8	25.6	26.5	90
				base	61.9	65.3	69.6	94
	15.9	1	10**	face	17.3	18.8	20.3	29
Cement Board	12.7	1	3	face	13.1	15.1	16.0	>60‡
	12.7	2	8	face	13.8	15.3	16.0	50
				base	34.7	40.3	42.5	65
Gypsum-concrete	25	1	7	face	24.8	27.7	28.8	38
	38	1	6	face	43.9	49.6	55.1	93

* Test assembly with a single layer 15.9 mm thick plywood substrate (all other test assemblies with double layer plywood).
** Non-standard fire exposure.
‡ Cement board had not fallen off when test stopped at 60 min.

Notes:
Criteria 1 (CAN/ULC-S101): 140ºC average or 180ºC single-point temperature rise.
Criteria 2 (CAN/ULC-S124): 195ºC average or 250ºC single-point temperature rise.
Criteria 3 (European criteria): 250ºC average or 270ºC single-point temperature rise.

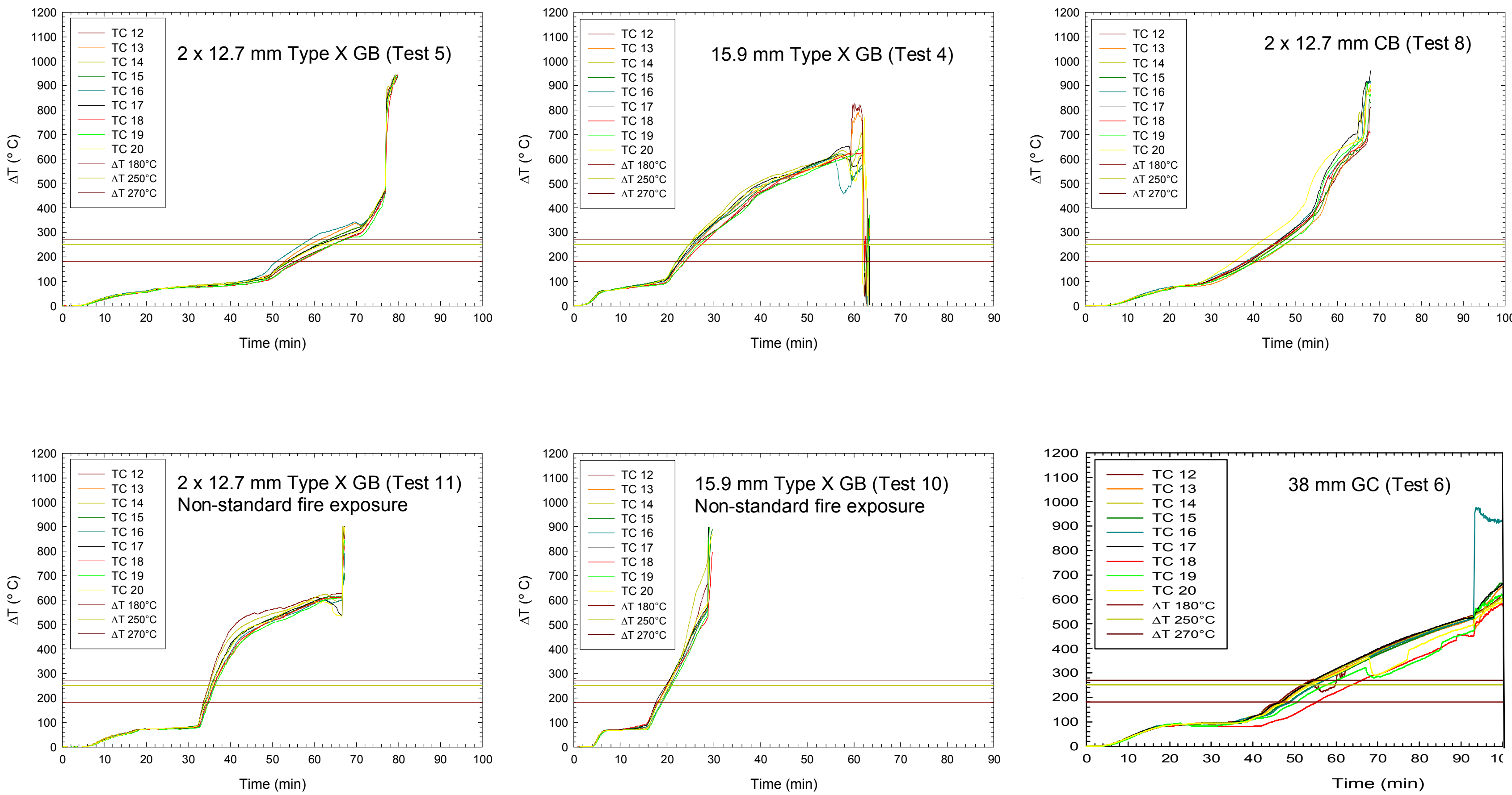

Figure 9. Temperature rise value profiles at the interface between the encapsulation material and the plywood substrate in intermediate-scale furnace tests (GB: gypsum board; CB: cement board; GC: gypsum–concrete).

9.4.3.1 Interface Temperature Rise in Tests with Standard Fire Exposure

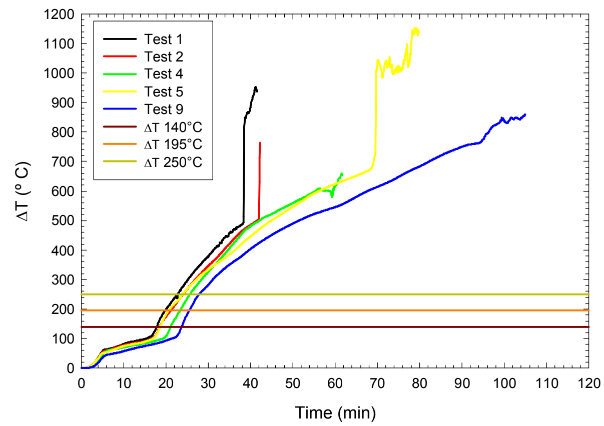

Figure 10. With standard fire exposure, average temperature rise between face layer gypsum board and plywood or gypsum board base layer.

In the fire tests with the standard fire exposure, the temperatures were measured at the interface between the gypsum board and the plywood substrate for tests with a single layer of Type X gypsum board, and at the interface between the face and base layers of gypsum board for tests with two layers of gypsum board. The profiles of the average temperature rise values at the interface are shown in Figure 10.

The profiles followed the same general trend (the typical three-stage heat transfer pattern) in each test. There was an initial temperature rise value of 50-70°C within the initial 5-6 min, followed by a period with a gradual temperature increase at the interface during the calcination of the face layer of gypsum board. After calcination of the face layer of gypsum board, the temperature rise values increased more rapidly.

Two initial tests were conducted using a single layer of gypsum board, to investigate the effect of the thickness of the plywood substrate on the temperature rise at the interface between the encapsulation material and the substrate. The rate of increase of the temperature rise value and the calcination of the gypsum board were slightly faster in Test 1 with two layers of plywood as the substrate, compared with Test 2 with a single layer of plywood. The rate of increase of the temperature rise values within the wood frame cavity were also faster in Test 2 indicating that there was more heat loss through the specimen in the test with a single layer of plywood substrate. As a result, two layers of 15.9 mm thick plywood were used as the substrate for the encapsulation materials in all subsequent tests, resulting in a faster rate of increase of the temperature rise values at the interface between the encapsulation material and the substrate.

For the tests using the standard fire exposure with two layers of gypsum board (Test 5 and Test 9 for 12.7 mm and 15.9 mm Type X gypsum board, respectively), the rates of the initial increase in the temperature rise values and the calcination of the face layer of gypsum board were slower than for the assemblies with the single layer of gypsum board attached to the plywood substrate. These different results indicate that there was more heat loss to the underlying material from the face layer of gypsum board for the double layer assemblies.

However, the time differences in the temperature rise values up to 300°C are small and tests with the two layers of gypsum board could be used to provide initial estimates for the time required to reach a given temperature rise criteria for the face layer.

The profiles of the average temperature rise values for the 12.7 mm and the 15.9 mm thick Type X gypsum board were similar during the initial stages of the tests. However, there was an earlier calcination of the thinner gypsum board and, thus, an earlier start of the faster increase in the temperature rise value in the latter stage of the test.

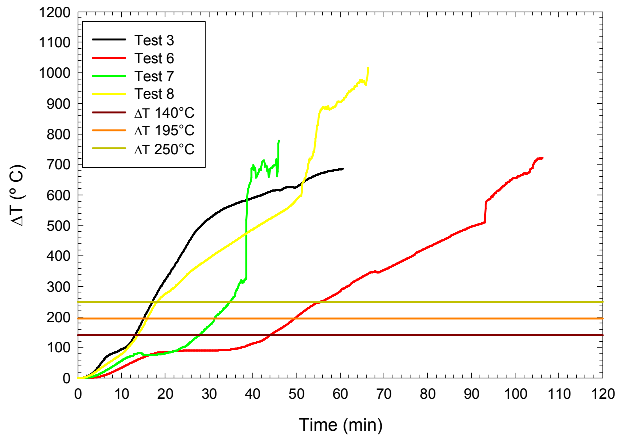

Figure 11. With standard fire exposure, average temperature rise beneath face layer cement board and gypsum-concrete encapsulation materials.

The profiles of the average temperature rise value for a single layer of 12.7 mm thick cement board in single or double layer applications (Tests 3 and 8) and the 25 and 38 mm thick gypsum-concrete (Tests 7 and 6, respectively) are shown in Figure 11. These profiles were somewhat similar to those for one layer of gypsum board, with an initial temperature rise followed by a stage during which the water in the cement board or the gypsum-concrete was removed followed by a third period with a more rapid increase in the temperature rise value.

For the single (face) layer of cement board, the rate of the initial increase in the temperature rise value and removal of the water from the sample occurred within a short time (approximately 10 min). This process was longer for the two gypsum-concrete samples, which were 2 and 3 times thicker than the cement board.

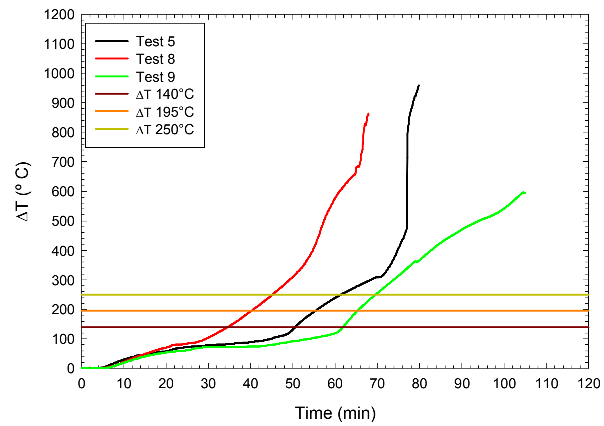

Figure 12. With standard fire exposure, average temperature rise beneath base layer of two layers encapsulation material.

The profiles of the average temperature rise values at the interface between the base layer of the encapsulation material and the plywood substrate for the tests with two layers of the board materials are shown in Figure 12. The general trend was the same for the three encapsulation materials with a gradual increase in the temperature rise values starting at 4 – 5 min. This gradual increase continued until calcination of the gypsum board materials (Tests 5 and 9) and the removal of the water from the cement board (Test 8). After calcination/removal of the water from the encapsulation material, the rate of the increase in the temperature rise values accelerated.

9.4.3.2 Interface Temperature Rise in Tests with Non-Standard Fire Exposure

Two tests (Tests 10 and 11) were conducted using a non-standard fire exposure derived from the average upper layer temperature measured in a full-scale fire test from a separate research project to develop information to be used as a basis for establishing 'design fires' for multi-family residential buildings [45]. The intermediate-scale furnace was re-calibrated for the non-standard time-temperature curve. This non-standard curve was then used to control the intermediate-scale furnace during the tests.

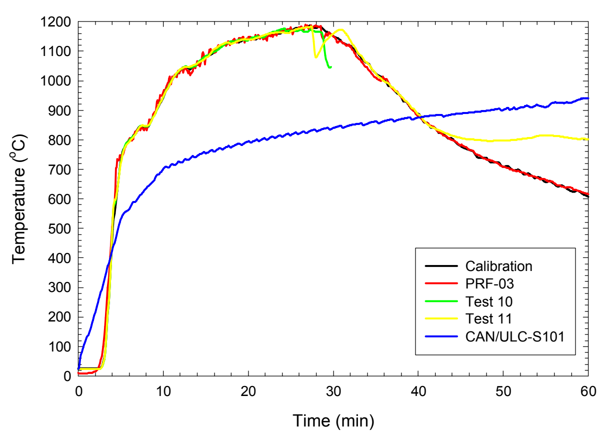

Figure 13. Average furnace temperatures with standard and non-standard time-temperature curves.

Figure 13 shows the average furnace temperature measured during the calibration test and the non-standard time-temperature curve (PRF-03), which agreed very well. The average furnace temperatures measured in Test 10 and Test 11 along with the standard time-temperature curve (CAN/ULC-S101) are also shown in Figure 13.

For Test 10, the average furnace temperature was comparable to the PRF-03 time-temperature curve throughout the test duration. The test was stopped at approximately 29 min shortly after the fall-off of the single layer of gypsum board. Once the gypsum board fell-off exposing the plywood substrate, there were extensive flames from the furnace vent and the test was terminated.

For Test 11, the average furnace temperature was generally comparable to the PRF-03 time-temperature curve. There was, however, a small decrease in temperature between 27 and 30 min. At approximately 27 min, the gypsum board face layer fell off and temporarily interfered with the temperature measurements in the furnace. After approximately 41 min, the average temperature in the furnace was higher than the PRF-03 curve, even though the only heat supplied to the furnace was by the pilot burners. The furnace thermocouples may have been affected by the fall-off of the gypsum board face layer. Also, by 41 min, the average temperature at the interface between the base layer of gypsum board and the plywood substrate was above the piloted ignition temperature of the substrate and there may have been some heat provided by burning of gases from the plywood substrate (piloted ignition discussed later in Section 9.4.3.4.1).

The tests with the non-standard time-temperature curve resulted in a more severe initial exposure to the encapsulation material, with the average temperature in the furnace higher than the standard time-temperature curve between approximately 4 and 40 min. The peak temperatures were 1172°C.

The average temperature rise values measured at the gypsum board interface with the plywood substrate in Test 10 and Test 11 (G_b/Substrate) and at the interface between the two layers of gypsum board in Test 11 (G_f/G_b) are shown in Figure 14.

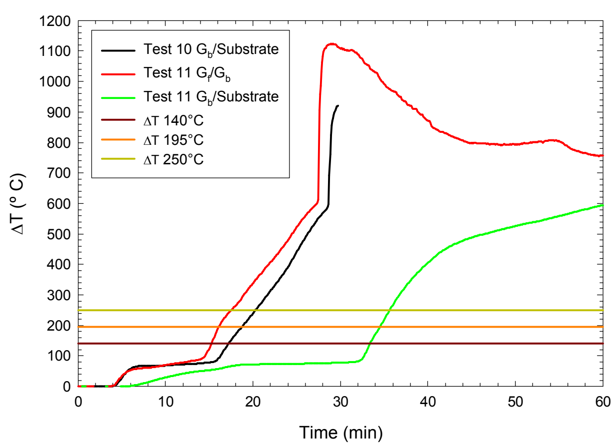

Figure 14. With non-standard fire exposure, average temperature rise at interface below gypsum board face and base layers, Tests 10 and 11.

The average temperature rise values measured with the non-standard time-temperature curve have a similar trend as those for the tests with the standard time-temperature curve. For the face layer, there was an initial fast increase in the temperature rise value followed by a period with a gradual increase during the calcination of the gypsum board and a subsequent period with a rapid increase of the temperature rise values until the face layer fell off. Once the face layer fell off, the average temperature rise value was comparable to the average temperature rise in the furnace. However, with the higher temperature exposures in the tests with the non-standard time-temperature curve, the calcination of the gypsum board occurred earlier.

For Test 11, with the two layers of 12.7 mm thick Type X gypsum board, the average temperature rise value at the interface between the base layer of gypsum board and the plywood substrate had the same general trend as observed in the similar test specimen (Test #5) with the standard time-temperature curve. There was an initial time delay in the increase of the temperature rise value at the interface between the plywood and base layer, followed by a gradual increase during the calcination of the gypsum board base layer and a subsequent increase in the temperature rise value. However, with the non-standard exposure, the rate of the increase in the temperature rise value began to decrease as the average furnace temperature decreased. These results indicate that, as the fire decays, the effects on the encapsulation material and the underlying structural assembly would also decrease, reducing the likelihood that the encapsulation material would fall off.

9.4.3.3 Fall-Off of Face Layer Gypsum Board

The fall-off times in all the intermediate-scale fire tests for the face layer of encapsulation material are provided in Table 14. The fall-off times were based on the time at which there was a rapid increase in the average temperature at the face layer interface with either a second layer of the encapsulation material, or at the interface with the plywood substrate for those assemblies with a single layer of encapsulation material.

The fall-off of the face layer of encapsulation material has a substantial impact on the heat transfer in the test assembly. While the face layer was in place, the temperature rise value at the interface between the face layer and the underlying material was due to conduction through the face layer. With the fall-off of the face layer, the temperature at this interface with the underlying material increased rapidly to the temperature in the furnace. For the assemblies with a single layer of encapsulation material, the fall-off resulted in the exposure of the plywood substrate to the furnace environment and resulted in an increased burning of the substrate. For the assemblies with two layers of encapsulation material, the fall-off of the face layer resulted in higher temperatures on the exposed face of the base layer of the encapsulation material and a resulting increase in the rate at which heat was conducted through the base layer to its interface with the plywood substrate.

The fall-off times for the face layer are quite long in some cases. For tests with 2 layers of gypsum board, the increased time to fall-off, compared to single layer cases, was 30 min (Test #1 vs. Test #5) for the 12.7 mm thick Type X gypsum board and 31 min (Test #4 vs. Test #9) for the 15.9 mm thick Type X gypsum board.

One factor that likely affected the fall-off time was the furnace geometry and the arrangement of the test assembly on the furnace. In particular, the edges of the encapsulation material were supported by the test furnace. This may account for some increase in the time for which the encapsulation material remained in place during the test. However, it would not account for the large differences in the stability of the face layer when attached to a second layer of the encapsulation material rather than directly to the plywood substrate, since in both instances the edges of the encapsulation material were supported by the test furnace.

9.4.3.4 Encapsulation Times in Intermediate-Scale Tests

9.4.3.4.1 Encapsulation times – standard time-temperature curve

The single point and average temperature rise values measured at the interface between the encapsulation material and the plywood substrate and between the face and base layers for the tests with 2 layers of the board materials were used to determine encapsulation times for the materials. The encapsulation times were determined for each of the three sets of the temperature rise criteria described in Section 9.2.1.

The average temperature rise criteria are shown on the plots for the average temperature rise values measured in the intermediate-scale furnace tests Figure 10, Figure 11 and Figure 12. The time at which the average temperature rise criteria were exceeded was in the time period with a rapid increase in the temperature rise value after the calcination/removal of water from the encapsulation material. As a result, the difference in times determined using the three criteria was small.

The relative performance of the encapsulation materials under the standard time-temperature exposure is shown in Figure 15. The time difference between Criteria 1 and 3 was < 3 min for the single layer of cement board, 3 - 6 min for the single layer of gypsum board, 8 min for the 2 layers of board products, and 11 min for the 38 mm thick gypsum-concrete.

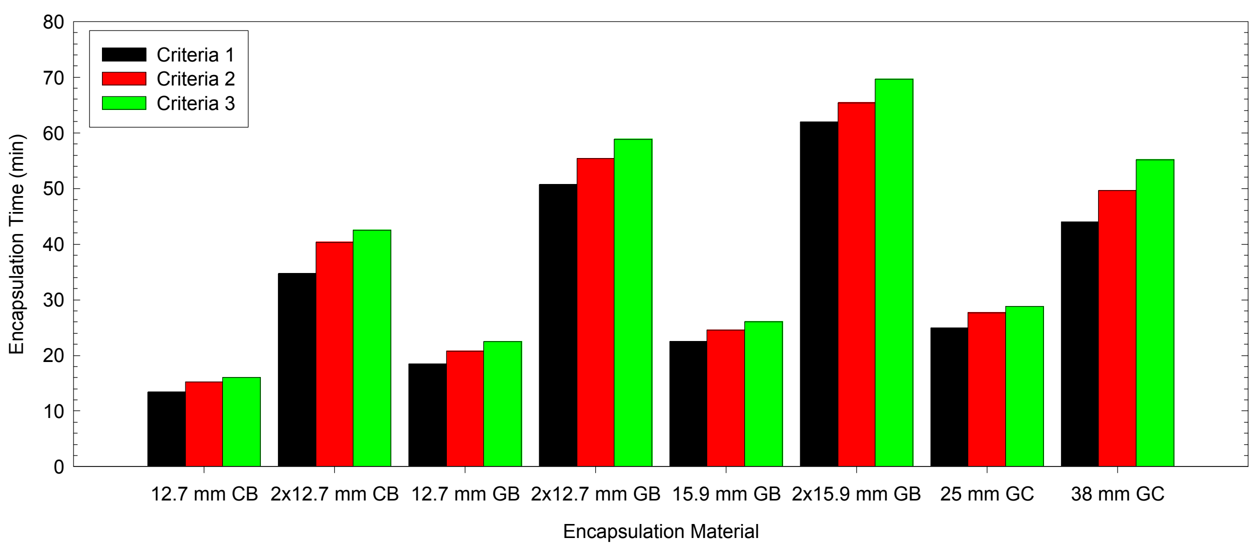

Figure 15. Encapsulation times in intermediate-scale tests with standard fire exposure.

For Criteria 1 and 2, the average temperature rise criterion was typically exceeded first, whereas for Criteria 3 the single-point temperature rise criterion was more likely to be exceeded first. Factors contributing to this trend are [34]:

1. The temperature difference between the average and single-point temperature rise requirements used for Criteria 3 (20°C) is smaller than for Criteria 1 and 2 (40°C and 55°C respectively).
2. There was increased variation in the temperature rise values measured by the 9 thermocouples located at the interface between the encapsulation material and the substrate with increasing temperature. There are likely two factors contributing to the temperature variations:
   a. Temperature variations within the furnace. The temperatures measured by the furnace thermocouples were comparable but there was a tendency for slightly higher temperatures at the one end of the furnace near the exhaust vent. For longer tests, such as those with the two layers of 15.9 mm Type X gypsum board, the temperature variations in the furnace had a small effect on the temperature rise measured by individual thermocouples located at the interfaces in the test assembly.
   b. Non-homogeneous test specimens. There were large temperature variations measured at the interface between the encapsulation material and the plywood substrate for tests with cement board and gypsum-concrete. These variations started at relatively low temperature rise values and resulted in large variations in the time at which the temperature rise values reached 270°C. The location at which the most rapid increase of temperature rise values occurred varied from test to test, indicating the variations were likely due to non-homogeneous test specimens.

The primary objective of using encapsulation materials to protect combustible structural elements is to delay the time at which the structural element ignites and contributes to the fire severity. Criteria 1 has been used as the insulation criteria for fire-resistive barriers (assemblies) in standard fire resistance tests since 1926. The temperature rise criteria were derived from the piloted ignition temperature data available for wood at the time. However, these values are not consistent with the current values [46]. The genesis of Criteria 2 was not determined. Criteria 3, as noted previously, were based on the temperature at which wood-based products begin to char [1]. Thus, encapsulation times determined using Criteria 3 provide an estimate of when the protected structural element will be affected by the fire.

The results of the tests with the intermediate-scale furnace [34, 35], as well as cone calorimeter tests [32], indicate that the protected combustible element will not ignite or contribute significant heat to a fire until average temperatures of 325 – 380°C or higher are attained at the interface between the encapsulation material and the combustible substrate. These temperatures are consistent with the piloted ignition temperatures for wood-based materials [42]. As such, it is suggested that Criteria 3 provides a technically-based and conservative set of criteria for assessing the performance of encapsulation materials.

Based on Criteria 3 under the standard time-temperature exposure, the single layer encapsulation materials provide protection times of 16 min (cement board) to 28 min (25 mm thick gypsum-concrete). The thicker encapsulation materials, 2 layers of the board materials and 38 mm thick gypsum-concrete, provide protection times of 42 min (2 layers of cement board) to 69 min (2 layers of 15.9 mm thick Type X gypsum board).

In principle, a single test with two layers of the encapsulation material could be used to estimate the performance of both one and two layers of the encapsulation material. As shown in Table 14, the times determined for the face layer material based on the tests with two layers of the encapsulation material were comparable to, but consistently higher than, those with only single (face) layer material directly attached to the plywood substrate. The extended time for fall-off of the face layer in the tests with two layers of the encapsulation material does affect the rate of increase of the temperature rise values at the interface with the plywood substrate.

9.4.3.4.2 Encapsulation times – non-standard time-temperature curve

Two tests were conducted using a non-standard fire exposure derived from the average upper layer temperatures measured in a full-scale room fire test [45]. The single point and average temperature rises measured at the interface between the encapsulation material and the plywood substrate and between the face and base layers for the tests with 2 layers of the board materials were used to determine encapsulation times for the materials.

As shown in Table 15, the time to reach Criteria 3 was reduced by 5.6 min (25%) and 5.2 min (20%) for a single layer of 12.7 mm and 15.9 mm Type X gypsum board, respectively, comparing results from non-standard fire exposure to the standard fire exposure. For two layers of 12.7 mm thick Type X gypsum board, the time at which Criteria 3 was reached was reduced by 23.6 min (40%). The large reduction in time with the two layers of material may be due in part to the earlier fall off of the face layer of gypsum board (27 min in the test with the non-standard fire exposure versus 68 min with the standard time-temperature curve).

Table 15. Comparison of encapsulation times based on Criteria 3 for standard and non-standard time temperature exposures.

Type X Gypsum Board		Encapsulation Time (min)	
Thickness (mm)	Layers	Standard	Non-Standard
15.9	1	25.5	20.3
12.7	1	21.9	16.3
12.7	2	58.8	35.2

9.5 Assembly Encapsulation in Full-Scale Furnace Tests with Standard Fire Exposure

9.5.1 Encapsulation Performance of Assemblies Tested under This Project

As described in Section 7, the full-scale fire-resistance furnace tests conducted for the six encapsulated LWF wall assemblies had additional temperature measurements for the determination of the encapsulation times provided by two layers of 12.7 mm thick Type X (fire-resistant) gypsum board under the standard fire exposure. The temperatures were measured at the interface between the gypsum board used to protect the structural elements, on the studs and in the wall cavity as shown in Figure 16.

The measured temperature profiles followed the typical three-stage pattern for heat transfer through the gypsum board: an initial phase with the temperatures rising to approximately 100°C; a second phase with steady temperatures at approximately 100°C during the calcination of the gypsum board; a third phase with a more rapid increase in the temperatures once the calcination was complete.

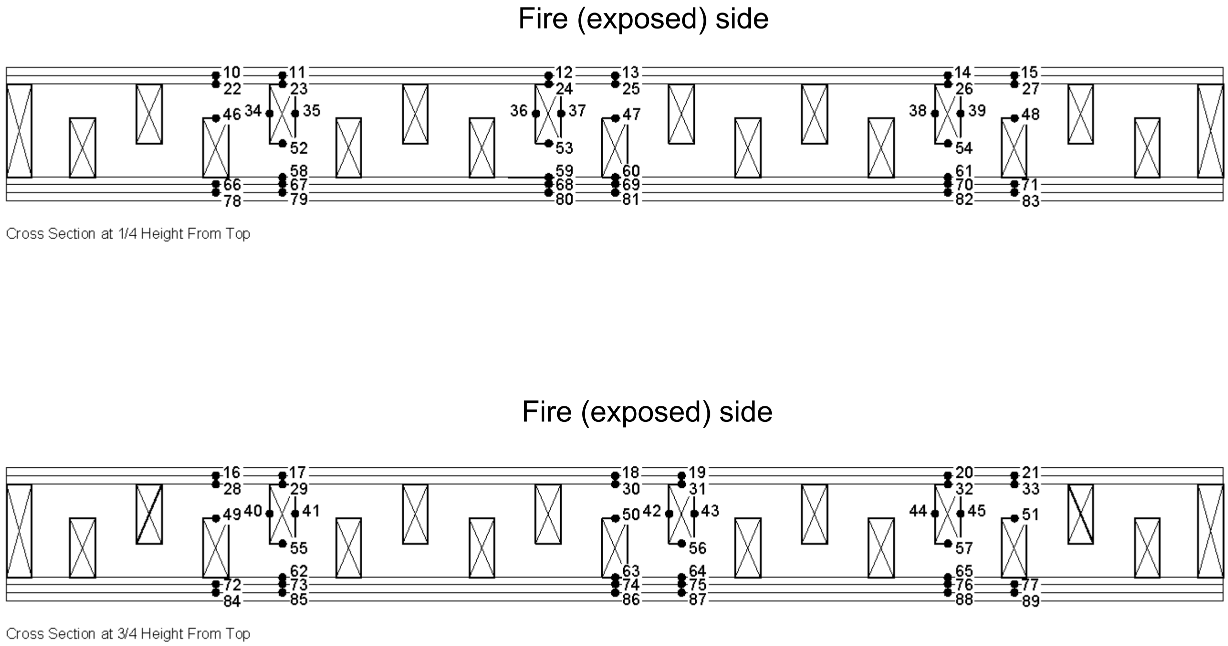

Figure 16. Exemplar thermocouple locations at two heights (Wall Assembly #1 – Table 8) [18].

9.5.1.1 Average Temperatures - Exposed Side of Wall Assemblies

The average temperatures measured at the interface between the gypsum board face and base layers on the exposed side of the assembly are shown in Figure 17. The time at which the average temperature at the interface between the face and base layer of gypsum board on the exposed side reached 300°C is provided in Table 16. After the average temperature exceeded 300°C, there was a slower increase in the average temperature until the gypsum board face layer began to fall off. Eventually, the average temperature reached temperatures equivalent to the furnace temperature. The times at which this occurred are also provided in Table 16 to indicate the fall-off time for the gypsum board face layer. The times in the table were determined using the temperature of 900°C.

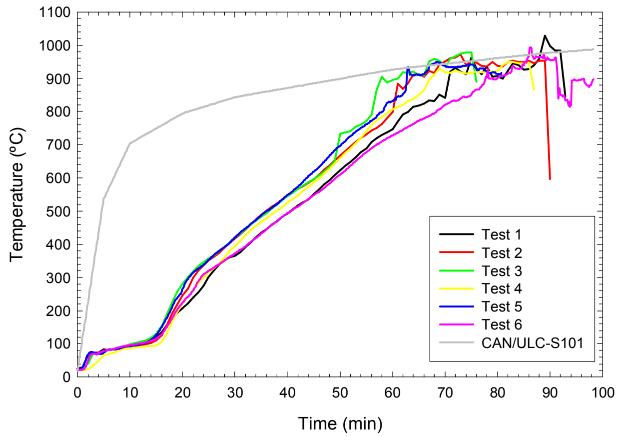

Figure 17. **Average temperature profiles at interface between gypsum board face and base layers.**

Table 16. **Time to average temperatures of 300°C and fall-off of gypsum board face layer.**

Test Assembly FEP (min)	Time temperature >300°C (min)			Gypsum Board Face Layer Fall-off (min)
	GB_f/GB_b	GB_b/Stud	GB_b/Cav	
#1 (92)	24	56	50	71
#2 (90)	22	51†	49	64
#3 (75)	21	49†	47	58
#4 (87)	24	54	48	68
#5 (81)	21	52	47	63
#6 (98)	24	55	50	79

FEP – Fire endurance period
GB_f – Gypsum Board face layer, exposed side
GB_b – Gypsum Board base layer, exposed side
Cav – Wall Cavity, exposed side
† Base layer of gypsum board attached to resilient metal channels with thermocouple attached to the gypsum board.

The average temperature profiles at the interface between the gypsum board base layer on the exposed side and the studs, and at the interface between the gypsum board base layer and the wall cavity, are shown in Figure 18 and Figure 19, respectively. The times at which the average temperatures exceeded 300°C at these interfaces are also provided in Table 16. (After the time at which the temperatures at the interface or space between the studs and the base layer of gypsum board on the exposed side of the test assembly exceeded 300°C (GB_b/Stud), the wall assemblies began to deflect away from the furnace as discussed in Section 7.2; this corresponded to the start of charring of the studs.) The average temperatures measured at these locations followed a similar general trend:

1. For the test assemblies without resilient metal channels installed on the exposed side of the framing, the time for the temperature to exceed 300°C at the interface between the gypsum board base layer on the exposed side and the stud framing was 52 - 56 min.
2. The time at which the average temperature exceeded 300°C on the back side of the gypsum board base layer at the interface in the wall cavity was 47 - 50 min. The earlier

times in the cavity area than at the stud are likely due to two factors: the heat loss from the gypsum board base layer to the studs and the insulation in the wall cavity reducing heat losses from the gypsum board base layer.

3. For the two assemblies with the gypsum board attached to resilient channels on the fire exposed side, the time for the average temperatures measured on the back side of the gypsum board base layer at the stud locations to exceed 300°C were shorter than for the assemblies with the gypsum board directly attached to the studs. The times (49 and 51 min, respectively) were comparable to the times to exceed 300°C on the back side of the gypsum board base layer at the interface in the wall cavity. These results indicate that the air gap between the studs and the gypsum board base layer reduced the heat losses from the gypsum board.
4. The temperatures continued to increase at both locations until the end of the test. The temperatures remained lower than the furnace temperatures indicating that most of the gypsum board base layer remained in place until the end of the test. This is consistent with observations made during the tests.

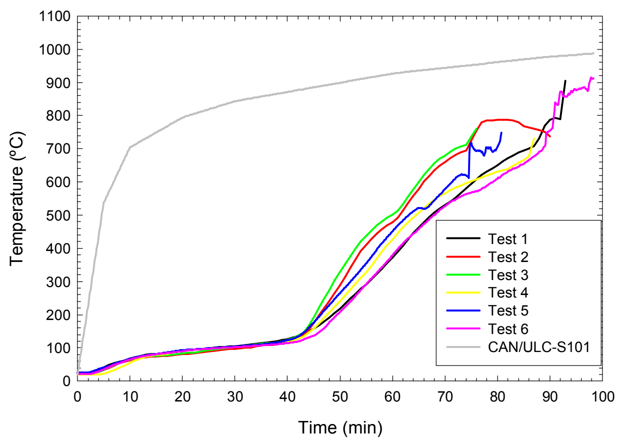

Figure 18. Average temperatures at interface between gypsum board base layer (exposed side) and stud framing.

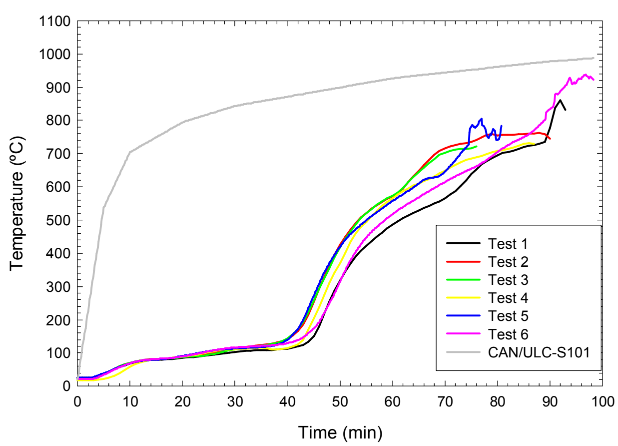

Figure 19. Average temperatures at interface between back side of gypsum board base layer (exposed side) and cavity.

9.5.1.2 Average Temperatures in the Wall Cavity

Temperatures were measured on various stud surfaces in the wall cavity (see Figure 16). This included the sides and the unexposed face (facing away from the fire) of the row of staggered studs on the exposed side of the test assembly and the exposed face (facing the fire) of the row of staggered studs on the unexposed side of the test assembly. The temperatures were also measured on the base layer (gypsum board or OSB shear membrane) on the unexposed side of the test assembly in the wall cavity.

The average temperatures measured on the two sides of the studs on the exposed side of the test assembly are shown in Figure 20. There was a gradual increase in the temperatures starting at approximately 10 min. The average temperatures were less than 100°C until 53 - 59 min for the assemblies constructed using 38 mm x 89 mm studs and 64 - 69 min for the two assemblies constructed using 38 mm x 140 mm studs. Subsequently, the temperatures on the side of the studs began to increase. The rate at which the temperature increased on the sides of the studs varied depending on the test assembly, with the fastest temperature rise within Wall Assembly #3 and the slowest within Wall Assembly #6.

The times at which the average temperatures on the two sides of the studs exceeded 300°C are summarized in Table 17. The temperatures on the sides of the studs exceeded 300°C near the end of the test. The longest period between the time for the temperature to exceed 300°C and the structural failure was for Wall Assemblies #1 and #2 (14 and 11 min, respectively). Assemblies #3 and #4 failed structurally within 8 and 6 min after the temperature on the side of the studs exceeded 300°C. The two assemblies (#5 and #6) with the 38 mm x 140 mm studs failed 5 and 3 min, respectively, after the temperature on the sides of the studs exceeded 300°C. Overall, these results suggest that there was a limited time period near the end of the test during which there was gasification/pyrolysis occurring on the sides of the studs. The primary effects of the fire on the studs on the exposed side of the test assemblies was from the heat transfer at the interface/space between the gypsum board base layer and the studs.

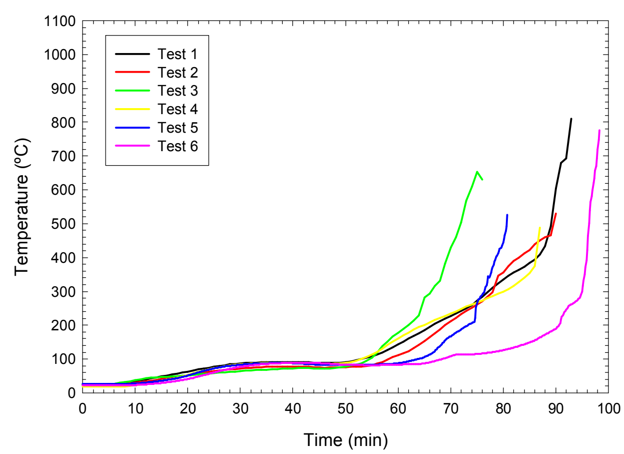

Figure 20. Average temperatures on the sides of the studs on the exposed side of the test assemblies.

Table 17. Time to average temperature > 300°C in wall cavity.

Test Assembly FEP (min)	Time temperatures >300°C (min)			
	Sides of Studs	Face Unexp Studs	Face Exp Studs	Base Layer
#1 (92)	78	76	89	89
#2 (90)	79	74	90	90
#3 (75)	67	72	DNR	DNR
#4 (87)	81	71	DNR	87
#5 (81)	76	73	77	77
#6 (98)	95	80	95	95

FEP – Fire endurance period
Sides of Studs – Temperatures on sides of studs on exposed side of wall assembly.
Face Unexp Studs – Temperatures on the exposed face of the studs (facing the fire) on the unexposed side of the test assembly.
Face Exp Studs – Temperatures on unexposed face of the studs (facing away from the fire) on the exposed side of the test assembly.
DNR – Did not reach

The average temperatures measured on the exposed face of the studs (facing the fire) on the unexposed side of the test assembly are shown in Figure 21. The average temperatures were less than 100°C until 51 – 60 min with the longest time occurring with Assembly #3, with the 100 mm stud spacing. Subsequently, the average temperatures at this location had a steady increase until near the end of the test.

The times at which the average temperatures on the face of the studs facing the fire on the unexposed side of the test assembly exceeded 300°C are summarized in Table 17. For Assemblies #1, #2, #4 and #6, the average temperatures at this location exceeded 300°C between16-18 min prior to the structural failure of the test assembly. For Assemblies #3 and #5, the time difference was 3 and 8 min, respectively. Overall, these results suggest that there was a limited time period near the end of the test during which there was gasification/pyrolysis occurring on the face of the studs on the unexposed side of the test assemblies. The results also indicate that the structural failure for Assemblies #3 and #5 was primarily due to the fire effects on the studs on the exposed side of the test assemblies.

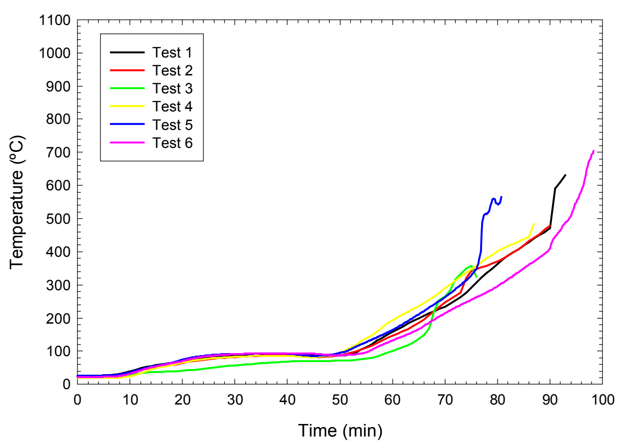

Figure 21. Average temperatures on the exposed face of the studs (facing the fire) on the unexposed side of the test assembly.

The average temperatures measured on the unexposed face of the studs (facing away from the fire) on the exposed side of the test assembly and on the base layer on the unexposed side of the test assembly are shown in Figure 22 and Figure 23, respectively.

There was an initial gradual increase in the average temperatures at both locations. The temperatures were less than 100°C until between 65 – 84 min, with the longest time occurring with Assembly #6. Subsequently, there was a more rapid increase in temperature at both locations. The times at which the temperatures exceeded 300°C are provided in Table 17. For some assemblies, this target temperature was not reached. For the other assemblies, the average temperature exceeded 300°C at or just prior to (less than 5 min) structural failure. These results indicate that gasification/pyrolysis of the structural elements on (or facing) the unexposed side of the wall occurred during the last few minutes of the test, if at all.

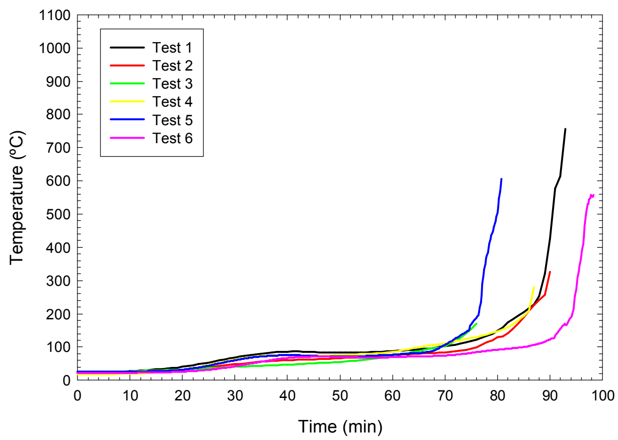

Figure 22. **Average temperatures on the unexposed face of the studs (facing away from the fire) on the exposed side of the test assembly.**

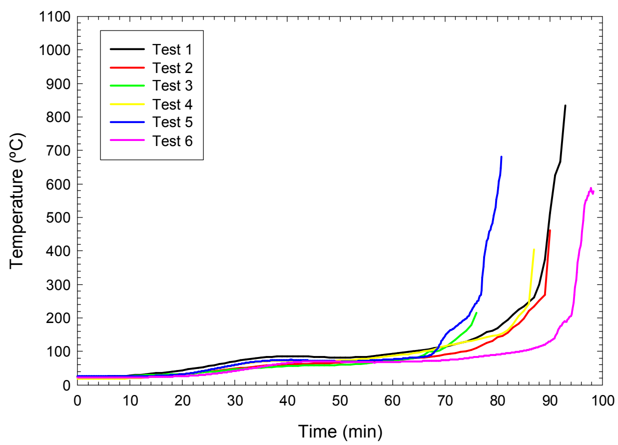

Figure 23. **Average temperatures measured on the base layer on the unexposed side of the test assembly.**

9.5.1.3 Average temperatures unexposed side of test assembly

The temperatures were measured at various locations on the unexposed side of the test assemblies. The temperatures at structural failure of the test assembly are provided in Table 18. At most locations, the temperatures were below 200°C at the end of the test.

Table 18. Temperatures on unexposed side of test assembly at failure.

Test Assembly FEP (min)	GB_b/Stud (°C)	OSB/Stud (°C)	OSB/GB_b (°C)	GB_b/GB_f (°C)	Unexp (°C)
#1 (92)	NA	122.7	179,1	73.7	53.6
#2 (90)	58.9	NA	NA	72.8	71.5
#3 (75)	121.1	NA	NA	81.3	56.3
#4 (87)	85.4	NA	NA	91.5	67.9
#5 (81)	NA	857.3	101.5	64.8	42.1
#6 (98)	NA	84.8	112.3	58.4	41.7

FEP – Fire endurance period
GB_f – Gypsum Board face layer, unexposed side
GB_b – Gypsum Board base layer, unexposed side
Unexp – Unexposed surface of GB face layer, unexposed side
NA – Not applicable

High temperatures were measured at the interface between the studs and the OSB base layer for Assembly#5. However, the high temperatures only occurred within the last 2-3 min of the test. The results indicate that some of the thermocouples were exposed due to deflections in the wall assembly.

9.5.1.4 Encapsulation Times in Full-Scale Furnace Tests

Table 19. Times for temperature rises to exceed criteria*.

Test Assembly FEP (min)	GB_f/GB_b (min)	GB_b/Stud (min)	GB_b/Cav (min)
#1 (92)	22	50	47
#2 (90)	21	48†	44
#3 (75)	18	46†	46
#4 (87)	21	51	45
#5 (81)	20	50	43
#6 (98)	20	48	43

FEP – Fire endurance period
GB_f – Gypsum Board face layer, exposed side
GB_b – Gypsum Board base layer, exposed side
Cav – Wall Cavity, exposed side
*ΔT250°C average/ΔT270°C single point
† Base layer of gypsum board attached to resilient metal channels with thermocouple attached to the gypsum board.

Table 19 shows the encapsulation times provided by the face layer of 12.7 mm thick Type X gypsum board and by the two layers of gypsum board, based on Criteria 3. The encapsulation times provided by the face layer of gypsum board were determined based on temperature rise measured at the interface between the face and base layers of gypsum board. The encapsulation times for the two layers of 12.7 mm thick gypsum board were determined using the temperature rise measured at the interface between the gypsum board base layer and the studs.

The times at which the target temperature rise was measured on the back surface of the base layer of gypsum board at the interface with the cavity are also provided in Table 19. All the times provided in Table 19 are based on single point temperature measurements. The time to reach the average temperature rise criteria was comparable to but slightly longer than the single point times.

The time for the temperatures at the gypsum board base layer/stud interface to exceed 300°C were 2-6 min longer than the encapsulation times provided by the gypsum board. As such, the encapsulation times provide a conservative estimate of the time at which the wood structural elements would be affected by the fire at the interface between the base layer gypsum board and the stud framing. However, the fire effects were initially localized at the gypsum board/stud interface. The temperatures measured at various locations in the wall cavity indicated that the temperatures measured on the studs did not exceed 300°C until much later in the test (beyond 67 min and up to 95 min).

Note that the structural failure of the test assemblies occurred 29 - 50 min after the encapsulation times provided by the two layers of 12.7 mm thick Type X gypsum board. During the encapsulation times (46 - 51 min), the wood structural elements were not affected by the standard fire.

9.5.2 Comparison with Intermediate-Scale and Other Full-Scale Tests with Standard Fire Exposure

Since the early 1990s, several fire research test series were conducted, primarily to evaluate various wall and floor assemblies to determine both acoustic and fire-resistance ratings for reference as generic acceptable solutions in the 2010 NBC [5]. All the assemblies used gypsum board as the primary protective membrane on the fire-exposed side. However, other parameters varied including the type of stud or joist (wood and steel) framing, number of layers of gypsum board, cavity insulation (none, glass, rock and cellulosic fibre), resilient channels, among others. Thermocouples were embedded at various locations in the assemblies, including at the interfaces between gypsum board layers, at the interface between the gypsum board and the framing element and on the gypsum board in the stud/joist cavity spaces. Further information on the various test series for generic wall and floor assemblies and the data mining results are provided in Reference [47].

The data from the various test series was reviewed to determine encapsulation times for the gypsum board arrangements used in the tests. The encapsulation times determined by data-mining the full-scale fire resistance test results are shown in Figure 24, Figure 25 and Figure 26 for a single layer of 12.7 mm thick Type X gypsum board, a single layer of 15.9 mm thick Type X gypsum board and 2 layers of 12.7 mm thick Type X gypsum board, respectively.

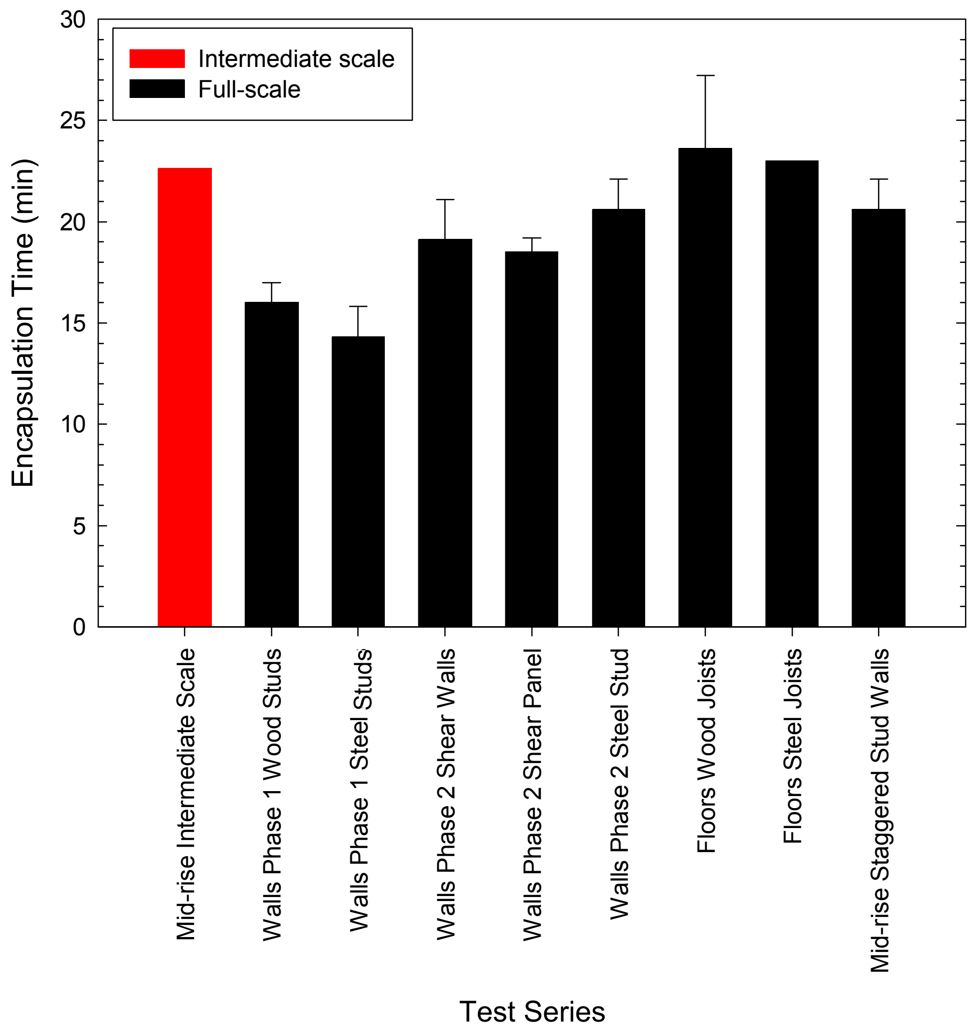

Figure 24. Encapsulation time 1 layer 12.7 mm thick Type X gypsum board using Criteria 3.

The encapsulation times shown for the full-scale fire resistance tests are the average times determined for the test series and were based on the times determined at the interface between a single layer of gypsum board with either a base layer of gypsum board or with the structural element, with one exception. The ‘shear panel’ tests had a shear membrane on the fire exposed side of the test assembly and the encapsulation time was determined at the interface between the gypsum board and the shear membrane. For the ‘shear wall’ assemblies, the shear membrane was mounted on the unexposed side of the test assembly, and the encapsulation time was based on the interface between the gypsum board on the fire exposed side and the wood stud framing.

For the assemblies with two layers of gypsum board, the encapsulation time was determined at the interface between the gypsum board base layer and the structural element. The results do not include encapsulation times determined on the gypsum board in the cavity space formed by the structural elements, which had shorter encapsulation times since there was less heat loss from the gypsum board into the cavity than to the structural elements resulting in a faster temperature rise at this location.

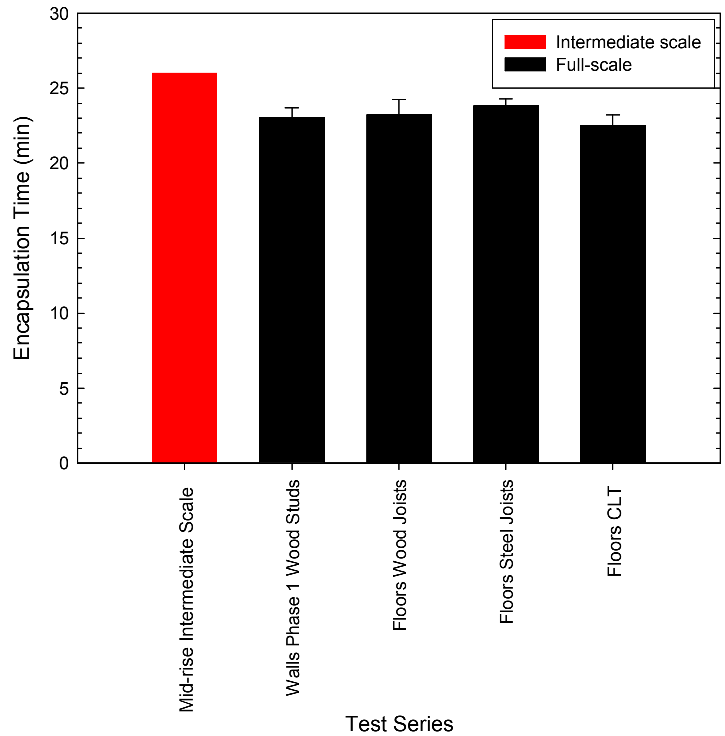

Figure 25. Encapsulation time 1 layer 15.9 mm thick Type X gypsum board using Criteria 3.

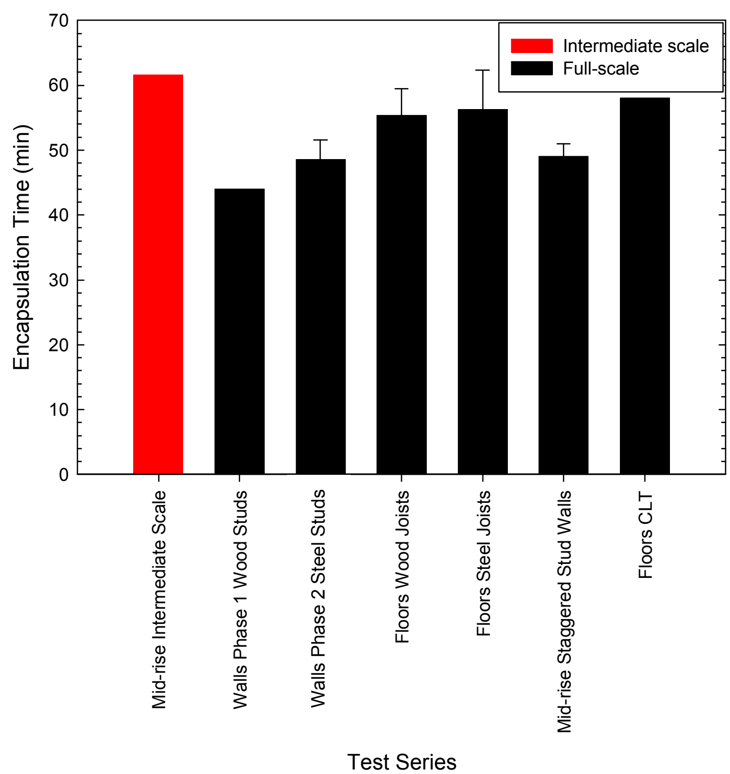

Figure 26. Encapsulation time 2 layers 12.7 mm thick Type X gypsum board using Criteria 3.

The error bars shown for the encapsulation times based on the full-scale fire resistance tests are the standard deviations for the encapsulation times determined for each test series.

The encapsulation times based on the earliest full-scale fire resistance tests (Walls Phase 1) with 12.7 mm thick Type X gypsum board conducted in the early 1990s are shorter than for later test series (Figure 24 and Figure 26). Gypsum board produced by the same manufacturer was used for all the test series. However, the Type X gypsum board used for the early project was discontinued in the mid-1990s and a second Type X gypsum board was used for all subsequent projects, including the intermediate scale furnace tests.

The encapsulation times for the single and double layer of 12.7 mm Type X gypsum board (Figure 24 and Figure 26) determined using the intermediate-scale tests are comparable to but slightly longer than the times determined from the full-scale fire resistance tests conducted since the mid-1990s with the same gypsum board product.

There was minimal variation in the encapsulation times determined for the 15.9 mm Type X gypsum determined from the historical test series (Figure 25). The encapsulation times determined using the intermediate-scale tests are comparable to but slightly longer than the full-scale values.

In the historical test series, there were only two tests with full-scale floor assemblies conducted using 2 layers of 15.9 mm thick Type X gypsum board. The average encapsulation time for these two assemblies was 61.5 min, which is considerably shorter than the 69.5 min determined in the intermediate-scale test (see Figure 3-Test #9). This time difference is likely due in part to the 90 min fall-off time for the face layer of gypsum board in the intermediate-scale test. The presence of the face gypsum layer limits the temperature on the exposed side of the base layer of gypsum board in the later stages of a test and thus limits the heat transfer through the gypsum board base layer.

In addition to the fall-off time of the face layer of the encapsulation material, there are other factors that affect the heat losses at the interface between the gypsum board base layer and the structural element and thus the encapsulation time. A primary consideration is the thermal losses through the substrate. The review of the full-scale test data in the historical test series indicated that the increase of the temperature rise value was typically faster on the unexposed side of the gypsum board in the cavity space than at the structural element [47]. These results would suggest that a thicker substrate for the encapsulation material may be required in the intermediate-scale tests to more closely match the encapsulation times based on the full-scale fire resistance tests.

9.6 Large-Scale Apartment Encapsulation Tests

Four large-scale apartment fire experiments were conducted to evaluate the encapsulation approach for protecting the combustible structural elements. These experiments are documented in a series of reports [37, 38, 39, 40]. The fire performances of two “encapsulated” combustible wood systems – a lightweight wood-frame (LWF) system (2 experiments) and a cross-laminated timber (CLT) system (1 experiment) – as well as a code compliant lightweight (cold-formed) steel-frame (LSF) system were evaluated in the fire experiments. Each experiment involved construction of a test set-up of an apartment unit, representing a portion of a six-storey mid-rise residential building. The intent was to use the results of the LSF system as a reference for a code-compliant noncombustible construction and to compare the impacts on fire severity of the encapsulated LWF and CLT systems with that of the reference. The second large-scale LWF apartment fire experiment was conducted with a similar but slightly different encapsulated LWF system, compared to the first LWF structure that was tested.

In the context of the current mid-rise code change proposals, which include mandatory sprinklers, the experimental designs do not take the impact of sprinklers on fires into account. Sprinklers are highly effective in controlling or suppressing fires large enough to activate the sprinklers, as discussed in Section 6. These apartment scale fire experiments were used to investigate the mid-rise building fire scenario where sprinklers are assumed to have failed to operate and/or control the fire.

9.6.1 Large-Scale Apartment Fire Test Facility

A three storey test setup was constructed to represent a three-storey section of a building bounded on four sides (three internal walls and an exterior wall) within the lower storeys of a mid-rise (e.g. six-storey) building. The test setup had a footprint comparable to a one bedroom apartment and was located under a large calorimeter hood, which was used for measurements of the heat release and smoke production rates produced by the fire in a furnished apartment in the test setup.

Figure 27 shows an elevation view and plan view of the test setup. Figure 28 shows photographs for one of the test setups. A detailed description of the structural assemblies and the test arrangement is provided in a series of reports [37, 38, 39, 40].

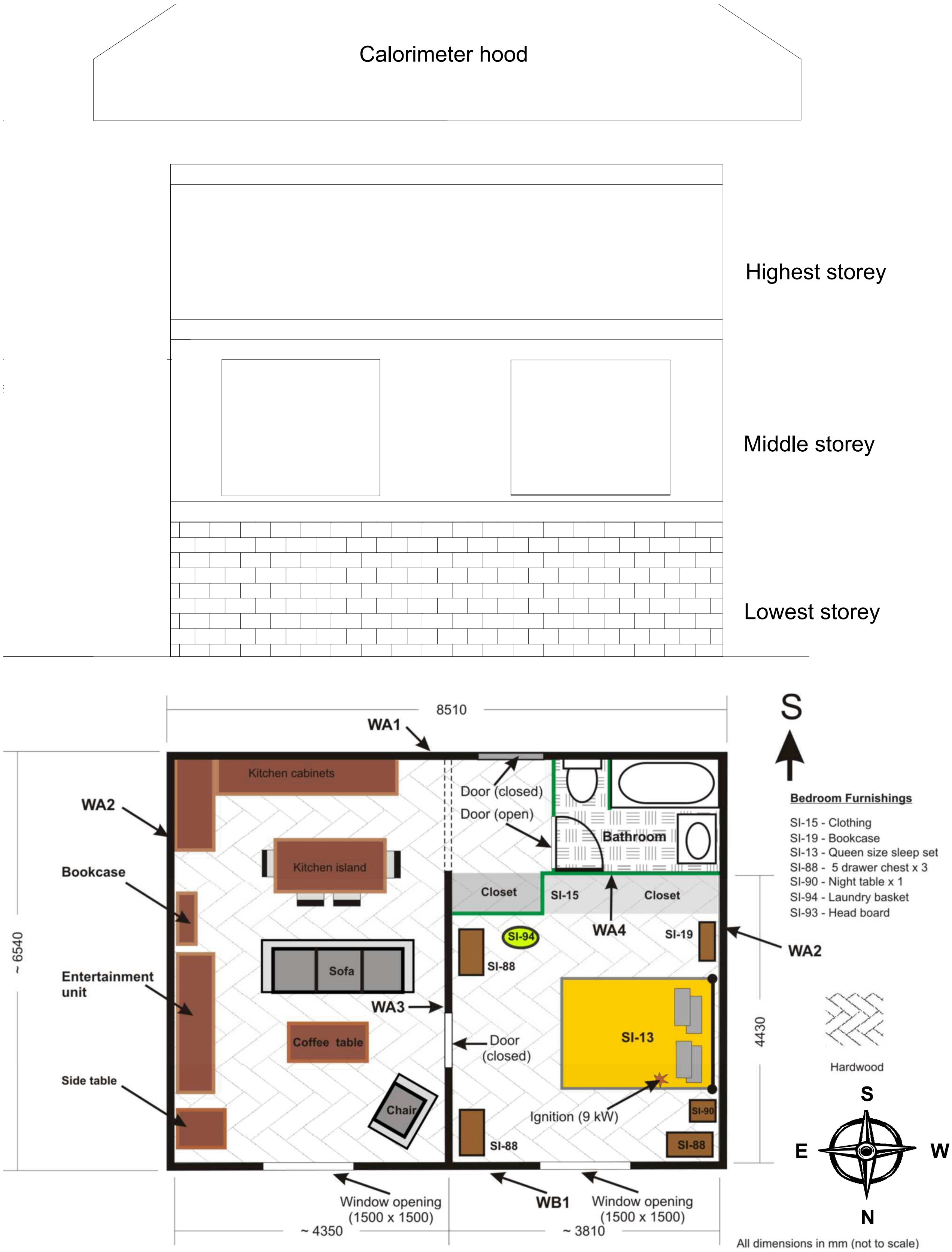

Figure 27. Large-scale apartment encapsulation test setup.

Figure 28. One of the large-scale apartment test setups.

9.6.1.1 Test Structure

The lowest storey was constructed of concrete blocks for walls, including a beam across the middle of this storey to support the middle loadbearing walls of the upper storeys.

The middle storey was constructed to simulate a one-bedroom apartment unit with a separate living room kitchen area. The fire was originated in the bedroom of the apartment unit on this middle storey. Table 20 to Table 23 show details of the wall, ceiling and floor assemblies used in the full-scale test setup. Figure 29 shows the test structures under construction.

One of the four walls forming the apartment's perimeter was an exterior wall assembly (WB1). The other three perimeter walls (WA1 and WA2) were intended to represent interior fire separations with a fire-resistance rating not less than 1 h, with WA1 separating the apartment from a corridor and WA2 separating the apartment from adjacent suites. The wall between the bedroom and the living room (WA3) was designed to be loadbearing and was also constructed as a fire-resistance rated assembly (at least 1-h fire-resistance-rated). The partition walls between the bedroom and entranceway/bathroom (WA4) were nonloadbearing and were not fire-resistance rated assemblies.

The ceiling and floor assemblies were also designed to represent typical fire-resistance rated assemblies (1-h fire-resistance rated fire separations). Acoustic insulation materials used in the floor assemblies were selected based on cone calorimeter tests [48]. The materials used for the experiments had the highest heat output (total heat release) and total smoke release of the typical flooring materials in the bench-scale tests.

A steel door with a 45 minute fire-protection rating was located in the WA1 wall in the entryway. Hollow-core wood fibre doors were used for the doorways on the bedroom and bathroom.

Two rough openings were used in the exterior wall (WB1) to provide ventilation air for the fire. One opening was in the bedroom and the other in the living room. Both openings were 1.5 m x 1.5 m. The size of the openings was based on previous tests conducted as part of a project to develop information to be used as a basis for establishing design fires for multi-family residential occupancies [45] and were chosen to maximize the fire severity and its exposure to the structural assemblies used for the test apartment.

The highest storey had the same layout as the middle storey.

Four test structures were constructed using lightweight wood frame (LWF) for two experiments, and cross-laminated timber (CLT) and lightweight (cold-formed) steel frame (LSF) for one experiment each.

The CLT structural panels used in the construction of the test structure conformed to ANSI/APA PRG 320 standard [49].

The LSF test setup conformed to the NBC minimum requirements with the structure designed to have 1-h fire-resistance ratings for the floor assemblies, loadbearing walls, and internal fire separations enclosing the apartments using UL listed assemblies. Structural and fire protection engineering firms and a construction company were hired for the structural design, third-party design review, fire protection specifications and construction of the LSF test structure.

9.6.1.1.1 Structural elements

The CLT apartment was constructed using 105 mm thick 3-ply CLT structural panels for WA1, WA2 and WA3 loadbearing wall assemblies as well as WB1 exterior wall assemblies and using 175 mm thick 5-ply CLT panels for floor/ceiling assemblies.

The LWF1 and LWF2 apartments were constructed using wood studs at close spacing for WA1, WA2, WA3, WB1 wall assemblies. The close stud spacing was used to simulate walls located in the lower storeys of mid-rise buildings with large structural loads [even though the exterior wall system (WB1) in the present design was non-loadbearing]. This maximized the potential fire load provided by the structural elements. Single studs were used for the walls, rather than a system with built-up studs, to maximize the stud area exposed to the fire, should the fire penetrate the encapsulation material.

In the LWF1 and LWF2 apartments, a shear layer using 15.9 mm thick OSB panels was attached to one side of the loadbearing walls: WA1, WA2 and WA3 (unexposed side of WA1 and WA2; living room side of WA3). The location of the shear layer was selected to minimize the time for the fire to penetrate to the primary structural elements (studs) and to maximize the potential contribution of the combustible structural elements to the fire. The floor/ceiling assemblies were constructed with 241 mm deep wood I-joists and 15.9 mm thick OSB subfloor.

The LSF apartment was constructed using cold-formed steel structures. The loadbearing WA1, WA2 and WA3 were constructed using cold-formed structural steel studs in accordance with the requirements in UL Design No. U423 BXUV.U423 for a 1-h fire resistance rating. The exterior wall WB1 was non-loadbearing and constructed using cold-formed structural steel studs; and is not required to provide a 1-h fire resistance rating. The interior loadbearing and exterior walls included bracing on one side. The floor/ceiling assemblies were constructed in accordance with UL Design No. G534 and had a 1-h fire resistance rating. A 0.46 mm thick galvanized steel pan with 15 mm ribs was mounted on the steel joists. A 38-mm-thick lightweight concrete subfloor was poured on the steel pan.

The non-loadbearing interior partitions WA4 were constructed using normal studs and spacing. Identical 38 mm x 89 mm wood stud walls were used in the CLT, LWF1 and LWF2 apartments; a steel stud partition wall was used in the LSF apartment.

9.6.1.1.2 Insulation

Glass fibre insulation was used as the insulation material in all insulated assemblies. All the floor/ceiling and wall assemblies in the LWF1 and LWF2 apartments were insulated. For the CLT and LSF apartments, the wall assemblies WA1, WA2 and WB1 were insulated but the WA3 wall and floor/ceiling assemblies were not insulated. The non-loadbearing interior partition WA4 was insulated in the CLT, LWF1 and LWF2 apartments but was not insulated in the LSF apartment.

In order to install insulation on the CLT wall panels (WA1, WA2 and WB1), vertical 38 mm x 38 mm wood strapping spaced at 600 O.C. was attached to one side of the CLT; the cavity formed by the wood strapping was filled with the insulation. The wood strapping with insulation was installed on the exposed side of WA1 and WA2 (inside the apartment). This serves two purposes in real applications: 1) to provide a space for electrical and plumbing services and 2) to improve acoustical performance. The wood strapping with insulation was installed on the exterior side of WB1 as an outboard insulation system.

9.6.1.1.3 Encapsulation

For the CLT, LWF1 and LWF2 apartments, the loadbearing and fire separation wall structures (WA1, WA2 and WA3) were protected using two layers of 12.7 mm thick Type X gypsum board on both sides (except that only a single layer was used on the unexposed side of CLT panels for WA1 and WA2). For the LSF apartment, the WA1, WA2 and WA3 steel structures were protected using one layer of 15.9 mm thick Type X gypsum board on both sides in accordance with UL Design No. U423 BXUV.U423 for a 1-h fire resistance rating.

The non-loadbearing interior partition WA4 in all tests was protected using one layer of 12.7 mm thick regular gypsum board on each side.

For the exterior wall assemblies WB1, all tests used one layer of 12.7 mm thick regular gypsum sheathing on the exterior (unexposed) side. This gypsum sheathing was combustible and had a flame spread rating of 20 and a smoke development index of 0, which was sufficient to limit upward flame spread in the CAN/ULC-S134 tests conducted for this project. Exterior cladding was not used in the tests (in real applications, a non-combustible cladding is recommended). The interior (exposed) side of WB1 was protected using two layers of 12.7 mm thick Type X gypsum board for the CLT and LWF1 apartments, but used only one layer of 12.7 mm thick regular gypsum board for the LWF2 and LSF apartments.

The wood floor/ceiling assemblies used in the CLT, LWF1 and LWF2 apartments were protected on the floor (top) side using two layers of 12.7 mm thick cement board. These two layers of cement board were used as an alternative to a concrete topping as an encapsulation material. An acoustic membrane was used under the cement board on the middle storey and was selected based on its fire properties measured in cone calorimeter tests [48]. The material that produced the highest total heat output among a range of membranes tested in the cone calorimeter was used for the apartment tests. The wood floor/ceiling assemblies were protected on the ceiling (under) side using two layers of 12.7 mm thick Type X gypsum board (attached with resilient channels for the LWF1 and LWF2 apartments).

The steel floor/ceiling assemblies used in the LSF apartment were protected on the ceiling (under) side using one layer of 12.7 mm Type X gypsum board on metal furring channels in accordance with UL Design No. G534 for a 1-h fire resistance rating. (The Type X gypsum board used for the assemblies was one of those specified in the UL design.)

9.6.1.1.4 Floor finish

In all tests, a floating hardwood floor with an acoustic membrane under the flooring was installed in all areas on the middle storey (fire floor) except for the bathroom, where no finished hardwood floor was installed. Hardwood flooring was not included on the highest storey.

9.6.1.2 Structural Load

For other than some smaller low-rise buildings, the prescriptive provisions of the NBC generally include two requirements for major structural load-bearing elements (floors, walls, roofs, etc.):

1. The elements must have sufficient structural fire resistance to limit the probability of failure or collapse during the time required for occupants to evacuate safely and emergency responders to perform their duties.
2. For larger and taller buildings, the NBC also requires the use of noncombustible construction.

Whenever the first requirement applies, and a particular level of fire-resistance rating is prescribed (e.g. 45 min, 1 h, 2 h), the level of structural fire performance (fire resistance) of a building element is addressed in the NBC by requiring testing in accordance with CAN/ULC-S101 [20]. Such as the standard fire resistance tests conducted for this and previous projects, the structural fire resistance performance of the wall and floor assemblies for mid-rise applications were determined to address the first requirement in [18, 19, 47, 50]. The design methods and loadings used are those required by the NBC and the superimposed load applied during the fire resistance test must represent a full specified load condition or a restricted load use condition. However, these standard fire-resistance tests do not evaluate the effect or performance expected or intended by the second requirement, that is, use of noncombustible structural elements.

The (primary) objective of the simulated apartment fire tests was to determine the fire performance capability of the gypsum board and cement board to effectively encapsulate the combustible structural elements (and thus provide an equivalent level of fire safety to that provided by the application of the noncombustible construction requirements). In this regard, critical observations include the ability of the encapsulation to both delay (or prevent) ignition of the combustible structural elements and also limit their subsequent contribution (due to burning of the elements) to the fire severity within the fire compartment.

Given the primary objectives of the research, the standard fire resistance test, CAN/ULC-S101 was not suitable for this portion of the project. The loadbearing LWF wall assemblies used in the LWF1 and LWF2 test structures, with the level of encapsulation used, would be expected to demonstrate a fire endurance period in the standard (CAN/ULC-S101) fire test of more than 1 h. The LWF floor assemblies, with the level of encapsulation used would be expected to have a fire endurance period of more than 1 h. The loadbearing 3-ply CLT wall assemblies used in the test CLT structure, with the level of encapsulation used, would be expected to demonstrate a fire endurance period of more than 90 min in the standard (CAN/ULC-S101) fire test The 5-ply CLT floor assembly, with the level of encapsulation used, would be expected to have a fire endurance period of more than 2 h. The loadbearing LSF wall assemblies and the LSF floor/ceiling assemblies used in the LSF test structure were UL listed assemblies with a 1-h fire resistance rating.

For each of the simulated apartment fire tests, the floor assembly of the middle storey (fire floor) was subjected to a superimposed live load arising from the presence of actual (typical) furnishings, fixtures and other contents. On the highest storey, concrete blocks were used to simulate live loads that were the same weight as the furniture and contents on the middle storey and also simulated larger items, such as the bed, in point loading. The loadbearing walls bounding the four sides and within the apartment structure (between bedroom and living room/kitchen) were subjected to the combination of the live loads on the middle and highest floors, along with the loads imposed by the self-weight (dead load) of the structure on the middle and highest storeys.

Table 20. Construction details of LWF apartment #1 (Apt LWF1)

Wall Assemblies	**Inside of Test Apartment or Bedroom**		**Structural Elements**	**Insulation**	**Outside of Test Apartment or Bedroom**	
	Gypsum Board				**Shear Layer**	**Gypsum Board**
WB1 Non-loadbearing exterior	2 layers, 12.7 mm thick Type X	Vapour barrier	38 mm x140 mm staggered wood studs @152 mm o.c; 38 mm x 184 mm double top plate, single bottom plate, end studs	glass fibre	N/A	1 layer, 12.7 mm thick regular sheathing
WA1 and WA2 Interior fire separations (WA2 load-bearing)	2 layers, 12.7 mm thick Type X		38 mm x 89 mm wood studs @152 mm o.c.	glass fibre	15.9 mm thick OSB	2 layers, 12.7 mm thick Type X
WA3 Load-bearing between bedroom and living room area	2 layers, 12.7 mm thick Type X		38 mm x 89 mm wood studs @152 mm o.c.	glass fibre	15.9 mm thick OSB (living room side)	2 layers, 12.7 mm thick Type X
WA4 Non-loadbearing interior partitions	1 layer, 12.7 mm thick regular		38 mm x89 mm wood studs @406 mm o.c.	glass fibre	N/A	1 layer, 12.7 mm thick regular
Floor/Ceiling Assemblies	**Ceiling Finish**		**Structural Elements**	**Insulation**	**Subfloor and Floor Finish**	
	Gypsum Board	**Resilient Channels**			**Subfloor**	**Finish**
Floor assembly (between lowest and middle storey)	2 layers, 12.7 mm thick Type X	Metal channels @406 mm, perpendicular to wood I-joists	241 mm deep wood I-joists @406 mm o.c., 38 mm x 89 mm solid wood flanges and 9.5 mm thick OSB web	glass fibre	15.9 mm thick OSB; acoustic membrane on top	2 layers of 12.7 mm thick cement board + floating hardwood floor with acoustic membrane in between
Ceiling assembly (between middle and highest storey)	2 layers, 12.7 mm thick Type X	Metal channels @406 mm, perpendicular to wood I-joists	241 mm deep wood I-joists @406 mm o.c., 38 mm x 89 mm solid wood flanges and 9.5 mm thick OSB web	glass fibre	15.9 mm thick OSB	2 layers of 12.7 mm thick cement board

Table 21. Construction details of CLT apartment (Apt CLT)

Wall Assemblies	Inside of Test Apartment or Bedroom		Structural Elements	Insulation	Outside of Test Apartment or Bedroom	
	Gypsum Board	Strapping and Insulation			Vertical Wood Strapping	Gypsum Board
WB1 Non-loadbearing exterior	2 layers, 12.7 mm thick Type X	N/A	105 mm thick 3-ply CLT panel, water resistant membrane on outside	glass fibre	38 mm x 38 mm wood strapping@610 mm o.c.	1 layer, 12.7 mm thick regular sheathing
WA1 and WA2 Interior fire separations (WA2 load-bearing)	2 layers, 12.7 mm thick Type X	38 mm x 38 mm vertical wood strapping@610 mm o.c. with glass fibre	105 mm thick 3-ply CLT panel	N/A	N/A	1 layer, 12.7 mm thick Type X
WA3 Load-bearing between bedroom and living room area	2 layers, 12.7 mm thick Type X	N/A	105 mm thick 3-ply CLT panel	N/A	N/A	2 layers, 12.7 mm thick Type X
WA4 Non-loadbearing interior partitions	1 layer, 12.7 mm thick regular	N/A	38 mm x 89 mm wood studs @406 mm o.c.	glass fibre	N/A	1 layer, 12.7 mm thick regular
Floor/Ceiling Assemblies	**Ceiling Finish**		**Structural Elements**	**Insulation**	**Floor Finish**	
	Gypsum Board	**Resilient Channels**				**Finish**
Floor assembly (between lowest and middle storey)	2 layers, 12.7 mm thick Type X	N/A	175 mm thick 5-ply CLT panel	N/A	acoustic membrane on top of CLT	2 layers of 12.7 mm thick cement board + floating hardwood floor with acoustic membrane in between
Ceiling assembly (between middle and highest storey)	2 layers, 12.7 mm thick Type X	N/A	175 mm thick 5-ply CLT panel	N/A		2 layers of 12.7 mm thick cement board

Table 22. Construction details of LSF apartment (Apt LSF)

Wall Assemblies	Inside of Test Apartment or Bedroom		Structural Elements	Insulation	Outside of Test Apartment or Bedroom	
	Gypsum Board				Shear Bracing	Gypsum Board
WB1 Non-loadbearing exterior	1 layer, 12.7 mm thick regular	Vapour barrier	600S162-33 staggered steel studs@305 mm o.c.	glass fibre	Diagonal strapping on studs	1 layer, 12.7 mm thick regular sheathing
WA1 and WA2 (as per UL Design No. U423) Interior fire separations (WA2 load-bearing)	1 layer, 15.9 mm thick Type X		362S162-54 (50) steel studs WA1@406 mm o.c. WA2@305 mm o.c.	glass fibre	Diagonal strapping on studs	1 layer, 15.9 mm thick Type X
WA3 (as per UL Design No. U423) Load-bearing	1 layer, 15.9 mm thick Type X		362S162-54 (50) steel studs@203 mm o.c.	N/A	Diagonal strapping on studs (living room side)	1 layer, 15.9 mm thick Type X
WA4 Non-loadbearing interior partitions	1 layer, 12.7 mm thick regular		250S162-33 steel studs@406 mm o.c.	N/A	N/A	1 layer, 12.7 mm thick regular

Floor/Ceiling Assemblies	Ceiling Finish		Structural Elements	Insulation	Subfloor and Floor Finish	
	Gypsum Board	Furring Channels			Subfloor	Finish
Floor assembly (between lowest and middle storey) as per UL Design No. G534	1 layer, 12.7 mm thick Type X*	Metal channels @610 mm, wired to screws on side of steel joists	1-800S162-54 (50) cold-formed steel joists spaced 610 mm o.c.	N/A	0.46 mm galvanized steel pan+38-mm-thick lightweight concrete	Floating hardwood floor with acoustic membrane underneath
Ceiling assembly (between middle and highest storey) as per UL Design No. G534	1 layer, 12.7 mm thick Type X*	Metal channels @610 mm,wired to screws on side of steel joists	1-800S162-54 (50) cold-formed steel joists spaced 610 mm o.c.	N/A	0.46 mm galvanized steel pan + 38-mm-thick lightweight concrete	

* The Type X gypsum board used for the assemblies was one of those specified in the UL design.

Table 23. Construction details of LWF apartment #2 (Apt LWF2)

Wall Assemblies	Inside of Test Apartment or Bedroom		Structural Elements	Insulation	Outside of Test Apartment or Bedroom	
	Gypsum Board				Shear Layer	Gypsum Board
WB1 Non-loadbearing exterior	1 layer, 12.7 mm thick regular	Vapour barrier	38 mm x140 mm staggered wood studs @152 mm o.c; 38 mm x184 mm double top plate, single bottom plate, end studs	glass fibre	N/A	1 layer, 12.7 mm thick regular sheathing
WA1 and WA2 Interior fire separations (WA2 load-bearing)	2 layers, 12.7 mm thick Type X		38 mm x 89 mm wood studs @305 mm o.c.	glass fibre	15.9 mm thick OSB	2 layers, 12.7 mm thick Type X
WA3 Load-bearing between bedroom and living room area	2 layers, 12.7 mm thick Type X		38 mm x 89 mm wood studs @305 mm o.c.	glass fibre	15.9 mm thick OSB (living room side)	2 layers, 12.7 mm thick Type X
WA4 Non-loadbearing interior partitions	1 layer, 12.7 mm thick regular		38 mm x 89 mm wood studs @406 mm o.c.	glass fibre	N/A	1 layer, 12.7 mm thick regular
Floor/Ceiling Assemblies	**Ceiling Finish**		**Structural Elements**	**Insulation**	**Subfloor and Floor Finish**	
	Gypsum Board	**Resilient Channels**			**Subfloor**	**Finish**
Floor assembly (between lowest and middle storey)	2 layers, 12.7 mm thick Type X	Metal channels @406 mm, perpendicular to joists	241 mm deep wood I-joists @406 mm o.c., 38 mm x 89 mm solid wood flanges and 9.5 mm thick OSB web	glass fibre	15.9 mm thick OSB; acoustic membrane on top	2 layers of 12.7 mm thick cement board + floating hardwood floor with acoustic membrane in between
Ceiling assembly (middle storey)	2 layers, 12.7 mm thick Type X	Metal channels @406 mm, perpendicular to joists	241 mm deep wood I-joists @406 mm o.c., 38 mm x 89 mm solid wood flanges and 9.5 mm thick OSB web	glass fibre	15.9 mm thick OSB	2 layers of 12.7 mm thick cement board

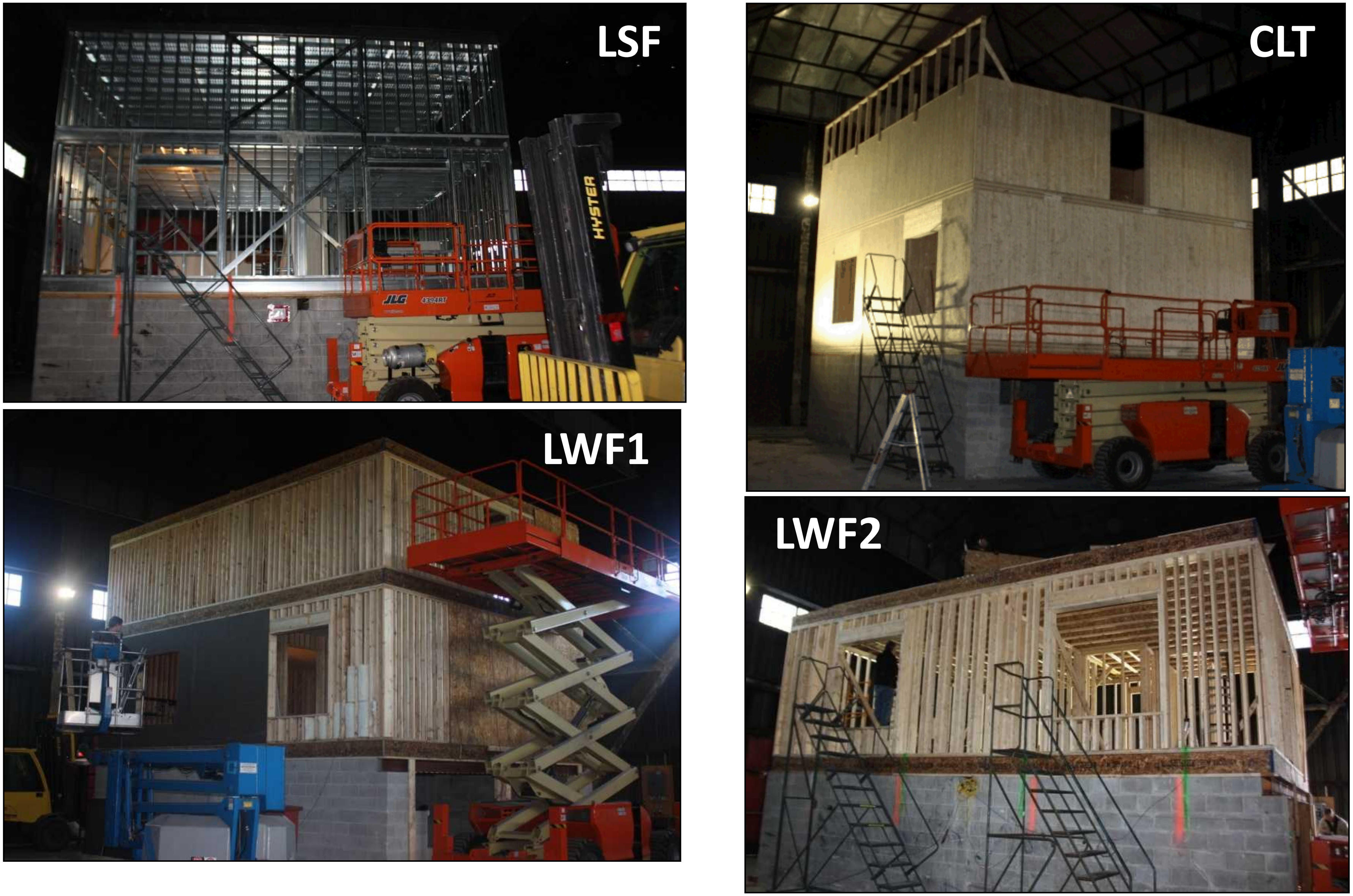

Figure 29. Large-scale apartment test structures under construction.

9.6.1.3 Fuel Load and Fire Origin

The full-scale fire experiments were conducted with the apartment fully furnished. The primary fuel load present within the fire floor (middle storey) was made up of typical furniture and contents found in residential occupancies. The items used in the apartment fire tests were based on previous fire tests conducted as part of a project to develop information to be used as a basis for establishing ‘design fires’ for multi-family occupancies [45]. These fuel loads were based on actual field surveys conducted to determine fuel loads in multi-family dwelling units [51]. The layout of the fuel load in the test area is shown in Figure 27. The labels (e.g. SI-13) on the items used in the bedroom refer to single item tests conducted on the fuel item [45].

In addition to the furniture and contents, fuel was also provided by the hardwood flooring, the kitchen cabinets and island including counter tops and by the wood framing used for the partition wall between the bedroom and the bathroom/entrance. The fire origin was located in the bedroom on the middle storey. The bed assembly was the first item ignited.

In the previous project to develop data regarding design fires for multi-family occupancies, one of the fire tests was conducted using a single bedroom setup with exactly the same bedroom dimension, ventilation opening, furniture and contents, but with noncombustible construction for all wall and ceiling assemblies (and no door opening). The test fire was also started by igniting the bed assembly. The average temperature profile based on the temperatures measured near the ceiling (2.4 m height) in the four quadrants of the fully furnished bedroom (PRF-03) is shown in Figure 30.

In this standalone bedroom test, the room temperature increased quickly after the ignition of the bedding and flashover occurred in approximately 3 min. The fire continued to grow in the bedroom and the temperature reached 1200ºC at 29 min. Then the fire started to decay, with the temperature dropping to below 600ºC after 60 min. This temperature profile reflects the contribution of the bedroom furniture and contents to the fire development.

Based on the earlier test series [45], the 1500 mm x 1500 mm ventilation openings used in the apartment experiments maximize the amount of combustion and thus the temperatures inside the room. As a result, the overall fire severity and heat exposure within the room are maximized.

Also shown in Figure 30 is the standard time-temperature curve used in standard fire resistance tests [20]. During the initial 40 min, the temperatures measured in the standalone bedroom test (PRF-03) were higher than the standard time-temperature curve. As a result, the fire involving the room contents during this period produced a more severe exposure to the room boundaries than is used for standard fire-resistance testing. Afterward, the decaying bedroom fire produced a less severe exposure to the room boundaries than the standard time-temperature curve. Today’s home furniture and contents have been recognized to potentially produce faster developing and hotter fires. Fire statistics shows that this bedroom fire scenario represents a disproportionally higher rate of fire death [52].

For the large-scale apartment tests, fire development and temperature profiles similar to those in the standalone bedroom would be expected during the time period in which wood structural elements were not involved in the fire. The actual fire development in the different apartment fire tests is discussed in Section 9.6.2.1 below.

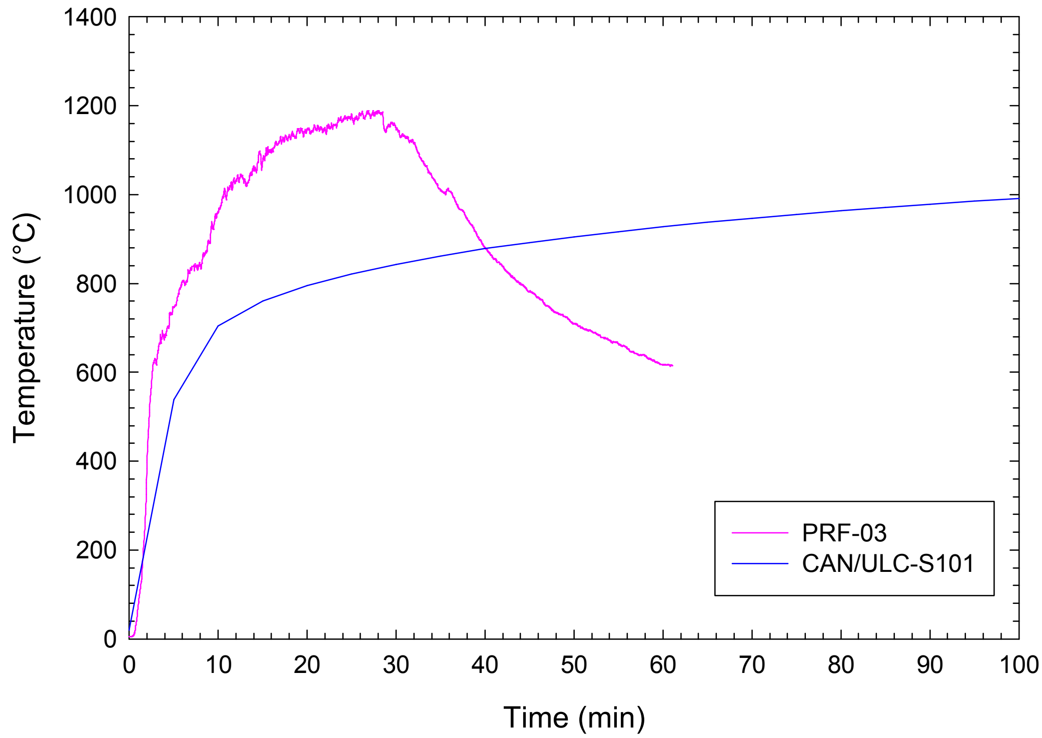

Figure 30. Contribution of bedroom furniture and contents to fire development and comparison with standard time-temperature curve.

9.6.2 Key Results from Large-Scale Apartment Fire Tests

Heat release rate, heat flux, smoke production, and temperatures throughout the test setup were measured for use in assessing the fire severity and performance of the encapsulation materials.

9.6.2.1 Fire Development in the Apartment

The furniture and contents as well as the hardwood flooring, the kitchen cabinets and counter tops in the fully furnished apartment produced high-intensity fast growing fires with similar initial fire development in all experiments. A smoke alarm was activated in less than 20 s. Flashover occurred in the bedroom at approximately 3 min and the door between the bedroom and the living room was fully breached at 5 min or earlier. Then the fire quickly developed in the living room area and subsequently progressed to the kitchen and entrance area. Localized flashover occurred in the living room/kitchen spaces – typically around 6 min in the living room area, and subsequently progressed to the kitchen area by 10 min and to the entry area by 19 min. Photographs taken after flashover in both the bedroom and living room area are shown in Figure 31.

Figure 32 shows the average temperatures in the bedroom based on the measurements using four thermocouple trees located at the center of the four room quadrants: a) the average near the ceiling at the 2.4 m height, and b) the average at the 1.4 and 2.4 m heights. In each test the temperatures were uniform with height in the upper portion of the bedroom. Higher temperatures were measured by the individual thermocouples indicating hotter regions in the bedroom. The location of the hot regions varied depending on the stage of the fire development. Peak temperatures of 1100-1200°C were reached in the bedroom at approximately 12 min in all tests, with the peak temperatures reached first in the SE quadrant.

The temperature profile from the previous standalone bedroom test (PRF-03) [45] is also shown in Figure 32. The furniture and contents used in Test PRF-03 were the same as that used in the apartment. However, there were some variations in the average temperature profiles.

After flashover in the bedroom, there were up to 10 min during which higher temperatures were measured in the apartment fire tests than in the standalone bedroom test. Since the door between the bedroom and the living room was destroyed by the fire, additional ventilation may have been provided to the fire in the bedroom prior to the full development of the fire in the living room, producing the higher temperatures.

The temperatures in the apartment bedroom began to decrease after reaching the peak values but the decrease occurred earlier than in the standalone bedroom test (PRF-03). The fire loads were similar in the apartment bedroom and the standalone bedroom except that the combustible subfloor (15.9 mm thick OSB) was not protected by cement board in PRF-03, providing additional fuel load for the fire in Test PRF-03. In the apartment bedroom, the partition wall between the bedroom and the bathroom/entryway was already breached by fire by this time in each test, releasing some hot gases from the bedroom. (Other reasons for the earlier temperature decay are discussed in the following sections.)

While the temperatures measured in PRF-03 kept decreasing till the end of the test, the temperatures in the apartment tests ceased decreasing after a certain time period in the LWF and CLT apartment tests, once the ceiling assembly was involved in the fire. (Further discussions are provided in the following sections.)

In the living room, kitchen and entryway areas, the temperatures were also uniform with height in the upper portion of the space (the average temperature at the 2.4 m height was similar to the average at the 1.4 and 2.4 m heights). However, the fire in the living room, kitchen and entryway did not develop uniformly throughout the entire area. This is illustrated in Figure 33, by the plots of the average upper layer temperature (1.4 and 2.4 m heights) in each area. The fire developed faster in the living room area than in the kitchen and entry area. Flashover occurred at approximately 6 min in the living room area; progressed to the kitchen area by 10 min; and then to the entry area by 19 min. Peak temperatures of above 1100°C were reached in the living room area by 25 min in all tests, with the peak temperatures reached later in the kitchen and entryway.

Also shown in Figure 32 and Figure 33 is the standard time-temperature curve used in standard fire-resistance tests [20]. The peak temperatures in the bedroom and the living area were much higher than the standard time-temperature curve used in fire-resistance tests. For a period in each test, the combustion of the room contents produced more severe fires in the apartment than the standard fire used in fire-resistance tests. As a result, the fire involving the room contents produced a more severe exposure to the room boundaries and challenged the structure more aggressively than in a standard fire-resistance test during this period. However, the duration with the higher fire intensity caused by the room contents was different from test to test depending on the ventilation conditions.

Figure 31. Flashover in both the bedroom and living room areas during large-scale apartment fire tests.

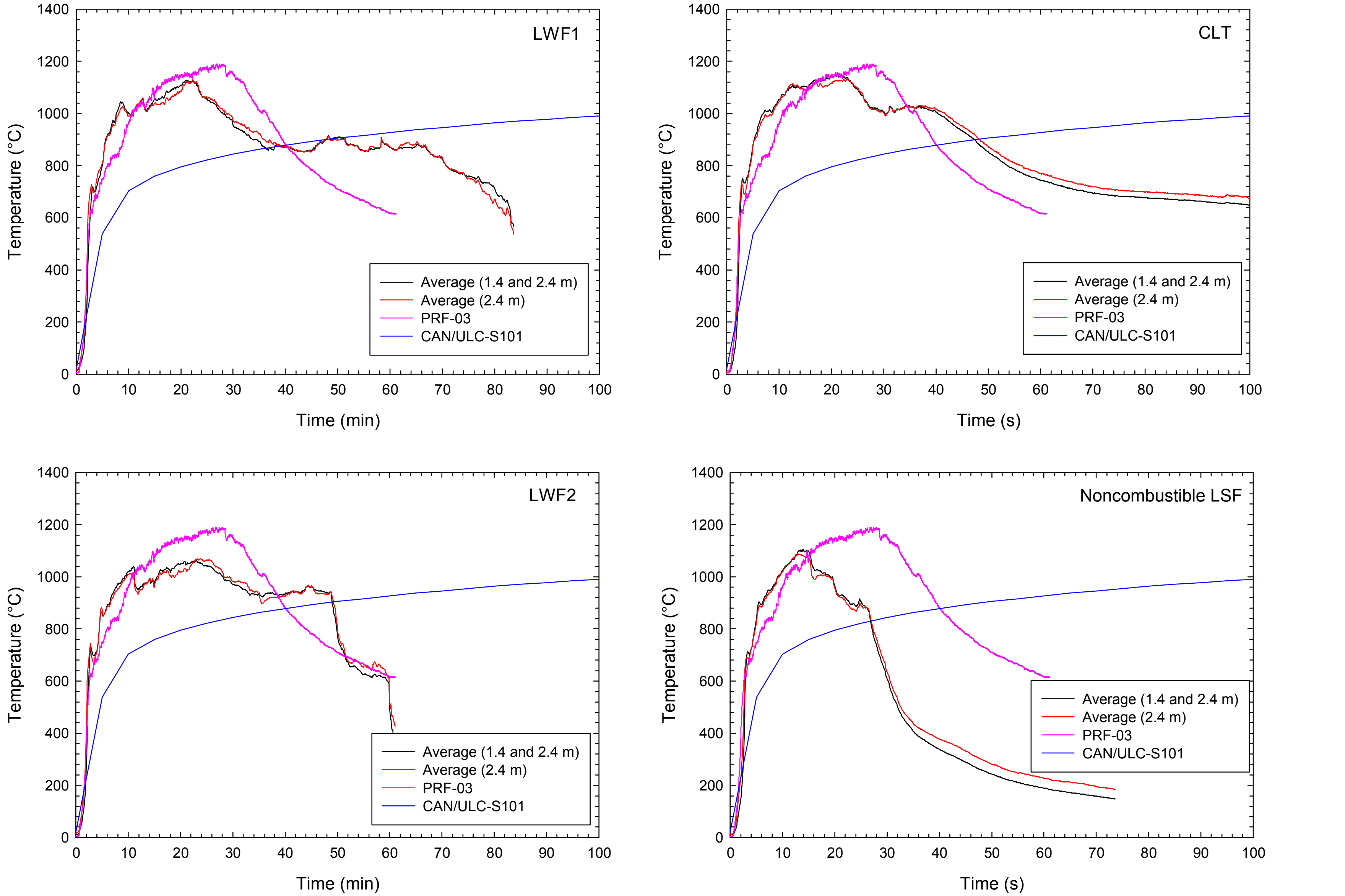

Figure 32. Average temperatures in bedroom.

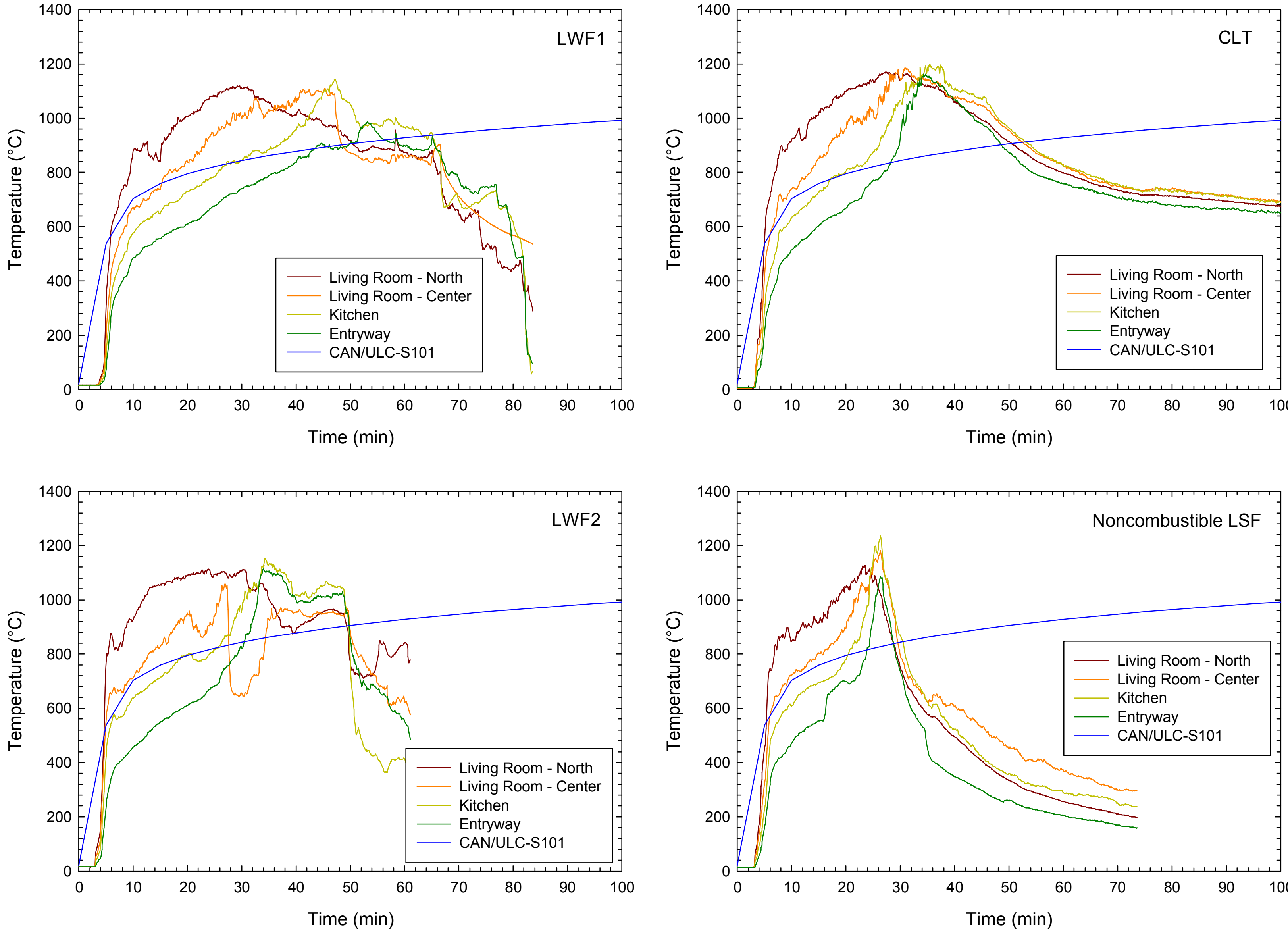

Figure 33. Average temperatures in living room, kitchen and entryway (1.4 and 2.4 m heights).

9.6.2.1.1 Apt LWF1

In the LWF apartment test #1, the peak temperatures (1100 – 1200°C) were sustained until 24 min in the bedroom. After 24 min, there was a general decrease in temperature until approximately 45 min followed by a temperature plateau with temperatures greater than 850°C that lasted until 65 min. This temperature plateau after 45 min corresponded to the initial fall-off of some of the base layer of gypsum board from the ceiling and the burning of the wood I-joists and the OSB subfloor in the ceiling assembly. In the living room, the wood I-joists and the OSB subfloor in the ceiling assembly also started to contribute to the fire after 45 min and the base layer of gypsum board had begun to fall off from the ceiling by this time. As shown in Figure 34, the ventilation condition from the exterior openings was basically unchanged before the ceiling assembly collapsed at 58.3 min. Data was collected for 83 min.

During the period with higher fire intensity (40 min in the bedroom and 45 min in the living area), the fire involving the room contents in the bedroom challenged the wood structure more aggressively than in a standard fire-resistance test during that period. After 45 min in the bedroom and living area, the wood structural elements in the ceiling assemblies began to contribute to the fire. However, since the fire involving the room contents was in the decay phase, the temperatures remained relatively steady and were comparable to the temperatures in the standard time-temperature curve. The fire severity was lower in the kitchen and entry area than in the living area during this period due to the nature and location of the fuel contents.

9.6.2.1.2 Apt CLT

In the CLT apartment test, the peak temperatures (1100 – 1200°C) were also sustained till 23 min in the bedroom. After 23 min, there was a general decrease in temperature until approximately 28 min followed by a temperature plateau with temperatures greater than 1000°C that lasted until 40 min. Subsequently, the temperatures in the bedroom decreased steadily until 128 min. In the living room/kitchen area, the peak temperatures were reached in 30-35 min, after which the temperatures also decreased steadily until 128 min. As shown in Figure 34, the ventilation condition through the exterior openings was unchanged until this time. The corridor door fell in at 128 min. This was followed by a further decrease in the temperatures until 175 min at which time there was an increase in temperature with the ignition of some of the CLT panels in the ceiling assembly. At the end of the test, the Type X gypsum board was still attached on most parts of the exposed surface of the ceiling and walls. The test was terminated at 185 min.

During the initial 48 min, the temperatures measured in the bedroom and the living area were higher than the standard time-temperature curve. As a result, the fire involving the room contents produced a more severe exposure to the room boundaries and the wood structure than is used for standard fire-resistance testing. The peak temperatures were reached later in the kitchen and entry area than in the living room area. After 48 min, the temperatures measured at all locations continuously decreased until near the end of the test when there were flames observed on some portions of the CLT ceiling. The fire severity in the CLT apartment test was less than the standard time-temperature curve during the later stages of the test (from 48 min to the end). Overall, the results indicate that the fire was contained within the room boundaries until the fire rated door failed at 128 min and that there was complete burnout of the fuel contents in the apartment.

9.6.2.1.3 Apt LSF

In the LSF apartment test, the peak temperatures of 1100 – 1200°C were sustained for a very short duration. At approximately 15 min, the bedroom temperatures started to decrease rapidly. This temperature decrease corresponded to a rapid increase in the temperature in the joist space in the bedroom, indicating that the calcination of the single layer of the gypsum board on the ceiling was complete by 15 min and there were increased thermal losses to the bedroom joist space. In addition, the ceiling gypsum board and the interior gypsum board on the exterior wall started to fall off at approximately 20 min, in both the bedroom and living room. In the living room/kitchen/entryway, the peak temperatures were reached at 26 min. As shown in Figure 34, by 26 min, the gypsum board on the ceiling and on the exterior wall and the exterior gypsum sheathing had completely fallen off in the bedroom and living room. The fully opened exterior wall created a large ventilation opening, which was three times the area of the original openings. This resulted in a very rapid burning of the room contents, which was followed by early decay in the temperatures within the apartment. Most of the fuel in the apartment had been consumed by this time. The test was terminated at 74 min.

During the initial 26 min, the temperatures measured in the bedroom and living area were higher than the standard time-temperature curve. As a result, the fire involving the room contents produced a more severe exposure to the room boundaries and the structure than is used for standard fire-resistance testing. However the duration of this high fire intensity was much shorter in the Apt LSF than in the Apt CLT and Apt LWF1 due to the dramatic change in ventilation conditions in Apt LSF. For the kitchen and the entryway area, the duration of high fire intensity was even shorter (10 min for the kitchen and 4 min for the entryway area). After 26 min, the temperatures in the bedroom continuously decreased until near the end of the test. The fire severity in the LSF apartment test was less than the standard time-temperature curve during the later stages of the test (after 26 min). Overall, the fire exposure or challenge to the Apt LSF was less severe than to the Apt CLT and Apt LWF1 because of the dramatic change of ventilation condition in Apt LSF.

9.6.2.1.4 Apt LWF2

The major difference between Apt LWF2 and Apt LWF1 was the gypsum board used on the interior (exposed) side of WB1 wall assembly. While the interior of WB1 in Apt LWF1 was encapsulated using two layers of 12.7 mm thick Type X gypsum board, only one layer of 12.7 mm thick regular gypsum board was used on the interior of WB1 in Apt LWF2. This was the same regular gypsum board that was used on the interior side of the WB1 wall assembly in Apt LSF (also the same gypsum board was used on the WA4 partition assemblies in all tests). The objective of using the single layer of regular gypsum board was to determine if, with less encapsulation, the exterior wall of the Apt LWF2 would be fully opened creating a similar ventilation condition and fire challenge to that observed in Apt LSF.

In the Apt LWF2 test, the peak temperatures (above 1000°C) were sustained till 24 min in the bedroom. After 24 min, there was a general decrease in temperature until approximately 35 min followed by a temperature plateau with temperatures greater than 900°C that lasted until

48 min. This temperature plateau after 35 min corresponded to the period during which the wood joists and OSB subfloor in the ceiling assembly were involved in the fire after the fall-off of the base layer of gypsum board on the ceiling. In the living room, the burning of the wood I-joists and the OSB subfloor in the ceiling assembly also occurred after 35 min after the fall-off of the base layer of gypsum board from the ceiling.

During the initial 35 min, the combustion of the room contents produced much higher temperatures in the bedroom and living room area than the standard time-temperature curve used in fire-resistance tests as shown in Figure 32. As a result, the fire involving the room contents produced a more severe exposure to the room boundaries and challenged the wood structure more aggressively than in a standard fire-resistance test during that period. The kitchen and the entryway area reached peak temperatures at close to 35 min, much later than the living room area. After 35 min, the wood structural elements in the ceiling assembly began to contribute to the fire, although the fire involving the room contents was in the decay phase.

Even with much less encapsulation, the exterior wall WB1 did not fully open/fail – the regular gypsum sheathing stayed on the exterior face of WB1 until the end of test, although the wood structural elements in the exterior wall began to burn after 20 min, when the single layer of the regular gypsum board fell off from the interior of WB1. As shown in Figure 34, with no change in the size of the openings in the exterior wall, the ventilation condition from the exterior openings was similar to that in Apt LWF1. This kept the heat inside the apartment resulting in a continued challenge to the ceiling structure. The loss of the encapsulation material on the exterior wall also provided another access for the fire to attack to the ceiling structure. The ceiling assembly collapsed at 48 min. Data was collected for 60 min. Overall, the fire exposure or challenge to the Apt LWF2 structure was greater than that experienced by Apt LWF1 and Apt LSF.

Figure 34. Ventilation conditions through the exterior openings during the large-scale apartment fire tests.

9.6.2.2 Heat Release Rate and Heat Flux from Fire

Table 24 shows the peak values for the heat release rate and heat flux in each test. Figure 35 to Figure 38 show the profiles measured during the tests.

9.6.2.2.1 Heat release rate

The measurement of the heat release rate (HRR) was based the oxygen depletion method using the large hood system mounted above the test setup. As shown in Figure 35, the heat release rates measured for the four apartment tests are similar at the early stage of the tests. The initial peak corresponded to the flashover in the bedroom at approximately 3 min then the HRR had a quick dip. As the fire developed in the bedroom and progressed into the living room area then the kitchen and entrance area, the HRR climbed to approximately 8 MW, which is the ventilation limit value based on the two openings. The HRR started to decline after 15 min. Depending on the test, the heat release rate started to increase again after a certain period, indicating that the fire grew again in the apartment. The time at which the fire re-grew in the apartment was 24 min in Apt LSF, 35 min in Apt LWF2, 45 min in Apt LWF1 and 175 min in Apt CLT.

For Apt LWF1, one of the three fans was not operating during the test; the two operating fans collected a portion of the smoke generated from the fire. The HRR for Apt LWF1 is estimated by scaling of the measurement by the two fans. Although the absolute heat release rate for Apt LWF1 was not measured, the times for various events are accurate and also confirmed by other measurements.

9.6.2.2.2 Heat flux to façade at 3.5 m above opening

Heat fluxes to the exterior façade were measured at 3.5 m above the top of the openings in the bedroom and living room, consistent with the location used for measuring heat fluxes in CAN/ULC S134 [21]. As shown in Figure 36, there was an initial peak in the heat flux from the flame that issued from the bedroom opening, corresponding to the flashover in the bedroom. The heat flux above the living room opening also quickly increased as the fire developed into the living room, with the initial peak heat flux being recorded approximately 3 min after the peak measured above the bedroom opening. The peak heat flux values were 26 kW/m^2 or lower in the Apt LWF1 and Apt CLT tests. This is well below the 35 kW/m^2 specified in the 2010 NBC for combustible components for exterior walls [5]. In the LSF test, the initial peak heat flux reached the maximum 35 kW/m^2 limit. Heat flux to the exterior façade was not measured in the Apt LWF2 test but flame spread on the façade was limited.

9.6.2.2.3 Heat flux at 2.4-m and 4.8-m distances

Heat fluxes were measured at 2.4 and 4.8 m away from the bedroom opening and from the living room opening, with heat flux transducers facing the centre of each opening.

As shown in Figure 37, there was a rapid increase in the heat fluxes measured at the target locations centered on the bedroom opening with flashover in the bedroom at approximately 3 min. After a brief dip, the heat flux at each distance increased to peak values. These peak heat flux values are comparable between the tests (23-28 kW/m^2 at the 2.4 m distance and 7-10 kW/m^2 at the 4.8 m distance) with Apt LWF2 at the high end and Apt LWF1 at the low end. After a period of decline, there was an increase again in the measured heat flux, corresponding to the burning of the wood elements in the ceiling assembly in Apt LWF1 and Apt LWF2 or the second growth of the fire in Apt LSF due to increased ventilation.

At the target locations in front of the living room opening, as shown in Figure 38, there was an initial heat flux measured as the flames projected from the bedroom opening. As the fire developed into the living room area and subsequently progressed to the kitchen and entrance area, there was a rapid increase in the heat flux with the flashover of the living room/kitchen area.

In the Apt LWF1 and Apt LWF2, the relatively steady heat fluxes measured for the living room opening are consistent with the progression of the fire from the living room to the kitchen and the eventual exposure and burning of the joists and subfloor. The peak heat flux was much higher in the Apt LSF test (33 kW/m^2 at the 2.4 m distance) than in the three apartment tests with wood structural elements (21-25 kW/m^2 at the 2.4 m distance). There was another increase in the measured heat flux, corresponding to the burning of the wood elements in the ceiling assembly in Apt LWF1 and Apt LWF2 or the second growth of the fire in Apt LSF due to increased ventilation.

Table 24. Peak Heat Flux and Heat Release Rate

Measurement	Location	CLT Apt	Apt LWF1	Apt LWF2	Apt LSF
Heat flux (kW/m^2) to façade at 3.5 m	Above bedroom opening	18	25	-	35
	Above living room opening	25	26	-	23
Heat flux (kW/m^2) to target at distance	2.4 m from bedroom opening	25	23	28	25
	2.4 m from living room opening	23	21	25	33
	4.8 m from bedroom opening	9	7	10	9
	4.8 m from living room opening	7	7	10	10
Heat release rate (MW)		8.4	8.0*	10.5	10.6

*estimated

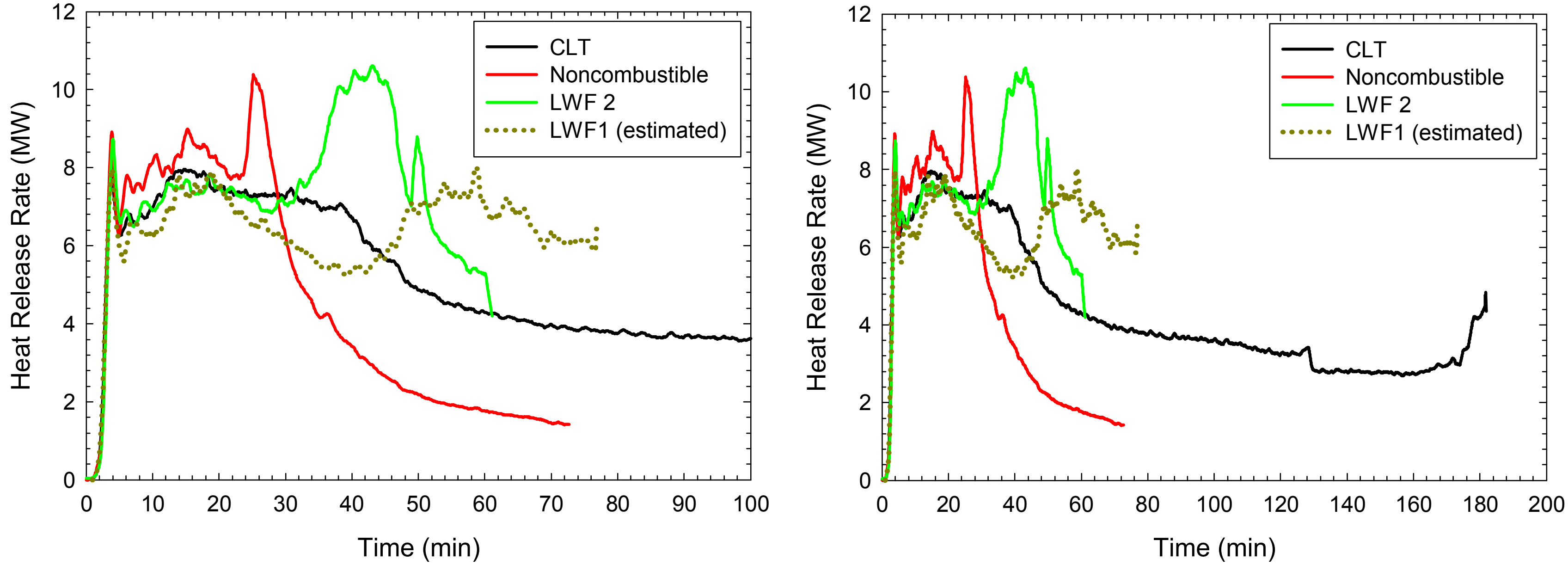

Figure 35. Heat release rate.

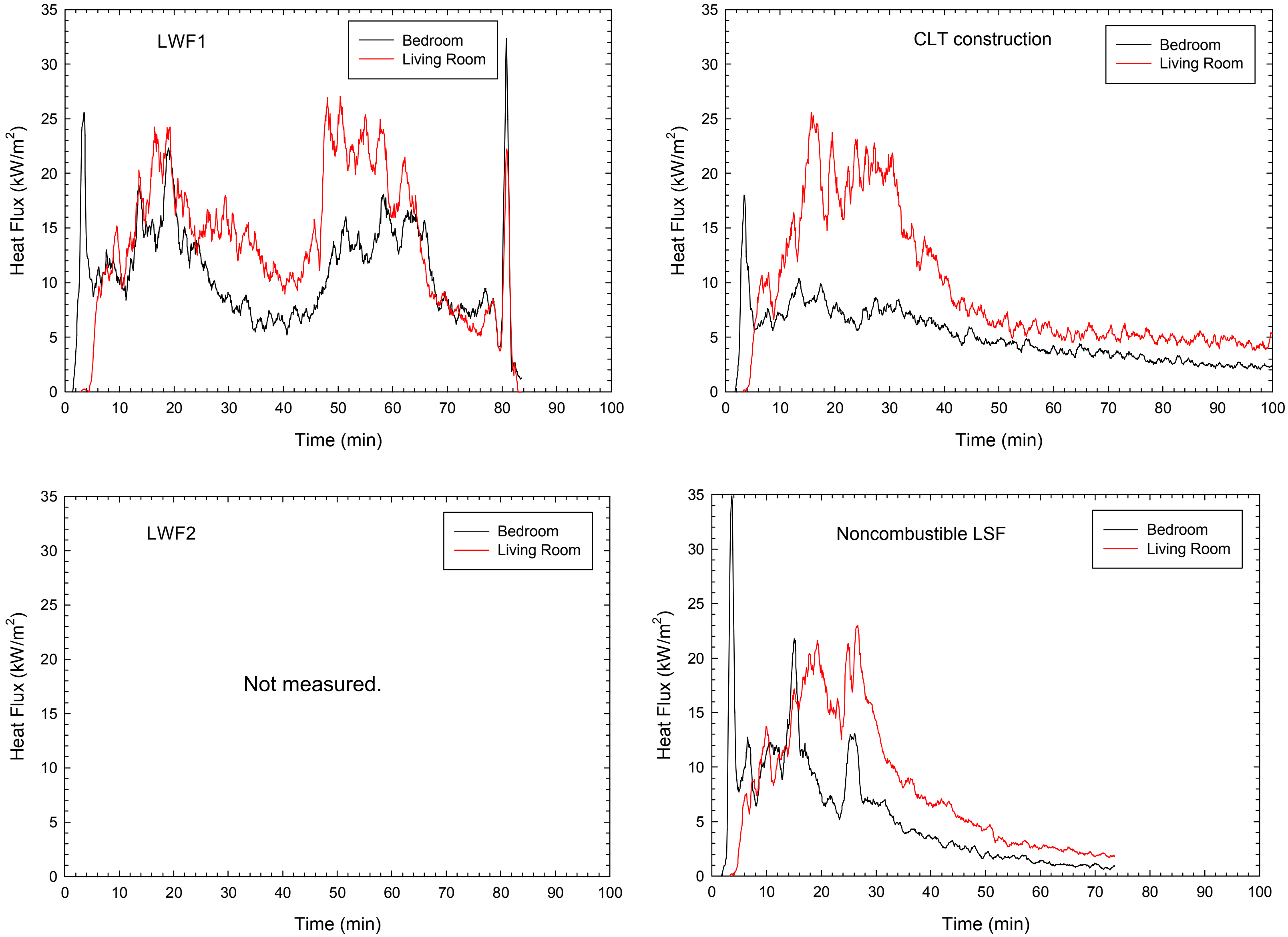

Figure 36. Heat flux from opening to façade.

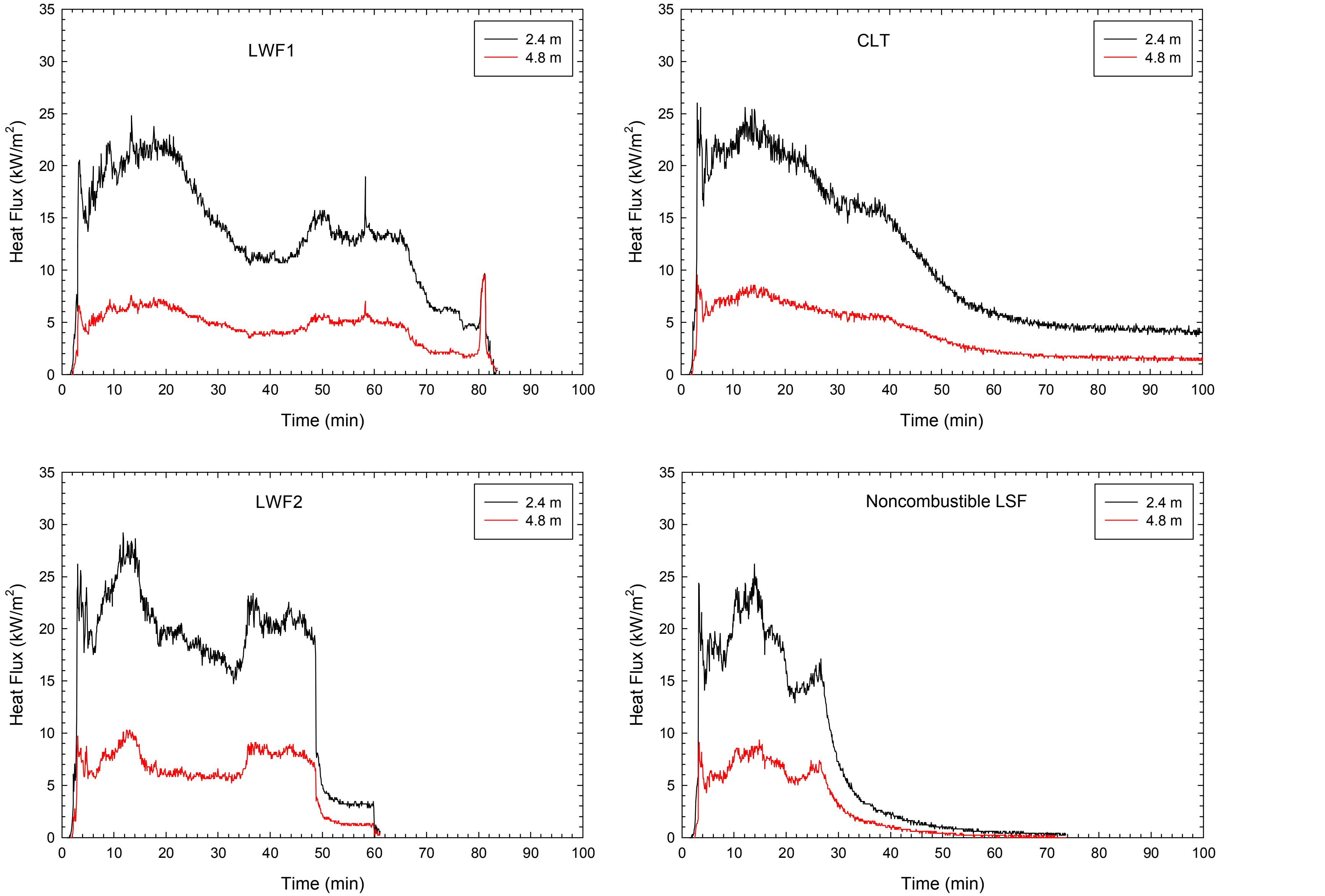

Figure 37. Heat flux from bedroom opening.

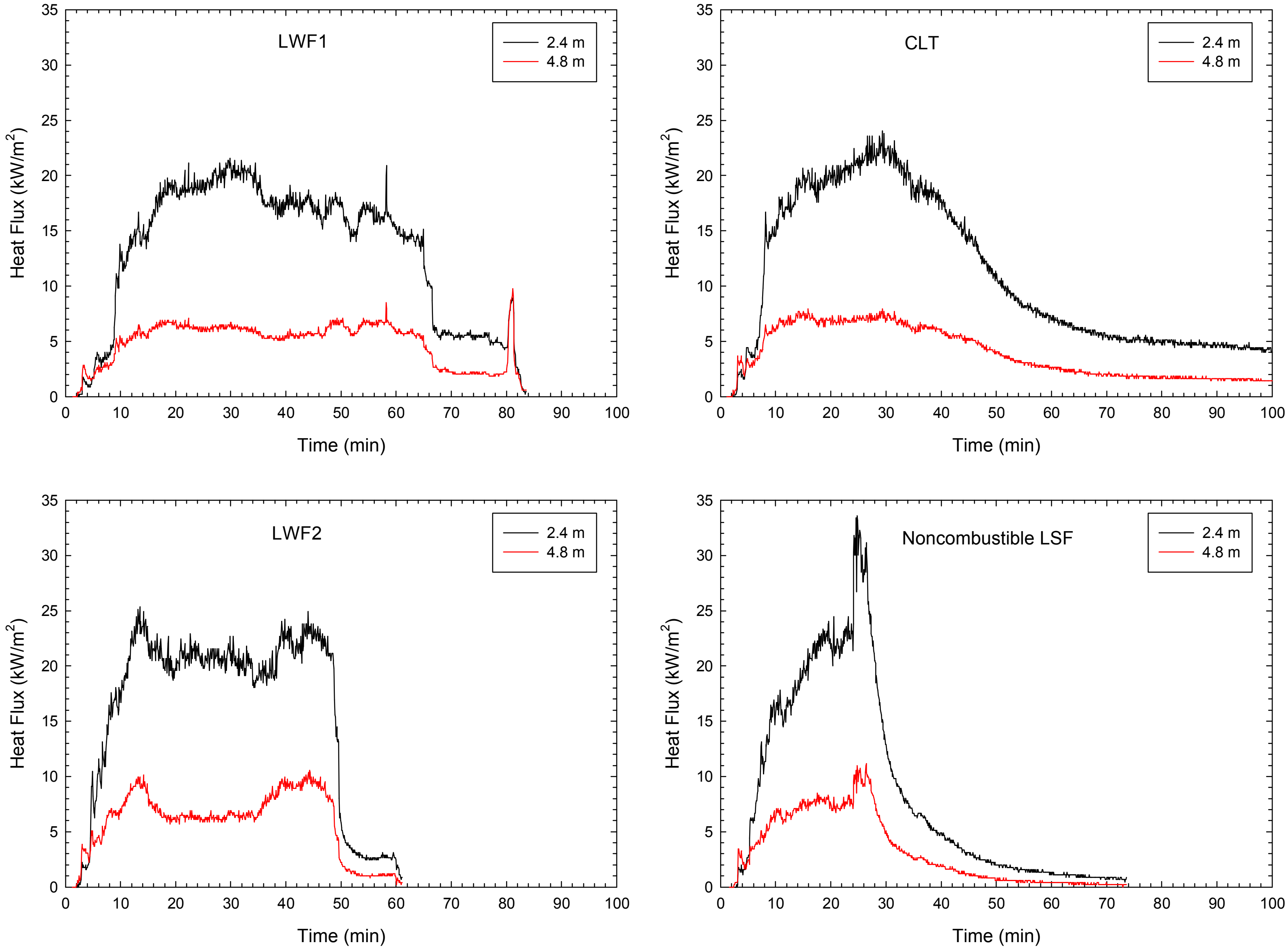

Figure 38. Heat flux from living room opening.

9.6.2.3 Reaction of Structural Assemblies to Fire

A primary objective of the tests was to investigate the protection (encapsulation time) provided for the structural elements by the encapsulation materials. For the three apartment tests with wood structural elements, the encapsulation times were determined using the European criteria (Criteria 3): the average temperature rise value over the exposed surface of the protected element is limited to 250ºC, and the maximum temperature rise value at any point on that surface does not exceed 270ºC. These criteria are based on a charring temperature for structural timber of approximately 300ºC [1, 42].

For the LSF test setup, the time to reach a specific temperature on the exposed surface of the protected steel elements was determined as a single point value and an average of multi-points. At high temperatures, both the yield and tensile strength of steel are reduced. In general, steel retains approximately 80% of its strength (at ambient conditions) at a temperature of 500°C, 50% at 600°C, 20% at 700°C and approximately 10% at a temperature of 800ºC [53].

The temperature profiles measured at various locations in the assemblies were used to determine the time required for the fire to penetrate the encapsulation material. Table 25 summarizes the times at which the temperature rise values exceeded the specific criteria for each assembly in each test.

9.6.2.3.1 Partition wall (WA4)

In all tests, the non-loadbearing interior partition between the bedroom and entrance/washroom were protected using one layer of 12.7 mm thick regular gypsum board on each side. The single layer of regular gypsum board provided very limited protection to the structural elements, in a range of 9-20 min; the partitions were breached at 13 to 21 min in all tests. Although WA4 is not required to be fire resistant, the breach of the partition posed a threat to the ceiling assembly in Apt LWF1, Apt LWF2 and Apt LSF. Measurements indicate that the temperatures in the ceiling cavities close to WA4 increased quicker than in ceiling cavities in other areas. The hot gases from the bedroom may have entered the ceiling cavities through the openings produced with the fall-off of the gypsum board on the partition wall. This indicates that the integrity and continuity of fire-resistance rated separations above a partition is critical to limit such breach.

9.6.2.3.2 Exterior wall (WB1)

All tests used one layer of 12.7 mm thick regular gypsum sheathing on the exterior (unexposed) side of the exterior wall WB1. The interior (exposed) side of WB1 was protected using two layers of 12.7 mm thick Type X gypsum board in Apt CLT and Apt LWF1, but used only one layer of 12.7 mm thick regular gypsum board in Apt LWF2 and Apt LSF.

During the test of Apt LWF1, the average temperature rise value measured over twelve measurement points in the wall cavities did not reach 250ºC. Based on the single point criterion, the encapsulation time for WB1 was greater than 57 min. The wood studs in WB1 did not contribute to the growth or spread of the fire. After 60 min, some charring of studs in limited areas in the cavity and burning in the lintel space occurred in the final stage of the test. Only two measurement locations exceeded 300°C at 80 min (with a maximum of 340°C and 370°C, respectively). The effective size of the ventilation openings remained unchanged since the gypsum board was still in place during this period.

Table 25. Time (min) to Reach Specified Value of Temperature or Temperature Rise (in cavities unless otherwise indicated*)

Assemblies	Test	CLT Apt		Apt LWF1		Apt LWF2		Apt LSF	
		average **ΔT=250°C**	single point **ΔT=270°C**	average **ΔT=250°C**	single point **ΔT=270°C**	average **ΔT=250°C**	single point **ΔT=270°C**	specified average **T** (°C)	specified single point **T** (°C)
WB1 bedroom Non-loadbearing exterior		44.8 GB/CLT	38.4 GB/CLT	DNR	65.1	21.5	21.3	21.9 (600°C) 25.2 (783°C)	16.2 (600°C) 19.5 (870°C)
WB1 living room Non-loadbearing exterior		42.2 GB/CLT	39.6 GB/CLT	DNR	57.3	19.5	20.2	24.0 (600°C) 26.2 (828°C)	19.8 (600°C) 22.4 (900°C)
WA1 Interior fire separation		87.0	65.7	DNR	DNR	DNR	DNR	(<300°C)	(<300°C)
WA2 bedroom interior fire separation (load-bearing)	*behind GB at stud or strap	33.1*	33.5*	46.7*	45.4*	37.9*	38.3*	33.4*(565°C)	33.4*(590°C)
	in cavities	67.6 99.2 strap/CLT	57.1 99.7 strap/CLT	DNR	71.9	DNR	52.8	(<390°C)	31.6 (500°C)
WA2 living room, interior fire separation (load-bearing)		65.1	38.3*	DNR	62.3	DNR	59.5	(<500°C)	(<500°C)
WA3 Load-bearing between bedroom (br) and living room (lr) area		38.8 GB/CLT br 46.6 GB/CLT lr	35.9 GB/CLT br 43.4 GB/CLT lr	74.7	73.5	40.6	33.6	25.8 (600°C) 30.0 (740°C)	22.5 (600°C) 29.2 (870°C)
WA4 Non-loadbearing partitions		13.5	13.3	20.8	20.8	9.1	10.5	14.7 (600°C) 16.0 (888°C)	14.3 (600°C) 17.2 (968°C)
Ceiling assembly bedroom	*above GB at exposed side of joist flange or CLT	68.6*	45.0* (27.8 center)	-	34.8*	-	26.2*	-	19.0*(600°C) 22.6*(860°C)
	in cavities	-	-	30.6	29.9	27.8	22.8	19.3 (600°C) 24.8 (700°C)	15.4 (600°C) 16.6 (900°C)
Ceiling assembly living room		54.6 GB/CLT	47.6 GB/CLT	46.8	42.1	33.7	31.5	26.0 (600°C) 28.3 (800°C)	22.9 (600°C) 26.3 (965°C)
Floor assembly bedroom	under CB or concrete	47.2 @CLT	35.9 @CLT (35.9-97.8)	DNR @OSB	78.7 @OSB	DNR @OSB	DNR @OSB	(<100°C)	(<100°C)
	in cavities	-	-	DNR	DNR	60+	60+	(<80°C)	(<80°C)
Floor assembly living room		-	-	DNR	DNR	60+	60+	(<80°C)	(<80°C)

CB – cement board GB – gypsum board DNR – Did not reach temperature rise criteria.
* This thermocouple may be in contact with gypsum board rather than in the cavity space.

Heat fluxes to the exterior façade were measured at 3.5 m above the top of the openings in the bedroom and living room, consistent with the location used for measuring heat fluxes in CAN/ULC S134 [21]. As shown in Figure 36, in the Apt LWF1, there was an initial 25 kW/m^2 peak in the heat flux from the flame from the bedroom opening, corresponding to the flashover in the bedroom. A peak value of 24 kW/m^2 was measured above the living room opening at a later time. There was a second peak after 45 min above both openings, with the heat flux from the living room being higher (26 kW/m^2), corresponding to the burning of the joists and the subfloor in the ceiling floor assembly. The heat fluxes were all below the 35 kW/m^2 as specified in the 2010 NBC [5] for combustible components for exterior walls. In addition, flame spread on the exterior wall façade was limited.

In Apt CLT, the 2 layers of gypsum board were directly attached to the interior side of the CLT wall panels with twelve thermocouples placed between the base layer of gypsum board and the CLT panels. The encapsulation time was 38-45 min. After that the interfacial temperatures reached 500°C at approximately 60 min and remained at these temperatures until the end of the test (185 min). Charring occurred on the interior side of the CLT panels.

Except for the lintel section, the exterior side of the CLT panels had no char due to the protection provided by the outboard insulation system. The CLT exterior wall panels did not contribute to the growth or spread of the fire. The effective size of the ventilation openings was unchanged throughout the test. Initial peak heat fluxes were 18 kW/m^2 and 25 kW/m^2 at 3.5 m above the openings of the bedroom and living room, respectively, then reduced to well below 10 kW/m^2.

In Apt LSF, the exterior WB1 wall had only a single layer of 12.7 mm thick regular gypsum board on the interior side. After 20 min, the gypsum board and gypsum sheathing started to fall off from both interior and exterior sides of the wall, respectively, resulting in an increasing effective size of ventilation openings. By 26 min, the effective ventilation openings tripled from the original size, drastically changing the ventilation conditions compared to those in the Apt LWF1 and Apt CLT tests. This resulted in a shorter fire challenge on the steel structure inside the apartment. Although WB1 was not designed to be a load bearing wall, it lost 50% of the steel strength at 600°C by 22 min and 90% of the strength at 800°C by 26 min. The initial peak heat flux was 35 kW/m^2 at 3.5 m above the bedroom opening. Subsequent peak fluxes were 22 kW/m^2 and 23 kW/m^2 above the openings of the bedroom and living room, respectively.

In Apt LWF2, the single layer of the regular gypsum board on the interior side of the exterior wall WB1 provided an encapsulation time of 20 min. The exterior façade did not open up although the wood elements in the exterior wall began to burn after 20 min – the regular gypsum sheathing stayed on the exterior of WB1 until the end of the test. The ventilation condition from the exterior openings was similar to that in Apt LWF1, but the reduced encapsulation for the exterior wall provided another path for the fire to attack into the ceiling structure. Heat flux to the exterior façade was not measured in this test, but flame spread on the façade was limited.

Like the WA4 partition, the fall-off of the single layer of the regular gypsum board on the interior side of the exterior wall WB1 posed a threat to the ceiling assembly in Apt LWF2 and Apt LSF. Measurements indicate that the temperatures in the ceiling cavities close to WB1 increased quicker or higher than in other areas. The hot gases from the bedroom may have entered the joist cavities through the openings produced with the fall-off of the gypsum board on the partition and exterior walls.

9.6.2.3.3 Fire separation walls (WA1)

Fire separation walls (WA1) between the apartment unit and the corridor were not affected by the fire at all in the Apt LWF1 and Apt LWF2 tests, neither the average nor any single-point temperature rise value exceeded the 250ºC or 270ºC limit. The maximum temperatures in the wall cavities were 220ºC and 100ºC or less in Apt LWF1 and Apt LWF2, respectively. In Apt CLT the wall (WA1) temperatures were measured within the cavities formed by the wood strapping with the insulation on the exposed side of the CLT. The encapsulation times, 66 min and 87 min, were based on the single and average temperature rise values in the cavities, respectively. The actual encapsulation time for the CLT wall panels would be greater than these values and there was no flaming combustion in the cavities before 130 min. Therefore, the three wood-based WA1 walls adjacent the corridor were not impacted by or involved in the fire and did not contribute to the growth and spread of fire, performing at least as well as the LSF WA1 wall adjacent the corridor.

9.6.2.3.4 Loadbearing fire separation walls (WA2)

For Apt LSF, based on the temperatures measured at the interface between the gypsum board and the steel studs in the bedroom, wall assembly WA2 lost more than 40% of the steel strength at 565°C at 33 min. The maximum temperature rise values measured using nine thermocouples covered with pads on the unexposed side of the LSF wall were 100ºC during the test.

For Apt LWF1 and Apt LWF2, in the LWF loadbearing fire separation walls (WA2) in both the bedroom and living room, the average temperature rise values did not exceed 250ºC in the wall cavities, the single point temperature rise value reached 270ºC in 62-72 min for Apt LWF1 and 53-60 min for Apt LWF2, indicating that the fire did not impact on the wood structural elements in the cavity areas for an extended time. Afterward, the single point temperature increased only slightly to 300°C.

Temperatures were also measured at each interface across the WA2 wall from its exposed to unexposed face at the centre in the bedroom. Figure 39 shows temperature profiles measured at various interfaces in the bedroom WA2 wall assembly at the mid-length and 1.2 m height.

The temperature rise values at the interface between the base layer gypsum board and the stud reached the 250°C and 270°C limits at 45 min in Apt LWF1 and at 38 min in Apt LWF2. Thus the studs would begin to char after this time due to direct heat transfer from the gypsum board to the studs, but the temperatures were below 500°C, which indicates no flaming combustion at the studs. Low temperatures were measured at the interfaces on the unexposed side of the WA2 wall, including the stud interface with the OSB shear layer (less than 90ºC), the interface between the OSB and gypsum board base layer (less than 60ºC) and the interface between the two layers of gypsum board (less than 50ºC). The temperatures measured using the nine thermocouples covered with pads on the unexposed side of the WA2 wall were 40 – 60ºC at the end of the test.

These results suggest that the fire did not affect the wood structural elements in the WA2 wall until after at least 45 min in Apt LWF1 and 38 min in Apt LWF2; the impact of the fire on the wood elements was limited on the gypsum board-stud interface with the direct heat transfer through the gypsum board into the studs. The WA2 wall assembly did not in any way contribute to the growth and spread of the fire.

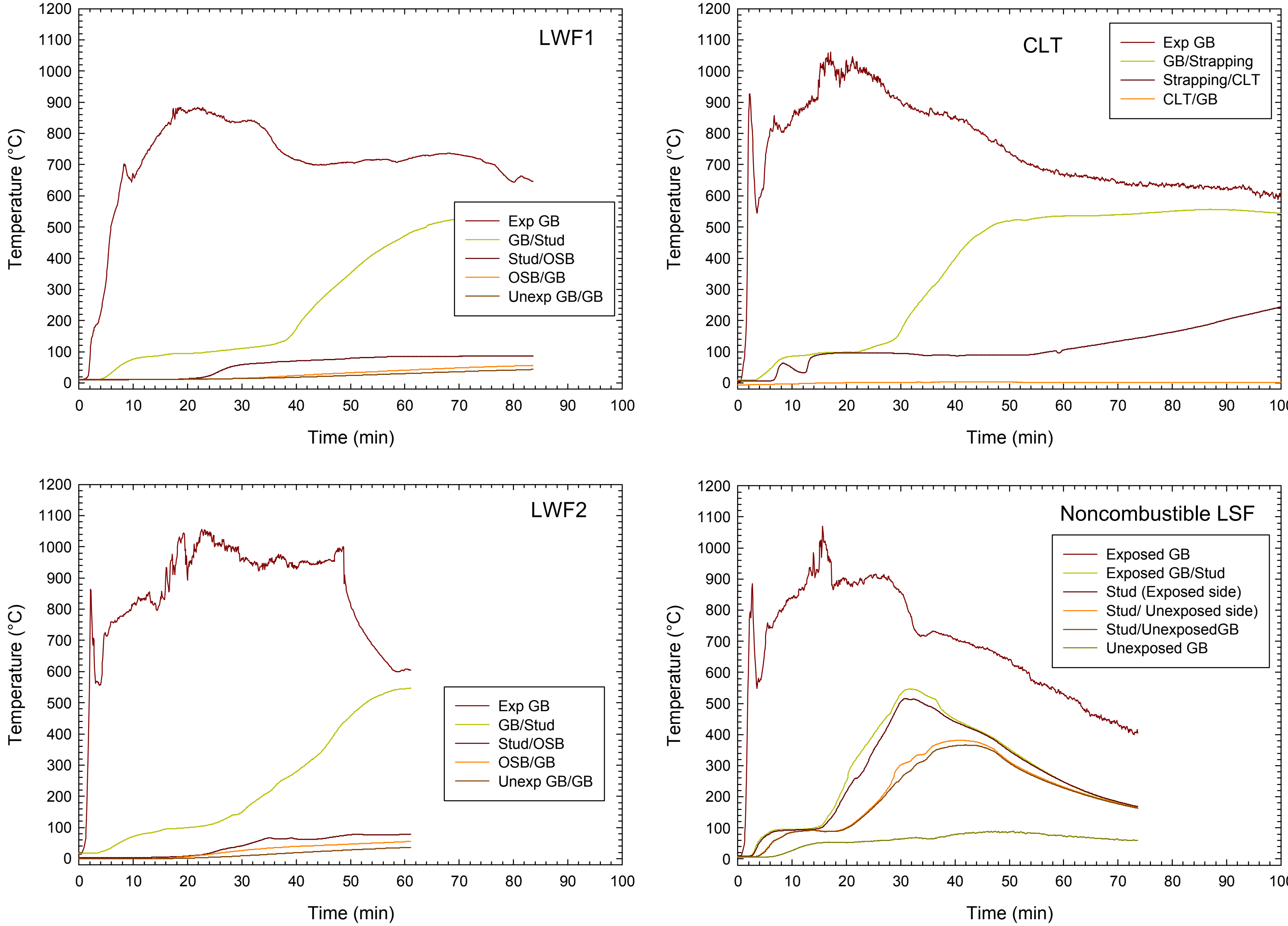

Figure 39. Temperatures at various interfaces in the bedroom WA2 wall assemblies (mid length, 1.2 m height).

For Apt CLT, the wall assembly WA2 was constructed with the CLT panels and the encapsulation times, based on the average temperature rise values measured in the cavities formed by the wood strapping with the cavity filled with insulation, were at least 65 min. The actual encapsulation time for the CLT wall panels would be greater. In fact, the encapsulation times based on the temperature rise values measured at the interface between the wood strapping and CLT panels in the bedroom were greater than 99 min.

In the WA2 wall cavities formed by the strapping close to the exterior wall in the living room of Apt CLT, there were a few localized hot spots with a shorter encapsulation time of 38 min. For 120 min, the insulated cavities had temperatures below 400°C and no flaming combustion. Flaming combustion occurred within the wood strapping cavities late in the test (beyond 130 min). The temperatures measured using the nine thermocouples covered with pads on the unexposed side of the CLT wall were 15ºC or below during the test. In general, the CLT Panels were not involved in and did not contribute to the growth and spread of fire until after 175 min.

9.6.2.3.5 Loadbearing wall (WA3)

The loadbearing wall WA3 between the bedroom and living room was generally more vulnerable to the fire than assemblies WA1 and WA2 because WA3 was exposed to fire from both sides and also connected to the non-loadbearing WA4 partition wall that was breached at 13 to 21 min in all tests. This was exacerbated in Apt LWF2 and Apt LSF where the single layer of the regular gypsum board had fallen off the interior side of the exterior wall WB1 after 20 min, providing the fire direct access to the wall cavities in WA3.

For Apt LSF, the temperatures in the wall WA3 cavities were well above 700°C by 30 min. At these temperatures, the steel would lose more than 80% of its strength.

For Apt LWF1, the encapsulation time based on the temperatures measured in the WA3 wall cavities was 74 min. The temperatures in the wall cavities were 130-240°C at 60 min at six measurement locations, and exceeded 300°C after 74 min near the end of the test, but no flaming combustion occurred in the cavities.

For Apt LWF2, the encapsulation time was 34-41 min, which is shorter than for Apt LWF1. There are two possible reasons for the shorter encapsulation time: the non-loadbearing partition WA4 was breached earlier (at 13 min) in Apt LWF2 and the single layer of the regular gypsum board fell off from the interior side of the exterior wall WB1 at approximately 20 min. As a result, the fire had earlier access to the wall cavities in WA3. However, there was no flaming combustion in the WA3 wall cavities (<600°C).

For Apt CLT, the double layer of the Type X gypsum board was directly attached to the CLT panels. The encapsulation time was 36 and 39 min based on the single point and the average temperature rise values measured between the gypsum board and the CLT on the bedroom side. The encapsulation time was 43 and 47 min for the single point and the average temperature rise values for the living room side of the wall. After the encapsulation time, the temperatures eventually reached a plateau of 550°C and remained at this temperature until the end of the test. This indicates that flaming combustion did not occur on the CLT panel in the area protected by the gypsum board.

9.6.2.3.6 Floor assembly of the fire floor

There were hardwood flooring, a double layer of 12.7 mm thick cement board as well as acoustic membranes, which were installed on top of the floor assembly in Apt LWF1, Apt LWF2 and Apt CLT. The hardwood flooring along with acoustic membrane was installed on the concrete subfloor of the floor assembly in Apt LSF.

In Apt LWF1, the OSB subfloor in the bedroom reached only 150ºC at 60 min and remained below 300ºC until 80 min. The encapsulation time provided to the OSB subfloor was more than 78 min based on the single point temperature rise value; the average temperature rise value on the OSB subfloor did not reach 250ºC during the test.

The temperature measured at the interface between the OSB subfloor and the floor joist at the centre of the bedroom had a gradual increase throughout the test to a maximum temperature of only 102ºC. The maximum temperatures in the floor joist cavities were 105ºC underneath the bedroom and much lower underneath the living room. The temperatures measured at the centre of the floor assembly at the interfaces between the bottom flange of the wood I-joist and the base layer of gypsum board, between the base and face layer of gypsum board, and on the unexposed face of the assembly had a temperature rise value of less than 5ºC above ambient.

In Apt LWF2, the OSB subfloor in the bedroom reached a maximum temperature of 200ºC during the test. The OSB subfloor and the floor structure below were fully protected by the encapsulation materials. Neither the single point nor the average temperature rise value on the OSB subfloor exceeded the encapsulation limits. The maximum temperatures in the floor joist cavities were below 60ºC.

The temperature results indicated that the LWF floor structural elements (subfloor and wood I-joists) were not affected by the fire during the tests and performed as well as the LSF floor structure in limiting the involvement of the structural materials in the fire and in limiting the contribution of the structural materials to the growth and spread of fire.

In Apt CLT, the encapsulation time for the CLT floor panels was 36 min, based on the single point temperature rise value, and 47 min based on the average temperature rise value, at the interface between the base layer cement board and the CLT panels. (This is shorter than the encapsulation time determined for the same system in the LWF apartment tests. The reason for the difference is not known but needs to be investigated.) The maximum temperatures at the interface at different locations were 400-500ºC after 60 min or later, which then declined until the end of the test. The CLT surface ply charred but there was no flaming combustion. This indicated that the CLT did not contribute to the growth and spread of fire.

In Apt LSF, the temperatures were below 100ºC underneath the concrete subfloor and below 80ºC in the cavities of the floor assembly during the test.

Figure 40 shows some exemplar temperature profiles measured at various interfaces in the bedroom floor assemblies.

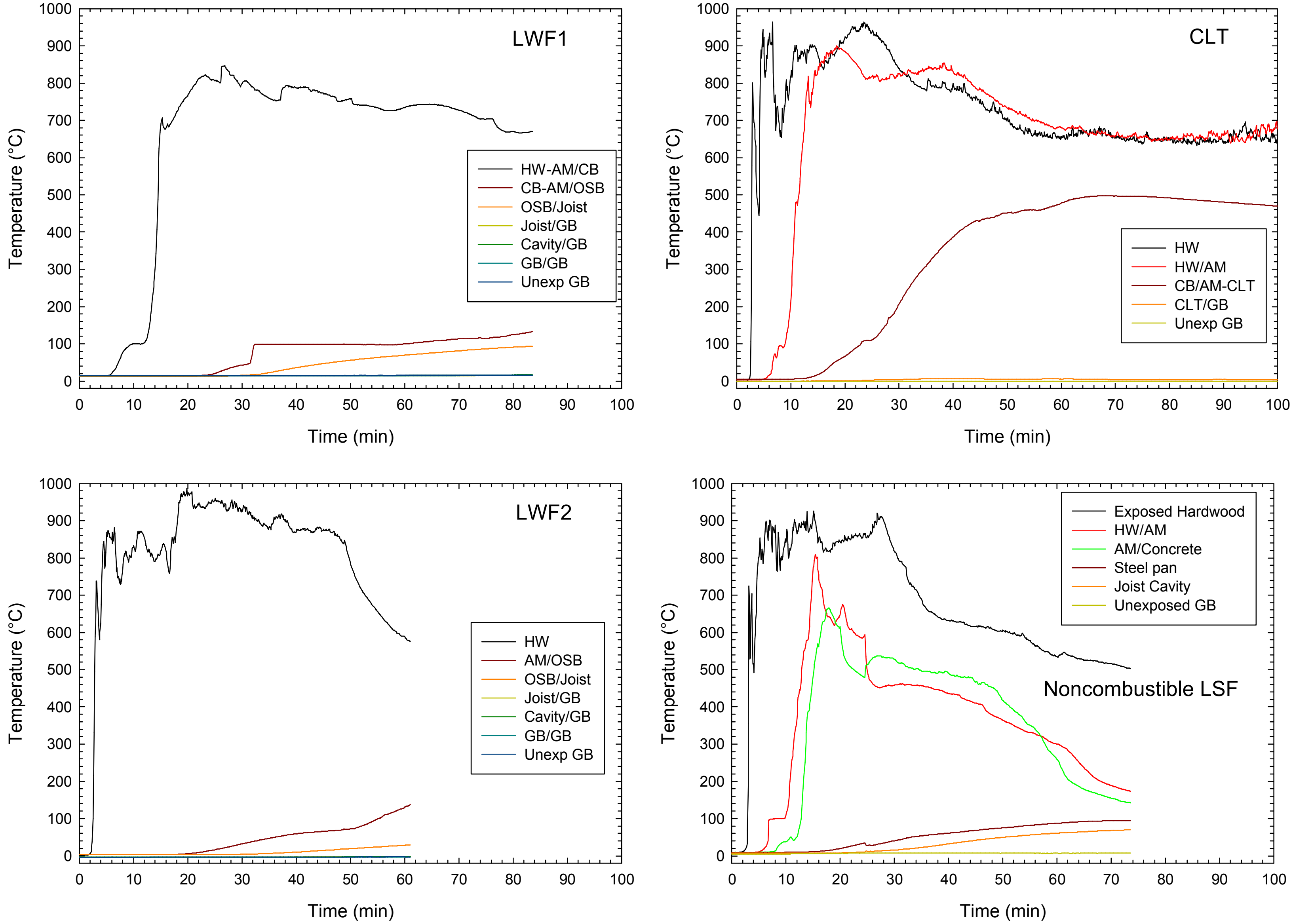

Figure 40. Temperatures at various interfaces in the bedroom floor assemblies.

9.6.2.3.7 Ceiling assembly of the fire floor

Two layers of 12.7 mm thick Type X gypsum board were used to encapsulate the ceiling assembly on the exposed side in the three test setups with the wood structural systems. The gypsum board was applied with resilient channels on the wood I-joists in Apt LWF1 and Apt LWF2, but directly applied to the CLT panels in Apt CLT. The steel joist ceiling assembly in Apt LSF was protected using one layer of 12.7 mm Type X gypsum board on the exposed side, in accordance with UL Design No. G534.

Temperatures were measured at various locations in the ceiling assemblies to determine the time required for the fire to penetrate the encapsulation materials and for heat transfer through the assemblies. These thermocouples were installed: in the floor joist cavities or between the CLT panels and encapsulation materials; at each interface across the ceiling assemblies from the exposed to unexposed side (bedroom only); on the unexposed side (top) of the ceiling assemblies.

Figure 41 to Figure 45 show the temperature profiles measured in the cavities and at various interfaces of the ceiling assemblies, along with the temperatures in the fire compartment at the ceiling height (2.4 m height) during the large-scale apartment tests.

LSF ceiling assembly

The temperature profiles indicate that calcination of the gypsum board on the ceiling was complete by approximately 11-14 min in the bedroom and 14-24 min in the living room, depending on the location. Subsequently, there was a rapid increase in temperature on the ceiling joists and in the joist cavities. At most measurement locations, the rapid increase of temperature at the joists and in the ceiling cavities coincided with the decrease in room temperature indicating heat losses from the fire compartment to the ceiling assemblies (heat was also transferred to the wall assemblies). Sustained temperatures above 600°C were measured in the ceiling cavity and on the steel joists from 15 to 30 min in the bedroom and from 22 to 42 min in the living room/kitchen area.

The average temperature in the bedroom ceiling cavities exceeded 600°C at 19 min and 700°C at 25 min while the single point temperature in the southeast joist cavity exceeded 600°C at 15 min and reached 900°C at 17 min. The cavity temperatures in the east side of the bedroom increased more rapidly than in the west side.

The average cavity temperature in the living room and kitchen area exceeded 600ºC at 26 min and 800ºC at 28 min. The single point temperature in the living room ceiling cavities exceeded 600ºC at 23 min and reached 965ºC at 26 min. The temperatures in the ceiling cavities of the living room area increased more rapidly than in the kitchen area. In addition, sustained temperatures above 800ºC and peak temperatures above 900ºC were measured in the cavity space on the East side of the living room/kitchen area.

The temperature measured at the gypsum board-steel joist interface and at the bottom of the joist at the centre of the bedroom ceiling assembly reached 800ºC at 20 min and a peak of 900ºC at 24 min. Steel joist temperatures measured at other locations were comparable to the temperature measured in the surrounding area. The temperature profile measured at the top of the joist was comparable to the ceiling cavity temperature profile. The top of the joists reached a temperature greater than 700ºC.

The temperatures measured on the unexposed side of the ceiling assembly using the thermocouples covered with pads were up to 166ºC, and the maximum temperatures measured on the third storey was 97ºC.

At elevated temperatures, the mechanical properties of steel deteriorate; both the yield and tensile strength of steel are reduced. Curves showing the strength reduction for steel are provided in Reference [53]. In general, steel retains approximately 50% of its strength at ambient conditions at a temperature of 600°C, 20% at 700°C, 10% at 800ºC, and less than 7% at 900°C.

Overall, the steel joists were exposed to temperatures of 700-900ºC for up to 15 min during the experiment. Had the exterior ventilation openings remained the same in size, the high temperature exposure to the steel joists would have been sustained much longer. However, the interior gypsum board on the exterior wall started to fall off at 19 min and the exterior gypsum sheathing started to lose small pieces at 21 min. By 26 min, the interior gypsum board and the exterior gypsum sheathing had completely fallen off the exterior wall — the entire exterior wall evolved to a huge ventilation opening (three times the original opening size). This introduced a large amount of fresh air into the fire compartment and resulted in a quicker fuel consumption leading to earlier fire decay in the apartment. Therefore, the high-intensity fire challenge to the LSF ceiling assembly was much shorter and less severe than to the three wood ceiling assemblies as the results of the dramatic change of ventilation in Apt LSF.

The LSF joists in the ceiling assembly were weakened significantly as indicated by the high temperatures measured on the steel and in the joist cavities and the sagging (100 mm) during the fire test. Post-fire observation of the unexposed side of the ceiling assembly (i.e. the third storey floor) indicated no warning signs of a weakened structure.

LWF1 ceiling assembly

The encapsulation time provided by the two layers of 12.7 mm thick Type X gypsum board for the ceiling assembly varied depending on the measurement location. Among the nine thermocouples located in the bedroom joist cavities, the earliest times to reach a temperature rise value of 270ºC were in the southeast and south center joist cavities. Based on the single point temperature rise value in the southeast cavity, the encapsulation time was 30 min. The thermocouples in these cavity locations were close to the non-loadbearing partition wall WA4, which was encapsulated using a single layer of regular gypsum board. Since the fire breached the WA4 wall by 24 min, the hot gases from the bedroom may have entered the joist cavities through the openings produced by the fall-off of the gypsum board on the partition wall. The temperatures in these bedroom ceiling cavities (southeast and south center) increased rapidly to 800 – 900ºC at 30 min. The time to reach the average temperature rise value of 250ºC in all locations was dominated by the measurements at these two locations. Other than the southeast and south-center thermocouples, the temperatures at the other 7 ceiling cavity locations were approximately 100ºC for more than 40 min. The time at which the temperature rise value reached 270ºC at the other 7 thermocouple locations was between 44 and 54 min.

The temperature rise value at the interface between the resilient channel and the joist exceeded 270°C at 35 min providing an estimate for the encapsulation time for the two layers of 12.7 mm thick Type X gypsum board and the resilient channel. This encapsulation time is comparable to the encapsulation time determined using one of the nine thermocouple measurements in the ceiling cavities (30 min, southeast).

The face layer of ceiling gypsum board started to fall off after 35 min and the base layer of ceiling gypsum board started to fall off after 43 min. The ceiling joist cavity was directly exposed to the fire after 45 min and the wood I-joists and subfloor started to contribute to the fire.

For the nine thermocouples located in the joist cavities in the living room and kitchen area, the time at which the temperature rise value reached 270ºC at the thermocouple locations was between 42 and 56 min. The earliest times to reach a temperature rise value of 270ºC were in the joist cavity space close to the window opening. Based on the single point temperature rise value in the northeast joist cavity, the encapsulation time was 42 min, which is 12 min longer than that in the bedroom — a further indication that the non-encapsulated partition wall WA4 weakened the encapsulation performance of the bedroom ceiling assembly. The time to reach the average temperature rise value of 250ºC in all living/kitchen cavity locations was 47 min. The temperatures measured in all ceiling cavities in the living/kitchen area were below 100ºC for more than 41 min. The base layer of ceiling gypsum board started to fall off at 45 min. The ceiling joist cavity was exposed directly to the fire after 48 min and the wood I-joists and subfloor started to contribute to the fire.

The temperatures measured on the unexposed side (top) of the ceiling assembly using the thermocouples covered with the pads were 107ºC or lower in the bedroom and living room area. The maximum room temperatures measured on the third storey was 40ºC at 58 min, after which the ceiling assembly collapsed at 58.3 min.

Depending on the location, the encapsulation time for the ceiling assemblies in Apt LWF1 was 30-47 min. Prior to this, the wood structural elements (wood I-joists and OSB subfloor) were not affected at all by the fire. The wood I-joists and OSB subfloor in the ceiling assemblies did not contribute to the fire until after 45 min.

For comparison, the steel joists for the ceiling assemblies in Apt LSF reached temperatures of 700-900ºC within 16-28 min. At these elevated temperatures, steel retains only 7% to 20% or less of its structural strength.

LWF2 ceiling assembly

The temperatures measured at the interface between the ceiling face and base layers of the gypsum board indicated that the face layer of gypsum board started to fall off at approximately 18 min. The encapsulation time provided by the two layers of 12.7 mm Type X gypsum board varied depending on the location of the thermocouple. The shortest time was 23 min based on the single-point temperature rise value measured in the southeast joist cavity, while the encapsulation time based on the average of the 9 thermocouples in the ceiling joist cavities was 28 min. The latter is comparable to the encapsulation time of 26 min determined using the measurements at the interface between the resilient channel and the joist at the centre of the bedroom ceiling assembly. Subsequently, temperatures in the joist cavities in the bedroom increased rapidly and the base layer of gypsum board started to fall off.

The temperature generally increased earlier in the bedroom ceiling joist cavities than those measured in the Apt LWF1 test. There was also no transition period before the rapid temperature increase phase, as normally occurred with heat transfer through gypsum board. The thermocouples located at the southeast and center-east cavities were close to the partition wall WA4 and the hot gases may have entered the joist cavities around the header of the breached WA4 partition. In addition, there may have been hot air leakage into the joist space cavity once the fire penetrated into the exterior wall cavity space.

The temperatures in the bedroom joist cavity exceeded 700ºC between 30 and 36 min depending on the location, indicating the fire had penetrated into the joist space. The wood structural elements — the wood I-joists and OSB subfloor — in the ceiling assembly began to be involved in, and contribute to, the fire in the bedroom after 35 min. Steady temperatures above 800ºC were sustained until approximately 48 min at which time the ceiling assembly collapsed.

The encapsulation time for the two layers of gypsum board used on the ceiling in the living room/kitchen was 32 min based on temperatures measured in the joist cavity. This was the earliest time to reach a temperature rise value of 270ºC at the thermocouple location on the East side of the living room at its mid-length. The encapsulation time based on the average temperature rise value measured at the nine thermocouple locations was 34 min. There was a rapid increase in temperatures in the joist cavities from 32 to 40 min, indicating falloff of the base layer of gypsum board at various ceiling locations. The temperatures in the joist cavities exceeded 700ºC between 34 and 41 min, depending on locations (first at the mid-length of the living area; last at the West side of the kitchen). The wood structural elements — the wood I-joists and OSB subfloor — in the ceiling assembly began to be involved in, and contribute to, the fire in the living room after 35 min. The temperatures subsequently increased to peak temperatures above 900ºC. After 48 min, the temperatures decreased with the collapse of the ceiling assembly.

The encapsulation times at various ceiling locations (23 to 34 min) were shorter in Apt LWF2 than in Apt LWF1. The interior side of the exterior WB1 wall was lined using one layer of 12.7 mm thick regular gypsum board in Apt LWF2 but was encapsulated using two layers of 12.7 mm thick Type X gypsum board in Apt LWF1. The exterior wall WB1 in Apt LWF2 was penetrated by the fire after 20 min and consequently created another access route for the fire to enter the ceiling cavities through the WB1 wall cavities. This was the reason that the encapsulation times for the ceiling structures were shorter in Apt LWF2 than in Apt LWF1.

The encapsulation times in test LWF2 are longer than the protection times provided to the ceiling assemblies in Apt LSF, where the steel joists were exposed to temperatures of 700ºC to over 900ºC within 16-28 min. At these elevated temperatures, steel retains only 7% to 20%or less of its strength. (The interior side of WB1 in Apt LSF was also lined with the same single layer of the regular gypsum.)

CLT ceiling assembly

The CLT ceiling panels were protected using the two layers of 12.7 mm thick Type X gypsum board directly attached to the CLT. The encapsulation time for the ceiling assemblies varied depending on the measurement location. The shortest time was 28 min at the centre of the bedroom ceiling assembly, based on the temperature rise value of 270°C at the interface between the base layer of gypsum board and the CLT. This encapsulation time is considerably shorter than at other locations in the ceiling assembly. There were another nine thermocouples installed at the gypsum board-CLT interface in the bedroom ceiling assembly. The encapsulation time was 45.0 min based on a single point temperature rise value of 270°C at the Southeast quarter point of the ceiling. The average temperature rise value of 250°C was reached at 69 min.

The encapsulation time for the CLT ceiling assembly in the living room was 48 min based on a single point temperature rise value of 270°C at the centre at the North end of the living room (close to the window opening). The average temperature rise value of 250°C was reached at 55 min.

After calcination of the gypsum board, the temperatures at the gypsum board-CLT interface continued to slowly increase. In the bedroom, the temperatures at the gypsum board-CLT interface remained below 500ºC until the end of the test, except for the central area of the ceiling, since the gypsum board stayed on most ceiling area until the end of the test. This indicates that there was minimal or no flaming combustion on the ceiling panels in the bedroom. In the living room, the gypsum board also stayed on most of the ceiling area until the end of the test; the maximum temperature at the gypsum board-CLT interface was 500°C or lower until 170 min, except for the area along the North-South centerline. It was also observed that the base layer of gypsum board remained in place in most areas until near the end of the test. These results suggest that the heat losses to the thicker CLT panels used for the ceiling assembly played a significant role in the performance of the gypsum board encapsulation material.

Peak temperatures above 600°C were measured at the gypsum board-CLT interface along the North- South centerline in the living room, indicating flaming combustion on the CLT ceiling panels. After 170 min, visible flames were observed on the CLT panels along the centerline of the living room, which soon spread to the entire ceiling. The test was terminated at 185 min with the fire extinguished by the local fire department using water hose streams.

The temperature rise values measured on the unexposed side of the CLT panels and at various interfaces on the unexposed side were less than 10°C, indicating minimal heat transfer through the CLT ceiling panels. The maximum temperature rise value in the space on the third storey was 15°C. Overall, the results suggest that heat losses to the CLT in the ceiling assembly improved the performance of the gypsum board. Further investigations are required to quantify the effect of the thickness of the CLT on the encapsulation time, the temperatures at the interface between the encapsulation material and the CLT, and the fall-off of the encapsulation material.

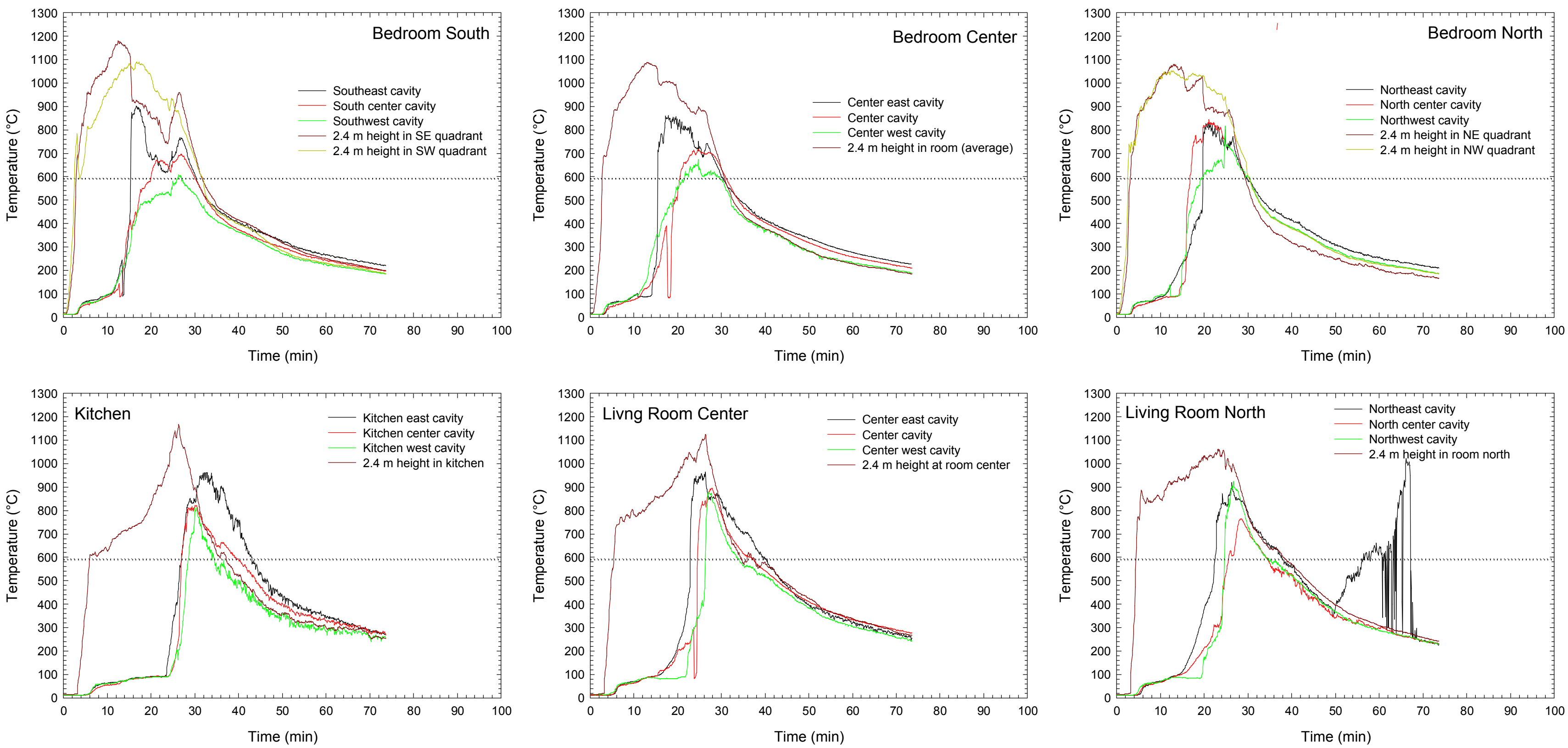

Figure 41. Temperatures in ceiling cavities versus temperatures in fire compartment at the 2.4 m height during Test Apt LSF.

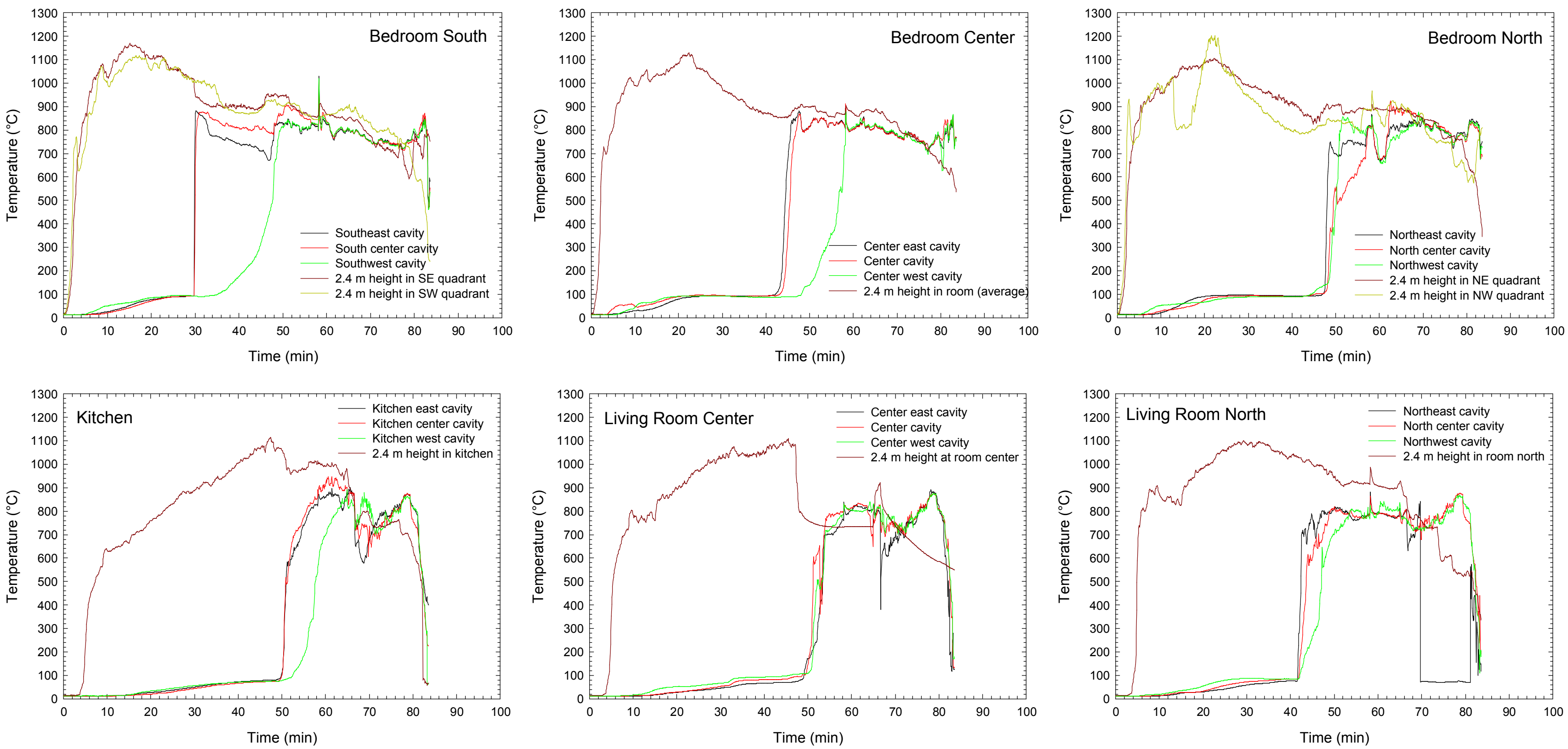

Figure 42. Temperatures in ceiling cavities versus temperatures in fire compartment at the 2.4 m height during Test Apt LWF1.

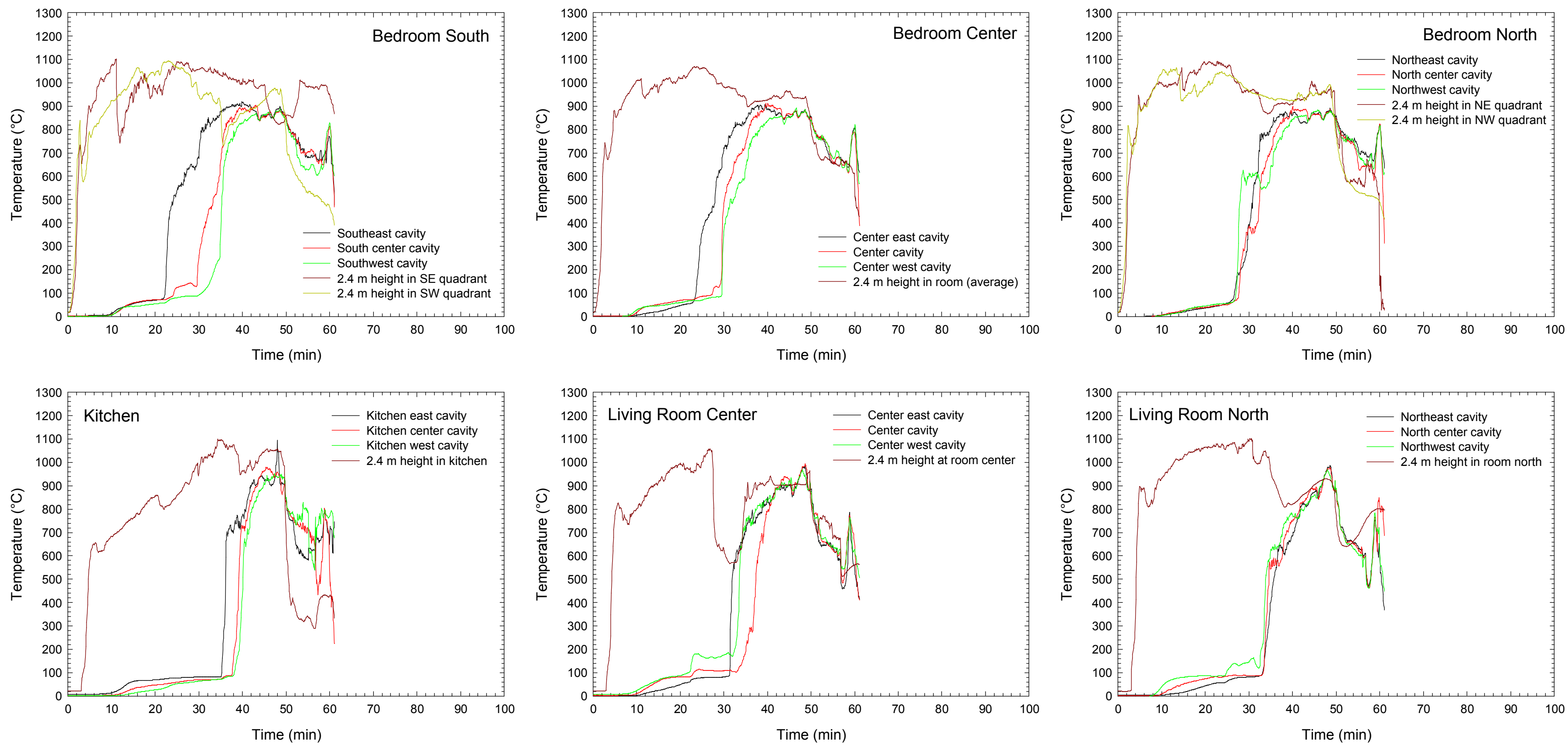

Figure 43. Temperatures in ceiling cavities versus temperatures in fire compartment at the 2.4 m height during Test Apt LWF2.

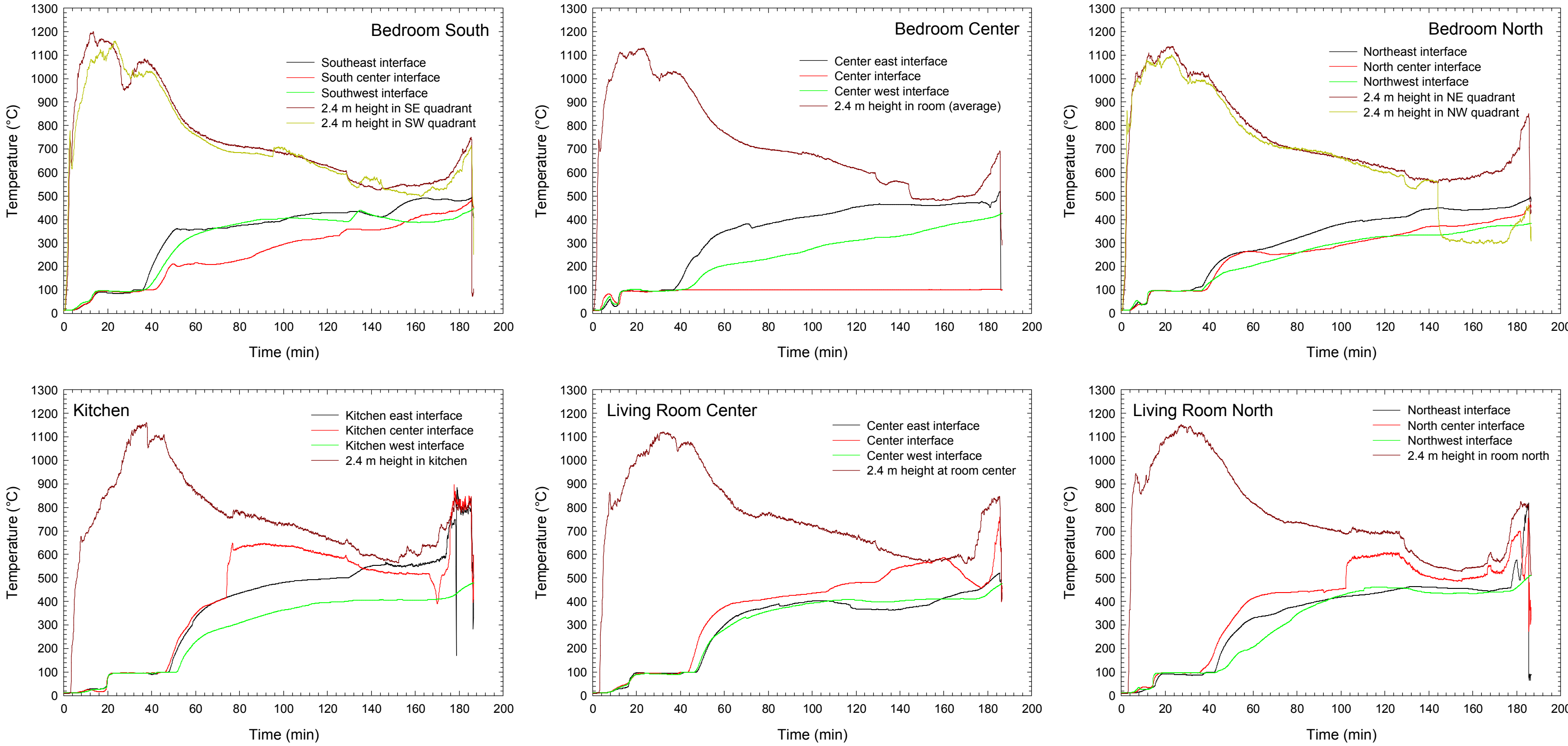

Figure 44. Temperatures at the interface between gypsum board and CLT in the ceiling assemblies versus temperatures in fire compartment at the 2.4 m height during Test Apt CLT.

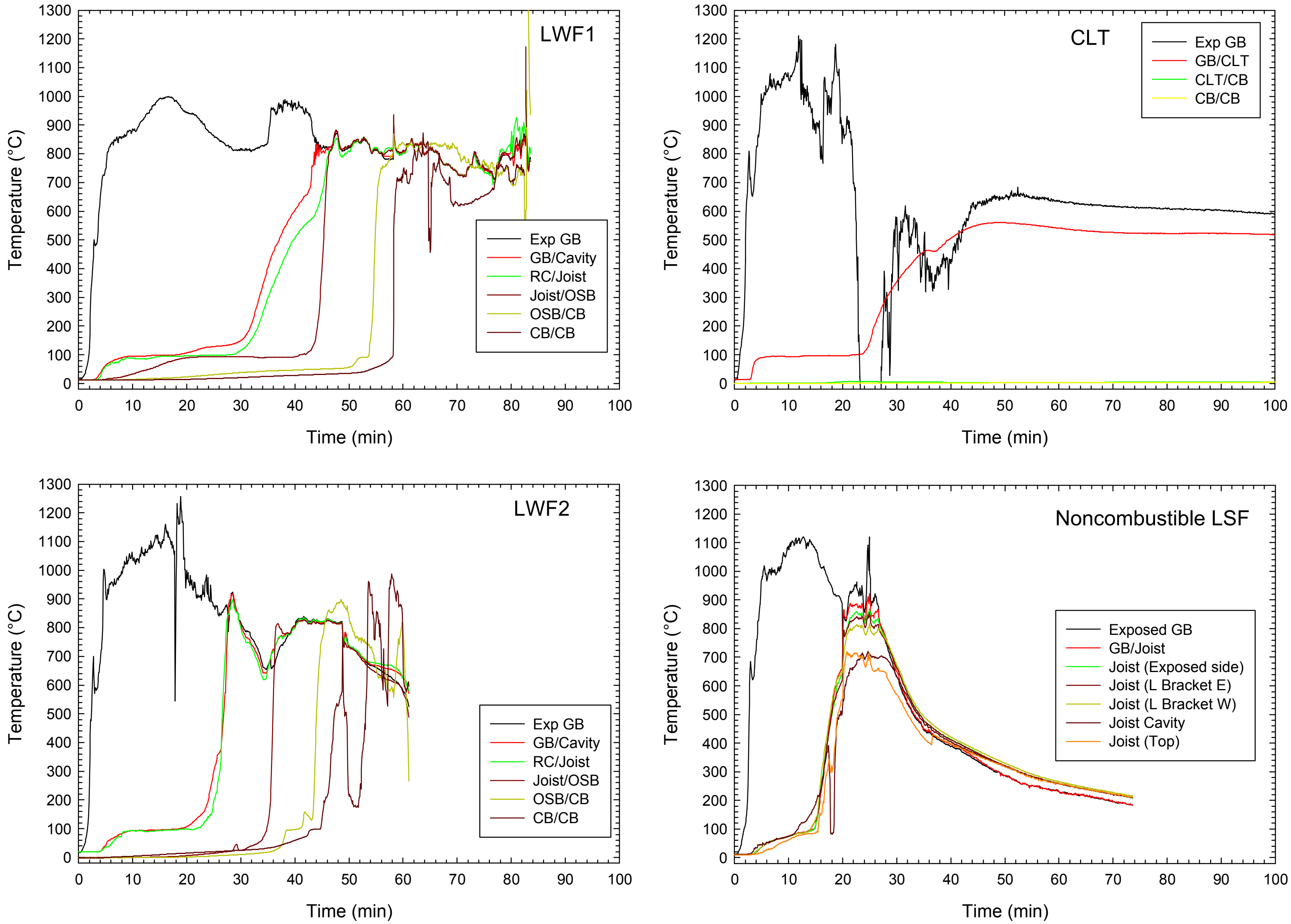

Figure 45. Temperatures at various interfaces at the centre in the bedroom ceiling assemblies.

9.6.3 Comparison with Intermediate-Scale Tests with Non-standard Fire Exposure

The times to reach the temperature rise value of 250ºC (single point) or 270ºC (average) at various interfaces in the bedroom ceiling and WA2 wall assemblies are compared with the results from the intermediate-scale furnace tests with the non-standard fire exposure. Table 26 shows the comparison of the encapsulation times determined from the full-scale apartment tests and the intermediate-scale tests (the single point or average temperature rise values, whichever occurred first, are used). The non-standard time-temperature curve used the Intermediate scale tests was the same as the PRF-03 curve shown in Figure 32. The time-temperature curves in the bedroom of the test apartments are also shown in Figure 32.

Table 26. Encapsulation times from large-scale apartment tests and intermediate-scale furnace tests (non-standard fire).

Type X Gypsum Board		Large-Scale Apt. Test average ΔT=250°C or single point ΔT=270°C at interface			Intermediate-Scale Test average ΔT=250°C or single point ΔT=270°C at interface	
Thickness (mm)	Layers	Test	Bedroom Ceiling (min)	Bedroom Wall WA2 (min)	Test	(min)
12.7	1	LWF1	16.8	16.1	#11	16.3
12.7	1	LWF2	16.0	18.4	#11	16.3
12.7	1	CLT	15.0	15.8	#11	16.3
12.7	1	LSF	14.2		#11	16.3
15.9	1	LSF		19.3	#10	20.3
12.7	2	LWF1	34.8	45.4	#11	35.2
12.7	2	CLT	27.8	33.1	#11	35.2
12.7	2	LWF2	26.2	37.9	#11	35.2

The encapsulation times for a single layer of 12.7 mm thick Type X gypsum board determined based on the full-scale tests were between 14 and 18 min. These values are comparable to the 16 min for the encapsulation time determined in the intermediate-scale test with the non- standard fire exposure.

For 15.9 mm thick Type X gypsum board, an encapsulation time was determined in the bedroom wall in Apt LSF. The value, 19 min, is comparable to the 20 min result based on the intermediate-scale tests.

There was considerable variation in the encapsulation times determined for the 2 layers of 12.7 mm thick Type X gypsum board based on the full-scale tests, with the results between

26 and 45 min compared with the 35 min for the intermediate-scale test with the non-standard time-temperature exposure.

Some of the variation was due to changes in the test arrangement with the apartment tests, which resulted in an increased fire exposure to the bedroom boundaries in the bedroom than in the tests in Reference [45]. The other critical factor was the fall-off time of the gypsum board face layer, which varied from test-to-test.

Considering the test-to-test differences in the fire exposures in the large-scale apartment tests and the variation in the fall-off time for the gypsum board face layer, the encapsulation times based on the intermediate-scale tests were representative of the large-scale results.

9.6.4 Summary of Large-Scale Apartment Fire Tests

The large scale apartment fire tests demonstrated the effectiveness of the encapsulation approach in delaying the time at which the wood structural elements were affected by and eventually contributed to the fire, if at all. Results show that, with encapsulation, the three test apartments constructed using wood structural elements provided the level of fire performance that meets the NBC intent statement assigned to the noncombustible construction requirement in limiting the involvement of the structural elements in fire and in limiting the contribution of the structural elements to the growth and spread of fire.

9.6.4.1 Apt LSF

The exterior wall WB1 started to lose the gypsum board and sheathing at 20 min. The interior gypsum board and exterior gypsum sheathing completely fell off the WB1 steel framing by 26 min. The fully opened exterior wall created a large ventilation opening, which was three times the original opening size. This resulted in a very rapid fire growth with accelerated burning of the room contents followed by early decay of fire in the apartment. As shown in Figure 35, the heat release increased rapidly at 24 min from 8 MW to over 10 MW. The steel studs were fully exposed to the fire and reached 800°C at 26 min. Although WB1 was not designed to be a load bearing wall, the steel studs would lose 90% of the strength at this time.

The breach of the partition wall WA4 (at 15 min) and the exterior wall WB1 (at 20 min) posed a threat to the ceiling assembly and the loadbearing wall WA3, providing the fire direct access to the wall and ceiling cavities. The temperatures in the WA3 cavities were well above 700°C by 30 min, temperatures at which the steel studs could lose more than 80% of their strength.

The steel joists for the ceiling assemblies reached temperatures of 700-900ºC within 16-28 min. At these elevated temperatures, steel retains approximately only 7% to 20% or less of its strength. Although the LSF joists in the ceiling assembly were weakened significantly during the fire test, there was no warning sign of a weakened structure based on post-fire observation of the unexposed side of the ceiling assembly (i.e. the third storey floor).

In summary, the steel studs in walls WB1 and WA3 and the steel joists in the ceiling assemblies were significantly impacted by the fire with more than 80% loss of the steel strength within 30 min. The response of the steel structure contributed to the rapid fire growth and potential for fire spread at 24 min.

9.6.4.2 Apt LWF1

The floor structural elements (subfloor and wood I-joists) below the fire floor were not affected by the fire during the test. The wall assemblies WA1, WA2 and WA3, as well as WB1, did not in any way contribute to the growth and spread of the fire. There was limited impact on the wood studs at the gypsum board-stud interface on the exposed (fire) side after 45 min; charring started to occur at the gypsum board-stud interface with direct heat transfer through the gypsum board into the studs, but there was no flaming combustion of the studs at any time.

The shortest encapsulation time occurred in the ceiling assembly in the bedroom (30 min). Prior to this time, the ceiling structural elements were not affected at all by the fire. Measurements indicated that the non-encapsulated partition wall WA4 decreased the encapsulation performance for the bedroom ceiling assembly, since hot gases gained direct access to the ceiling cavities through the breached partition wall WA4. This suggests that a systematic encapsulation approach would work better than assembly encapsulation. The wood I-joists and OSB subfloor in the ceiling assemblies started to contribute to the fire growth in the fire compartment after 45 min. As shown in Figure 35 to Figure 38, the fire growth due to the involvement of the wood joists and OSB subfloor in the fire led to the increase of the heat release rate and heat fluxes to the façade and adjacent structures.

The LWF1 test structure performed at least as well as the LSF structure. The structural materials were not affected by the fire for more than 30 min and the contribution of the structural materials to the growth and spread of fire was limited until after 45 min.

9.6.4.3 Apt LWF2

The floor structural elements (subfloor and wood I-joists) below the fire floor were not affected by the fire during the test. The wall assemblies WA1 and WA2 did not contribute to the growth and spread of the fire. There was limited impact on the wood studs at the gypsum board-stud interface on the exposed (fire) side until after 38 min; charring started to occur at the gypsum board-stud interface with the direct heat transfer through the gypsum board into the studs, but there was no flaming combustion of the studs at any time.

The loadbearing wall WA3 was not affected by the fire for at least 34 min, after which time there was charring of the studs but there was no flaming combustion in the WA3 cavities. The assembly WA3 did not contribute to the growth or spread of the fire at any time.

In general, WA3 was more vulnerable to a fire than WA1 and WA2 because WA3 was exposed to the fire from both sides and was also connected to the non-encapsulated partition wall WA4 (breached at 13 min). This was further exacerbated when the interior single layer of regular gypsum board fell off from the exterior wall WB1 after 20 min and the fire had direct access to the WA3 stud cavities at two locations. Although the encapsulation time for WA3 was shorter in Apt LWF2 than in Apt LWF1, this time was still longer than the time for the steel studs in the WA3 wall to reach well above 700°C (in 30 min) and lose more than 80% of the steel strength.

Flame spread on the façade of the exterior wall WB1 was limited. Unlike the Apt LSF test, the gypsum sheathing on the exterior façade stayed in place during the entire test and the size of the ventilation openings remained unchanged, although the wood elements in the exterior wall began to burn after 20 min. The reduced encapsulation for the interior side of the exterior wall provided a path to the ceiling joist cavities for the fire to attack the ceiling structure.

The encapsulation time based on the average temperature rise value of 250ºC was 28 min in the bedroom ceiling joist cavities and 34 min in the living room ceiling cavities. The shortest time was 23 min based on the single-point temperature rise value of 270ºC measured in the southeast joist cavity, which was close to the non-encapsulated partition wall WA4, which was breached prior to this time. The wood I-joists and OSB subfloor in the ceiling assemblies began to be involved in, and contribute to, the fire after 35 min. Figure 35 shows that the heat release rate started to increase after 35 min, which is approximately 10 min later than in the steel test.

The temperatures increased earlier in the ceiling joist cavities than in the Apt LWF1 test because hot gases were able to directly access the joist cavities once the fire penetrated the non-encapsulated WA4 partition (at 13 min) and WB1 exterior walls. Nevertheless, these encapsulation times (23-34 min) for the LWF2 ceiling assemblies are still longer than the corresponding times for the steel ceiling assemblies (see Table 25) to reach temperatures of 700ºC to over 900ºC (15-28 min). At these temperatures, steel would retain only 7% to 20% or less of its strength.

Therefore, the LWF2 test structure performed as well as the LSF structure in limiting the involvement of the structural materials in fire and in limiting the contribution of the structural materials to the growth and spread of fire.

The results suggest that encapsulation should be addressed using a systematic approach, ensuring the junctions between encapsulated and non-encapsulated assemblies are not the weak points for fire penetration or simply encapsulating the whole system. This approach should also apply to other systems designed for fire protection using encapsulation (e.g. lightweight steel systems).

9.6.4.4 Apt CLT

With the wood strapping and insulation combined with the double layer of 12.7 mm thick Type X gypsum board on the exposed side of WA1 and WA2, the encapsulation times for the CLT wall panels were at least 65 min and up to 99 min. During this time, the CLT panels were not affected by the fire. The loadbearing wall WA3 was more vulnerable to the fire than wall assemblies WA1 and WA2 because WA3 was exposed to the fire from both sides and did not include the insulation system; the average encapsulation time was 39-47 min after which there was charring of the CLT panels. The interior (exposed) side of the exterior wall WB1 was fully protected for 38-45 min after which there was charring on the interior side of the CLT panels. The exterior side of the CLT panels of WB1 had no charring (except for the small lintel section above the window) due to the protection provided by the outboard insulation system. None of the CLT wall assemblies, WA1, WA2, WA3 and WB1, contributed to fire growth or spread until after 175 min.

The encapsulation time for the CLT floor panels was 36-47 min (This is shorter than the encapsulation time determined for the same encapsulation system in the LWF apartment tests. The reason is unknown but needs to be investigated.). Subsequently, the CLT surface ply started to develop char but there was no flaming combustion since the maximum temperatures at the CLT surface were only 400-500ºC during the test. This indicated that the CLT did not contribute to the growth and spread of fire.

The time to reach the average temperature rise value of 250°C was greater than 55 min at the CLT ceiling panels on the exposed side of the ceiling assemblies, although there were a few hot spots that occurred earlier. However, there was minimal or no flaming combustion on the ceiling CLT panels until 170 min. After 170 min, visible flames were observed on the CLT panels along the centerline of the living room, which soon spread to the entire ceiling leading to a new phase of fire growth in the apartment.

The CLT test structure performed better than the LSF structure in limiting the involvement of the structural materials in fire and in limiting the contribution of the structural materials to the growth and spread of fire.

10 FURTHER INVESTIGATIONS NEEDED

The performance of encapsulation systems attached to strapping needs further investigation. For the CLT wall assemblies WA1 and WA2, with the cavities formed by the 38 mm x 38 mm wood strapping and filled with insulation on the exposed side, extended encapsulation times were determined using the temperature measurements in the cavity spaces formed by the strapping (more than 57 min). The initial effects of the fire on the assemblies were at the interface between the base layer of gypsum board and the strapping. Longer times were required before the temperatures in the cavities would affect the CLT structural elements. These results suggest that encapsulation systems with the encapsulation layer separated from the structural element should be investigated as a method of improving encapsulation times. This could also apply to the lightweight structural systems.

The combination of the hardwood flooring and the two layers of cement board provided only a 36 min encapsulation time for the CLT floor assembly below the fire floor, based on the single point temperature rise value between the base layer cement board and the CLT floor panels. But the same combination provided much longer encapsulation time (more than 79 min) for the LWF floor assemblies in the Apt LWF1 and Apt LWF2 tests. In the lightweight wood frame assemblies, the structural floor elements were not affected by the fire. The reason for the difference is not known but needs to be investigated.

The Type X gypsum board encapsulation system performed very well in the CLT test. The gypsum board stayed in place on most surface areas until the end of the test (180 min). The results suggest that heat losses to the CLT in the ceiling assembly improved the performance of the gypsum board. Further investigations are required to quantify the effect of the thickness of the CLT on the encapsulation time, the temperatures at the interface between the encapsulation material and the CLT and the fall-off of the encapsulation material.

Tests with encapsulation materials conducted with a cone calorimeter indicated that once the interface temperature between the encapsulation material and the wood substrate exceeded the ignition temperature for the wood materials, flaming combustion would occur on the exposed surface of the encapsulation material [32, 33]. This phenomenon may also have occurred in the full-scale apartment test. However, it is not possible to ascertain the extent and effect of this process based on the results of the apartment tests. The results from other projects need to be reviewed to determine if this process needs to be further investigated and the potential impacts quantified.

The test results for the two LWF apartment tests indicated that that the use of a single layer of regular gypsum board on the partition wall WA4 (as well as the non-encapsulated exterior WB1 in Apt LWF2) affected the encapsulation for the LWF ceiling assembly in the bedroom. Once the fire penetrated through the regular gypsum board on the walls, hot gases had direct access to the ceiling cavities through the cavities of the WA4 wall assembly (and WB1 in Apt LWF2). This suggests that encapsulation should be addressed at the system level rather than at the assembly level, ensuring the junctions between assemblies are not a weak point for fire penetration. The other option is to provide the same level of encapsulation for all assemblies. This issue also applies to lightweight steel systems.

11 CONCLUSIONS

The fire research activities conducted under the mid-rise research project investigated the encapsulation approach to protect the combustible structural elements to develop information to be used as the basis for alternative/acceptable solutions to meet the NBC fire safety requirements for mid-rise buildings (5- and 6-storey) using wood structural elements. Bench-, intermediate- and large-scale apartment fire experiments were conducted to evaluate the encapsulation approach. The experimental results have demonstrated the effectiveness of the encapsulation approach in delaying the time at which the wood structural elements are affected by and eventually contribute to the growth and spread of fire, if at all.

The LWF test structures performed at least as well as the LSF structure (a code-conforming solution) in limiting the involvement of the structural materials in the fire. None of the LWF floor assemblies below the fire floor or the loadbearing wall assemblies were affected by, or contributed to, the fire during the tests. The wood structural elements in the ceiling/floor assembly above the fire floor did not contribute to the growth and spread of the fire until after 45 min in the Apt LWF1 test and 35 min in the Apt LWF2 test. This was well after the failure of the encapsulation system that protected the steel structural elements in the ceiling/floor assembly in the LSF test. It was also after the time at which the exterior wall assembly was breached in the LSF test, resulting in a rapid increase in the fire size in the LSF apartment with the increased ventilation to the fire.

The LWF apartment test results suggest that encapsulation should be addressed using a system approach, ensuring the junctions between the assemblies do not become the weak points for fire penetration. This system approach should also apply to lightweight steel systems.

The CLT apartment fire test lasted for nearly 3 hours. After approximately 40 min when the furniture and room contents in the test apartment had been consumed, there was a continuous decay of the fire. As such, the compartmentation provided by the CLT structural assemblies allowed complete burn out of the apartment contents.

None of the CLT panels contributed to fire growth or spread until after 175 min. After 170 min, visible flames were observed on the CLT panels along the centerline of the living room. The flames soon spread to the entire ceiling. The CLT test structure performed better than the LSF structure in limiting the involvement of the structural materials in fire and in limiting the contribution of the structural materials to the growth and spread of fire.

The encapsulation times determined using the intermediate-scale furnace tests provided reasonable representation of the encapsulation times determined based on full-scale furnace and large-scale apartment tests. Therefore, the intermediate-scale tests can be used as a tool for screening the performance of encapsulation materials.

The research developed generic wood-based exterior wall assemblies with the wood elements and insulation material protected using noncombustible or low-combustible materials and/or fire retardant panels to limit exterior fire spread. The CAN/ULC-S134 tests conducted for this project demonstrated that a range of generic exterior wall systems can be constructed using LWF and CLT structural elements that meet the NBC requirements of limiting fire spread on the exterior surface (Sentences 3.1.5.5.(3) and 3.1.5.5.(4) in Division B of the 2010 NBC). The generic wood-based exterior wall assemblies also met the building envelope performance required by the NBC.

The research developed six generic staggered-stud wall assemblies for high structural load applications in mid-rise (5-6 storeys) wood buildings, with the fire endurance periods of 75–98 min. These wall assemblies meet the NBC requirements for fire resistance and acoustic ratings for mid-rise buildings.

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