NRC·CNRC

A Literature Review of the Fire Performance of Floor Assemblies Commonly used in Houses

Volume: Research Report
Report No.: A1-018027
Date: 9 December, 2022
Authors: Alex Bwalya, Joseph Su, Noureddine Bénichou

Construction Research Centre

National Research Council Canada
Conseil national de recherches Canada

Canada

Cat. No. NR24-110/1-2022E-PDF

ISBN 978-0-660-45799-4

Summary

A Joint Task Group (JTG) was established to address a request from the Canadian Commission on Building and Fire Codes (CCBFC) to determine the minimum level of structural performance for floor assemblies in houses. In support of the JTG, this report summarizes the results of the Phase 1 of the Fire Performance of Houses (FPH) Project that was conducted at the NRC and a literature review conducted recently on other related research and North American regulatory developments. The literature review covered more than 50 fire experiments (excluding the 16 tests conducted at NRC for the FPH) that have been conducted with floor assemblies constructed with dimensional lumber joists and five main types of engineered joists: wood I-joists, steel C-joists, metal-plate connected wood truss, finger jointed (glued) wood truss and metal-webbed truss. The tests reviewed were grouped into two main categories: standard and non-standard, defined by the type of fire exposure. Non-standard tests seek to simulate actual compartment fires using combustible fuel loads and the tests are typically conducted on structures that are constructed with representative construction materials. Non-standard tests also included tests that are conducted in fire resistance furnaces without following the CAN/ULC-S101/ASTM E119 temperature-time exposure. Such non-standard tests usually attempt to simulate temperature conditions that are consistent with compartment fires. Although many of the non-standard compartment tests were very well instrumented for temperature, heat flux and gas concentration measurements, only the tests conducted at NRC included a detailed tenability analysis along with a review of evacuation from typical single family houses in the event of a fire.

NRC Fire Performance of Houses (FPH) Research

The FPH research developed a wealth of information on the fire performance of a range of engineered floor systems, constructed with wood I-joists, steel C-joists, metal-plate and metal-webbed wood trusses, under fire scenarios (i.e., door to the basement open or closed) where the joists were either unprotected or protected. The safety of emergency responders to fires originating in single-family houses was outside the scope of this research project.

The FPH research found that the fire endurance (focusing on time to structural failure) for the unprotected engineered floor assemblies tested was 35-60% shorter than that for the unprotected dimensional lumber assemblies and that the failure of the unprotected floor assemblies in the fire scenarios used did not appear to be the critical issue affecting occupant life safety since the tenability limits were reached before the structural failure of the test floor assemblies occurred in all but one experiment. In that experiment (door closed), tenability limits on both the 1st and 2nd storeys were in fact reached prior to structural failure of the unprotected metal-webbed wood truss assembly. For the tests with unprotected floor assemblies that were conducted with the basement door open, the time to structure failure ranged from 5 min 25 s (metal-webbed wood truss assembly) to 12 min 20s (dimensional lumber assembly). Closing the basement doorway extended the time to structure failure for the three assemblies tested since the lower ventilation reduced the intensity of the fire. Under this scenario, the times to structure failure for the dimensional lumber,

metal-webbed wood truss and wood I-joist increased by 7 min 40 s, 2 min 29 s and 4 min 48 s, respectively. It was also concluded that an early alert to a fire was important in ensuring occupant life safety. The smoke alarm located in the basement compartment consistently took 30-50 s to activate. The experimental results highlighted the importance of the National Building Code of Canada (NBC) requirements for interconnected smoke alarms in houses.

In six experiments with the floor assemblies protected with either a 12.7 mm regular gypsum board ceiling or ceiling tiles, the period during which tenable conditions were maintained was similar to or slightly improved compared to that obtained in the experiments with unprotected assemblies. However, only the five assemblies with a gypsum board ceiling exhibited a significant improvement in the structural fire endurance, for instance the dimensional lumber assemblies improved by 9 min 40 s while the lowest performing unprotected assembly (metal-webbed wood truss) achieved the highest improvement of 18 min 19 s.

For the experiments with residential sprinkler-protected assemblies, the residential sprinkler systems protected the structural integrity of the test assemblies by effectively suppressing the fire. There was no ignition of the floor assemblies and structural failure did not occur during the experiments, while the tenability conditions remained viable throughout the experiments.

A study of evacuation times found that the required safe escape times (RSET), for a single family two-storey house, varied from minimum of approximately 2 min to a maximum of about 16 min 10 s based on the information that was available at the time of the study. The wide range in the RSET numbers is largely due to the effect of parameters such as the characteristics of each person, the building design features and the fire scenario.

Literature Review

The non-standard tests reviewed demonstrated that one of the key variables that had a strong influence on the structural fire endurance for identical assemblies was the superimposed live load that was applied to the test assemblies. Other variables in non-standard compartment fire tests included ventilation conditions and the fire load (quantity and composition), which created differences in fire severity. In addition, there were also variables associated with construction materials, such as the sub-floor and floor finish. The results showed that unprotected dimensional lumber assemblies exhibited a wide range of failure times, from about 6 min under high loading to about 20 min under lower loads and less severe fire conditions. For unprotected floor assemblies with engineered floor assemblies, the range of failure times were as follows (live load is given in parenthesis):

- Steel C-joist assemblies: 2.6 min (265 kg/m^2) to 8.3 min (139 kg/m^2)
- Wood I-joist assemblies: 4.7 min (151 kg/m^2) to 12.9 min (97 kg/m^2)
- Trusses (mostly metal-plate connected wood): 3.5 min (139 kg/m^2) to 6 min (139 kg/m^2)

The addition of a 12.7-mm regular gypsum ceiling to protect the assemblies resulted in a significant increase in the structural fire endurance for all assemblies, extending the failure time by as much as 10 min in many cases. For all of the tests in which a protective ceiling membrane (single layer) was installed, the failure times ranged from 13.1 min to 44.8 min (for a truss assembly), with other assemblies, including dimensional lumber, having failure times falling in between.

There were fewer standard tests that have been conducted with unprotected floor assemblies compared to non-standard tests, with none of the tests conducted at NRC in the FPH research. The effect of the applied load was clearly demonstrated by looking at results for the dimensional lumber assemblies; in standard tests with unprotected assemblies the failure time was as short as 6.5 min under a high (i.e., maximum) applied load of 387 kg/m^2, while it was significantly extended to 18.8 min at a lower loading of 97 kg/m^2. For unprotected floor assemblies the range of failure times for specific engineered floor assemblies were as follows (live load is given in parenthesis):

- Steel C-joist assemblies: 3.8 min (251 kg/m^2) - only one data point
- Wood I-joist assemblies: 6 min (97 kg/m^2) - only one data point
- Trusses: 13.1 min (139 kg/m^2) and 13.3 min (139 kg/m^2) – two data points

As was the case with non-standard tests, the addition of a ceiling membrane (typically 12.7 mm gypsum board) resulted in a significant improvement in structural fire endurance, with failure times ranging from 26 min to 80 min.

Regulatory Developments

With regards to regulatory developments, it was found that the 2012 International Code Council (ICC) International Residential Code in the US introduced a Code change that required residential floor assemblies that are not required to be fire resistance rated to meet specified performance requirements. The code (2012 IRC Section R501.3 and 2018 Section R302.13) requires floor assemblies to be provided with a 12.7-mm gypsum membrane, 15.9-mm wood structural panel membrane or equivalent on the underside of the floor framing with four exceptions (R302.13 (4)). One of the exceptions essentially requires non-dimensional lumber assemblies to demonstrate fire performance equivalent to that of 38 x 235 mm (nominal 2 x 10) dimensional lumber. Another exception (R302.13 (3.1)) permits a portion of any type of floor assembly to be unprotected, with the total unprotected ceiling area not exceeding 7.4 m^2 (80 ft^2) per storey. The equivalent fire resistance time of the reference joist was determined to be 15.5 min based on a calculation method contained in Chapter 16 of the American Wood Council (AWC) National Design Specification for Wood Construction, assuming an ASTM E119 fire exposure and a 50% design load when testing a single or multiple joist specimens.

One instance of a Canadian/US industry-developed technical guide / test protocol that was developed by Wood I-Joist Manufacturers Association (WIJMA) was documented, which determines equivalency to 2 x 10 lumber floor joists. The test method utilizes the ASTM E119 temperature-time exposure and the number of joist test specimens can be less than the entire width and constructed with as few as one joist. In addition, it should be noted that, based on I-joist industry presentations to the Canadian Commission on Construction Materials Evaluation

(CCCME) in 2019, the CCCME direction to the NRC Canadian Construction Materials Centre (CCMC) was to harmonize with the Canadian and US I-joist Industry protocol for CCMC evaluation of I-joists as of early 2020. Based on these tests, the CCMC Evaluation Reports with the fire protection solutions for I-joists have been published for acceptance by AHJs as of April, 2020.

Table of Contents

A Literature Review of the Fire Performance of Floor Assemblies Commonly used in Houses

By

Alex Bwalya, Joseph Su and Noureddine Bénichou

1 Introduction

During the last three decades, engineered floor joists, typically consisting of a web and flange design, have gained widespread use due to their superior design, structural rigidity, and the economic and productivity benefits to the construction industry. However, it has long been known [1] that in some building fires, floor assemblies constructed with engineered joists can experience structural failure in a shorter time compared to dimensional lumber joist assemblies due to various aspects of the design of the webs (e.g., reduced thickness, truss and metal-plate connections). In the context of this report, engineered floor joists refer to joists that are not made of dimensional lumber, such as those manufactured by bonding (fastening) together combinations of metal components, wood strands, veneers, small sections of solid lumber or other forms of wood fibre to produce a larger and integral composite units.

This report reviewed the results of the Phase 1 of the NRC's FPH research [2-8] and various related research and regulatory developments in the published literature to assist the work of the Canadian Commission on Building and Fire Codes (CCBFC) Joint Task Group (JTG) on Fire Performance of Floor Assemblies in Houses as it sought to define fire performance requirements for floor assemblies in houses.

In response to a request from the CCBFC and the Canadian Commission on Construction Materials Evaluation (CCCME), NRC undertook a project, called Fire Performance of Houses (FPH), to study the impact of engineered floor systems on the fire performance of houses with a focus on the life safety of residential occupants in fires originating in basements. The FPH research was focused on understanding the fire challenges posed by engineered floor systems, which had been replacing traditional dimensional lumber joist assemblies in the construction of houses. Phase 1 of the FPH research developed a wealth of information on the fire performance of a range of engineered floor systems, constructed with wood I-joists, steel C-joists, metal-plate connected and metal-webbed wood trusses, under basement fire scenarios where the joists were either unprotected or protected. Additional phases of the project, which were envisaged to address various fire performance aspects of other loadbearing elements of houses, determined in consultation with stakeholders, have not yet materialized.

Although the research established that the time to structural failure for the engineered floor assemblies tested was 35-60% shorter than that for the dimensional lumber assemblies, the failure of the unprotected floor assemblies in the fire scenarios used did not appear to be the critical issue affecting occupant life safety since the tenability limits were reached before the structural failure of the test floor assemblies occurred.

2 Review of the Fire Performance of Houses Phase 1 Results

The FPH Phase 1 project was completed in 2008 and the results are documented in a number of comprehensive publications [2-8]. The research established the typical sequence of events such as the smoke alarm activation, onset of untenable conditions, and structural failure of test assemblies, using fire scenarios that simulated basement fires in a full-scale test facility. The test facility represented a typical two-storey detached single-family house with a basement, which complied with the minimum requirements in the National Building Code of Canada (NBC 2005). The full-scale experiments addressed the life safety and egress of occupants from the perspective of tenability for occupants and structural integrity of structural elements as egress routes. The safety of emergency responders to fires originating in single-family houses was outside the scope of this research project.

The FPH project had the following objectives:

1. To determine the significance of the fire performance of structural materials used in houses to the life safety of occupants.
2. To identify methods of measuring the fire performance of unprotected and protected structural elements used in houses, as well as with and without sprinkler systems.
3. To measure and establish the fire performance of traditional house construction to facilitate the evaluation of the fire performance of innovative construction products and systems.

2.1 Experimental Setup

The fire tests were conducted in a test facility that was designed to represent a typical two-storey detached single-family house with a basement, which is shown in Figure 1.

Figure 1. FPH test facility

Each of the three levels of the test facility had a floor area of 95 m^2 and a ceiling height of 2.4 m. The basement was partitioned to create a fire room representing a 27.6 m^2 basement living area. The layout of each of the three storeys is shown Figures 2 – 4. For the basement fire room, a rectangular exterior opening measuring 2.0 m wide by 0.5 m high and located 1.8 m above the floor was provided in the south wall of the fire room. The size of the opening is equivalent to the area of two typical basement windows (1.0 x 0.5 m). A removable noncombustible panel was used to cover the opening at the beginning of each experiment.

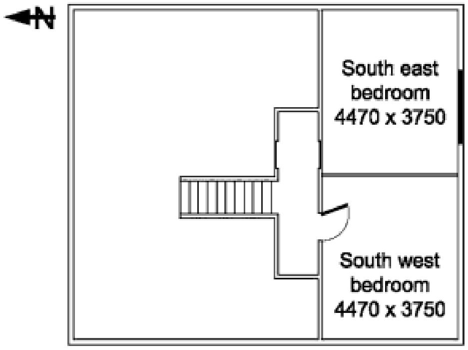

Figure 2. Second storey layout

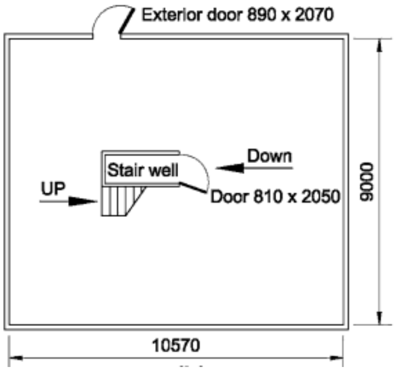

Figure 3. First story layout

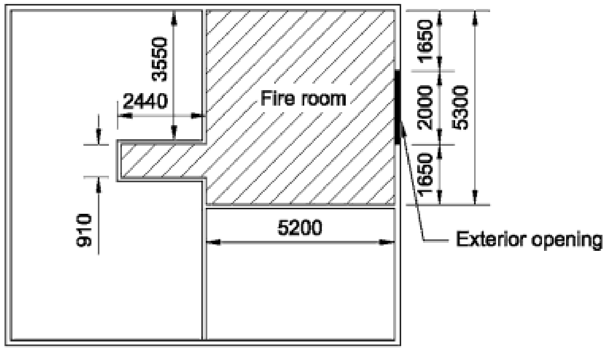

Figure 4. Basement layout

The test floor specimen was constructed on the first storey directly above the basement fire room. The subfloor consisted of single layer of oriented strand board (OSB) (without a floor finish material) for all test assemblies since there are no specific requirements for floor finishing materials atop the subfloor in the NBC. This was considered the code minimum and reduced the number of experimental variables. The floor load was applied to the floor assemblies as follows: the self-weight (dead load) of the assembly, plus an imposed load (live load) of 0.95 kPa or 97 kg/m^2 (i.e., half of the imposed load of 1.90 kPa prescribed by the NBC for residential occupancies). The rationale for this was the assumption that in a fire situation, only part of the imposed load is typically available. This assumption was consistent with the approach taken in various international standards that were cited in the FPH research reports.

The floor assemblies that were tested were constructed using the six types of floor joists given in Table 1. For each type of floor assembly tested, the floor joist/truss spans were either chosen from the appendices of the NBC or calculated based on the ultimate and serviceability limit states. Therefore, the floor joists/trusses could either span the entire length of the fire compartment space or require an intermediate beam support for shorter spans. When designing the assemblies, various factors were considered, such as the commonly used framing and subfloor materials at that time, serviceability limit states, typical spacing, typical spans, typical depths, etc.

Part 9 of the 2015 NBC, *Housing and Small Buildings,* provides prescriptive compliance options, referred to as acceptable solutions. The acceptable solutions include prescriptions for light-weight wood-frame floor construction. To facilitate the application of the framing requirements for light-weight wood-frame floor assemblies, tables are provided which prescribe the maximum permitted span for dimensional lumber floor joists (at ambient conditions). The tables consider: the species designation and grade of the lumber, the cross-section dimensions of the joist, the joist spacing, joist span, the intermediate bracing conditions (i.e. strapping, bridging), the attachment of ceilings with wood furring, and the presence of concrete topping. The use of the span tables is limited by the following assumptions:

1. The floor is framed with small repetitive structural members spaced not more than 600 mm o.c.,
2. The uniformly distributed live load on the floor does not exceed 1.9 kPa, and
3. The span of any structural member does not exceed 12.20 m.

If any of the limitations are exceeded, Part 9 of the NBC directs code users to Part 4 of the NBC, *Structural Design.*

Table 1: Types of joists used to construct the FPH test floor assemblies.

No.	**Type of Joist**	**Depth (mm)**	**Span (mm)**
1	Dimensional lumber	235	4170
2	Wood I-A[1]	302	4813
3	Wood I-B	302	4813
4	Steel C	203	4477
5	Metal-plate connected wood truss	305	4813
6	Metal-webbed wood truss	302	4813

[1] The main difference between the two Wood I Joists was the flange design (laminated veneer lumber – A; finger-joint lumber - B).

2.2 Instrumentation

The test facility was instrumented with various devices to measure:

- Temperatures in the fire room, floor assembly, spaces on the first and second storeys;
- Penetration of flames through the sub-floor;
- Deflection of the floor assembly
- Activation times of smoke alarms
- Smoke optical density and the concentration of gaseous products of combustion, on the first and second storey, required for evaluating tenability conditions.

- Velocity of gases flowing through various openings

2.3 Fire Scenario

Considering the objectives of the research, it was determined that the fire exposure would be provided using an actual combustible fuel load to simulate scenarios in room fires that give rise to relatively severe fire conditions (i.e., in terms of the rate of fire growth, temperatures and gaseous products of combustion), which would be more challenging to structural assemblies and tenability conditions in a house. Therefore, the standard fire resistance test method in accordance with ASTM E119 [9] or CAN/ULC S101 [10] or standard temperature-time exposure was not suitable for the project since the temperature rise would have been less severe and the relatively clean gaseous fuel used in fire resistance furnaces would not generate the type of smoke that would be as challenging to tenability conditions as that produced by a fire involving residential furnishings, such as upholstered furniture.

It is reported that the ASTM E119 standard temperature-time curve, that is also used in the CAN/ULCS101 test method was developed in 1917 with limited information about the actual extent and temporal development of temperatures in compartments [11]. The standard curve was developed using furnace temperature measurements at various laboratories and was considered to be a severe fire, at the time, which was suitable for comparing the fire endurance of building assemblies using a simplified test. However, actual room-scale fire tests carried out at the National Bureau of Standards (presently called the National Institute of Standards and Technology (NIST)) in the 1920s determined that temperatures in room fires were significantly different from the standard temperature-time curve. The Engineered Wood Association (APA), WIJMA and AWC [12] discussed the subject of standard test times versus fire resistance in actual fires and cautioned against using fire resistance tests as an indicator of performance in an actual fire as this was inaccurate. The actual performance of structures in real fires is a function of many variables such as ignition source, heat release rate and rate of fire growth, fuel load and type, ventilation conditions and compartment dimensions, all of which have an impact on fire severity. It was argued that the importance of standard tests was that they allow for the fire performance of materials and assemblies to be compared on a relative basis and to demonstrate regulatory compliance. This underscores the reason for selecting to use an actual room fire in the FPH research.

2.3.1 Fuel Package / Fire Exposure

The fuel package consisted of a mock-up sofa that was constructed with 9 kg of exposed polyurethane foam (the dominant flammable constituent of upholstered furniture) and 190 kg of wood cribs that was arranged as shown in Figure 5. The design of the fuel package took into consideration the fact that the floor assembly would contribute to the fuel load. The fuel package was placed at the centre of floor space of the basement fire room. The fire was started by igniting the mock-up sofa with a square gas burner that was positioned as shown in Figure 5.

Figure 5. FPH Fuel package

Tests were conducted with the basement doorway either in the open or closed position. Figure 6 shows the average temperatures at five elevations that were obtained during an experiment in which all of the walls and ceiling in the fire room were lined with a non-combustible sheathing and the basement doorway was left open during the characterization test, FS-1. Figure 6 also shows the difference between the standard CAN/ULC S101 temperature-time curve and the actual temperatures in the fire room for a duration of approximately 1800 s (30 min). The temperature rise was more rapid than that of the S101 curve during the initial 720 s (12 min), indicating a more severe fire exposure. Figure 7 shows that when the characterization test was conducted with the basement door closed, the peak temperature in the room was substantially lowered (less severe fire) due to the limited supply of combustion air to the fire room.

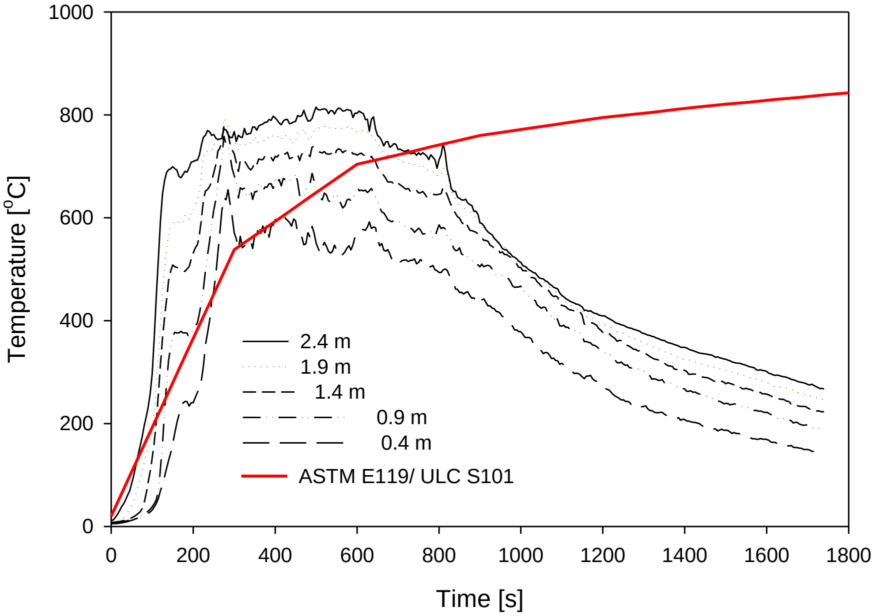

Figure 6: Temperature evolution in an actual room fire test (with non-combustible room linings and basement doorway open) compared to the ASTM E119 / ULC S101 standard temperature curve.

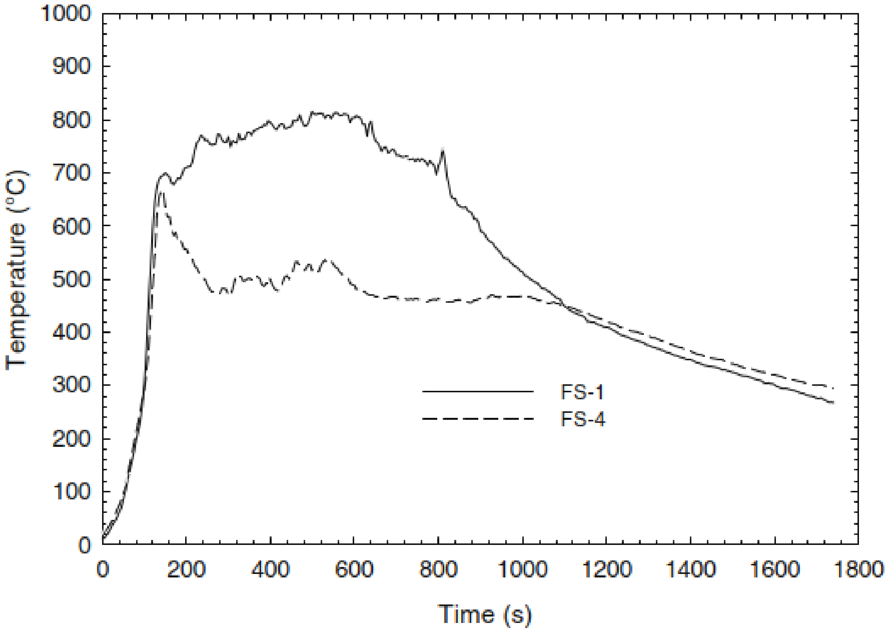

Figure 7. Average temperature profiles in the basement fire room at 2.4 m height for scenarios where the basement door was open (FS-1) and closed (FS-4).

2.4 Experimental Procedure

After igniting the fuel package, the non-combustible panel that covered the fire room's exterior window opening during the initial stage of each test was manually removed when the temperature measured at the top-center of the opening reached 300°C (simulated glass breakage). This condition was reached within 90 to 120 s after ignition in the experiments. The removal of the panel was to provide the ventilation necessary for combustion.

The exterior door on the first storey was opened in each test at 180 s after ignition and left open, simulating a situation where some occupants, who would have been in the test house, escaped leaving the exterior door open while other occupants may still have been inside the house. The tests were terminated when one of the following occurred (singly or in combination): a) excessive flame penetration through the floor assembly; b) structural failure of any part of the floor assembly; c) safety of the test facility compromised.

2.5 Results

The activation times of the smoke alarm in the basement compartment were within the range of 27 to 55 s, with a mean of 40 s and standard deviation of 8 s. This indicates that there was a relatively small difference in the smoke alarm activation times in many of the tests.

The potential exposure to the toxic and asphyxiating gases, heat and smoke obscuration under the test conditions was analyzed to estimate the time available for escape, using incapacitation as the endpoint. In fire situations, occupants would be exposed simultaneously to the gases, heat and smoke obscuration. The combined effect as a result of the simultaneous exposure is not well understood. In the FPH research, the gas exposure, heat exposure and smoke obscuration were analyzed independently without consideration of the combined effect. The tenability analysis was based on the methodologies contained in ISO 13571[13] and the SFPE handbook of Fire Protection Engineering [14], which include a fractional effective dose (FED) approach to quantify the time at which the accumulated exposure to each constituent species of the fire effluent exceeds a specified threshold criterion for incapacitation. This time was taken to represent the time available for escape relative to the specified thresholds (FED = 1 and FED = 0.3). The time available for escape calculated based on FED of 1 represents the time available for healthy adults of average susceptibility, which represents the level at which the median or 50 % of the population is likely to become incapacitated. An FED value of 0.3 typically relates to the most sensitive populations, which constitutes approximately 11 % of the population such as the elderly, young, or those with compromised immune systems [8].

Tables 2 and 3 summarize the results, for both unprotected and protected floor assemblies, of the average time to reach smoke obscuration and incapacitation limits (due to either heat exposure or inhalation of CO) measured in terms of optical density and FED, respectively. The results of the structural fire endurance for all of the 16 experiments that were conducted are given in Table 4. Smoke obscuration was the first hazard to arise in all of the experiments. The smoke obscuration limit (optical density = 2 m^{-1}) was reached consistently around 180 s in the experiments with the open basement doorway. Although smoke obscuration would not directly cause incapacitation, it could impede evacuation and prolong exposure of occupants to other hazards. It should be noted that individuals with impaired vision could become disoriented earlier at an optical density lower than 2 m^{-1}. The results showed that untenable conditions (for occupant incapacitation) were reached at comparable time frames in the experiments with the open basement doorway and, therefore, did not depend on the type of floor assembly. This confirmed that the fuel package was the dominant factor in creating untenable conditions in the test house, due to the rapid fire growth and smoke production associated with the combustion of the polyurethane foam material component of the fuel package. In the three experiments conducted with fire sprinklers using the same fire scenario as the experiments with protected floor assemblies, none of the tenability limits were reached since the sprinklers were able to quickly extinguish the fire. The results of three additional experiments [15] with fire sprinklers that were conducted with fire scenarios designed to challenge the sprinklers are not reported here since they were conducted for a different purpose.

In the experiments with unprotected assemblies that were conducted with the basement doorway closed, the times available for escape before the onset of untenable (occupant incapacitation) conditions were roughly doubled and the times to reach structural failure were approximately 50-60% longer than with open basement doorway scenario.

In all but one experiment, the structural failure of the test floor assemblies occurred after the untenable conditions were reached, suggesting that tenability conditions are more critical than structural issues for occupant life safety. The exception was Test UF-08 (basement doorway closed) with a metal-webbed wood truss, in which the floor assembly failed at 474s (7 min 54 s) before the FED = 1 tenability limit was reached at 486 s (8 min 6 s). However, for FED 0.3 (susceptible), the loss of tenability and visibility (optical density = 2 m^{-1}) on both the 1st and 2nd storeys occurred before structural failure in test UF-08. The times to reach structural failure for the unprotected wood I-joist, steel C-joist, metal-plate and metal-webbed wood truss assemblies were 35-60% shorter than those for the dimensional lumber assembly, resulting in a smaller time difference between the onset of untenable conditions and structural failure for these engineered floor assemblies. Three replicated tests (UF-06, UF-06R and UF-06RR) showed that the test results had good repeatability.

Table 2. Time to reach specified tenability limits for 8 experiments with unprotected floor assemblies with the basement door open.

	1st storey			2nd storey	
Threshold	OD = 2 m^{-1}	FED = 0.3	FED = 1	FED = 0.3	FED = 1
Mean	3 min	3 min 22 s	3 min 36 s	3 min 44s	4 min 13s
SD[1]	12 s	5 s	12 s	13 s	13 s
Min[2]	2 min 41 s	3 min 12 s	3 min 19 s	3 min 27 s	4 min 1 s
Max[3]	3 min 15 s	3 min 27 s	3 min 55 s	4 min 5 s	4 min 40 s

[1] Standard deviation; [2] Minimum [3] Maximum

Table 3. Time to reach specified tenability limits for five experiments with protected floor assemblies with the basement door open.

	1st storey			2nd storey	
Threshold	OD = 2 m^{-1}	FED = 0.3	FED = 1	FED = 0.3	FED = 1
Mean	3 min 26 s	4 min 3 s	4 min 48 s	5 min 6 s	4 min 46 s
SD[1]	17 s	18 s	26 s	20 s	49 s
Min[2]	3 min 12 s	3 min 40 s	4 min 15 s	4 min 42 s	5 min 42 s
Max[3]	3 min 45 s	4 min 20 s	5 min 15 s	5 min 25 s	7 min 40 s

[1] Standard deviation; [2] Minimum [3] Maximum

For the tests with unprotected floor assemblies that were conducted with the basement door open, the time to structure failure ranged from 5 min 25 s (metal-webbed wood truss assembly) to 12 min 20s (dimensional lumber assembly). Closing the basement doorway extended the time to structure failure for the three assemblies tested since the lower ventilation reduced the intensity of the fire. Under this scenario, the times to structure failure for the dimensional lumber, metal-webbed wood truss and wood I-joist A increased by 7 min 40 s, 2 min 29 s and 4 min 48 s, respectively.

For the five experiments in which the floor assemblies were protected with a single layer of gypsum board ceiling or ceiling tiles, the period during which tenable conditions were maintained was similar to or slightly improved than that obtained in the tests with unprotected assemblies. However, only the assemblies with a gypsum board ceiling exhibited a significant improvement in the failure time (see Table 4); for instance the dimensional lumber assemblies improved by 9 min 40 s while the lowest performing unprotected assembly (metal-webbed wood truss) achieved the highest improvement of 18 min 19 s. However, the assembly with the ceiling tiles showed only a marginal improvement in its structural fire endurance of 2 min 28 s although it followed the same sequence of fire events and had similar tenability results compared with the assemblies protected with a gypsum board ceiling.

Table 4. Results of the structural fire endurance for 16 experiments conducted with both unprotected and protected floor assemblies.

Type of Joist (used in floor assembly)	**Test**	**Basement doorway**	**Ceiling finish**	**Failure time (mm:ss)***
Dimensional[1] (235 mm deep)	UF-01	Open	None	12:20
	UF-02	Closed	None	20:00
	PF-01	Open	GB[6]	22:00
Wood I[2] (A) (302 mm deep)	UF-03	Open	None	8:10
	UF-09	Closed	None	12:58
	PF-04	Open	GB	20:47
	PF-05	Open	SCT[7]	10:38
Wood I (B) (302 mm deep)	UF-06	Open	None	6:22
	UF-06R	Open	None	6:20
	UF-06RR	Open	None	6:54
Steel C[3] (203 mm deep)	UF-04	Open	None	7:42
	PF-02	Open	GB	21:40**
MPCW[4] truss (305 mm deep)	UF-05	Open	None	7:49
MWW[5] truss (302 mm deep)	UF-07	Open	None	5:25
	UF-08	Closed	None	7:54
	PF-6C	Open	GB	23:44

[1] Dimensional lumber joist; [2] Engineered wood I-joist; [3] Steel C-joist; [4] Metal-plate connected wood truss; [5] Metal-webbed wood truss; [6] 12.7 mm thick regular gypsum board; [7] Suspended ceiling tiles

* Characterized by complete collapse of the assembly into the basement or visible “V” shaped collapse due to failure of joists or trusses near the center of the floor area.

** Time of structural failure determined by visual observation (i.e. assembly did not collapse entirely)

2.6 Evacuation Study

A study was undertaken, as part of the FPH project, to estimate the available safe escape time and the required safe escape time (ASET/RSET) for occupants of a single-family house in the case of a basement fire [16,17].

At the time of the study, there were limited egress models that could be used to define and assess the timing of the evacuation process in a single-family house. In a performance-based assessment, the evacuation time is often calculated using the ASET/RSET model illustrated in Figure 8. The ASET is the available safe escape time calculated from the time of ignition of a fire until the time at which the occupant tenability criteria are exceeded in the means of egress. The RSET is the required safe escape time, which is the time calculated from ignition until occupants can reach an area of safety. The timing of each phase of the evacuation process depends on a wide range of factors, such as fire location, combustibles in place, detector placement, space layout, and the characteristics of the occupants.

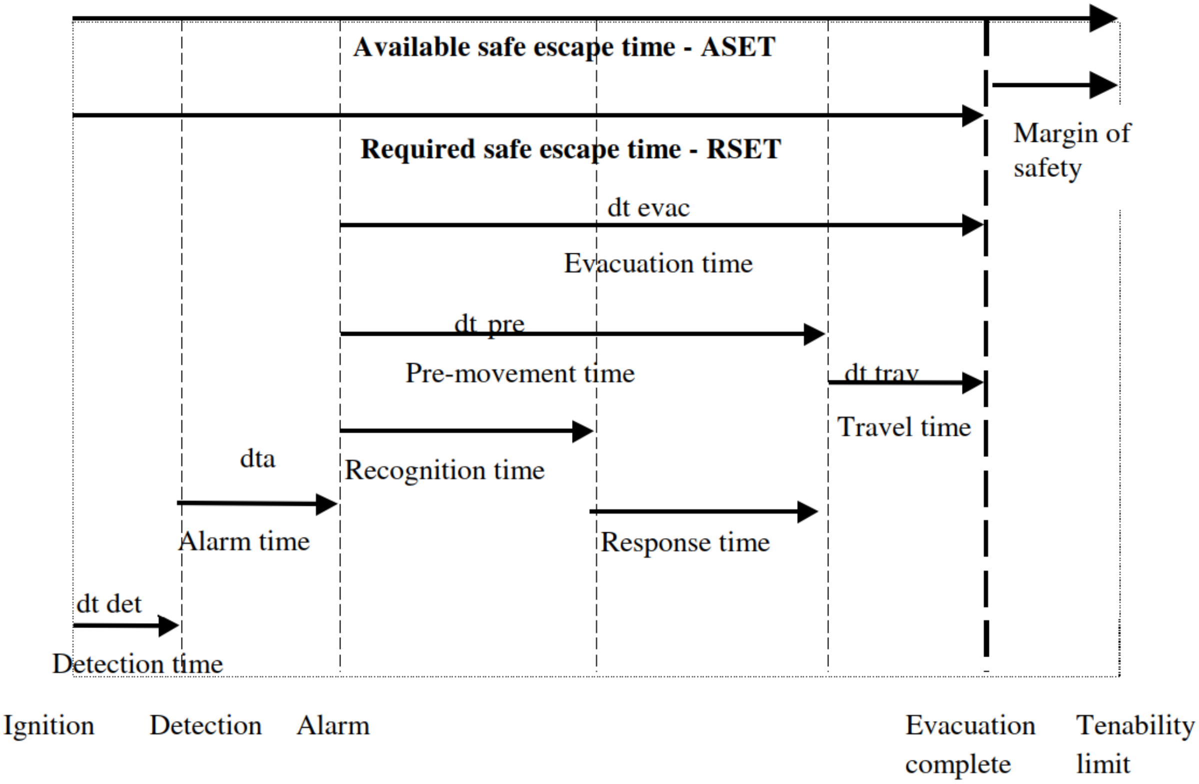

Figure 8. Egress time model [16]

It was noted that the ASET/RSET approach could not account for certain kinds of fire scenarios, for instance, those in which occupants who are intimate with fire ignition experience ignition of their own clothing or bedding such that their ASET is essentially nonexistent. Another scenario considers a lone occupant who has a disability or is immobile, such that their RSET will be unlimited as they cannot evacuate unaided. These scenarios are not considered in this analysis.

Table 5 presents the range of times of each phase of the Egress Time Model that were determined from the study. The times represent a best-case and a worst-case scenario, to establish the bounding range of RSET values, which varied from 120s to 970s (2 min to 16 min 10s). This represents the time from fire initiation to the time the occupant has reached a place of safety outside the house. The estimated evacuation time (the addition of the pre-movement and travel times) is 1 min for the best-case scenario and 11 min for the worst-case scenario. Given the broad range of evacuation times that can result from such analysis, it is clear that, depending on the specific circumstances of the fire, the building design and the characteristics of the individual, a distribution of times can be expected. However, there was insufficient data in the literature to conduct a detailed probabilistic analysis.

Table 5. Estimated Required Safe Egress Times for a Single Family House

Phase	**Best-Case time (mm:ss)**	**Worst-Case time (mm:ss)**
Detection	1:00	5:00
Alarm	0:00	0:10
Pre movement	00:30	10:00
Travel	00:30	1:00
Total RSET	**2:00**	**16:10**

2.7 FPH Phase 1 Conclusions

The research acknowledged that the two relatively severe basement fire scenarios used in the experiments did not represent common residential fire scenarios since the basement is not the most frequent room of fire origin in single-family houses. However, the basement is the location where a fire is mostly likely to create the greatest challenge to the structural integrity of the floor structure on the first story when the underside of the first floor assembly is unprotected. Therefore, the relatively severe fire scenarios used in the experiments were selected as they were more challenging to structural assemblies and tenability conditions in a house. Occupant tenability conditions were estimated based on measurements of smoke optical density and concentration of gaseous products of combustion and calculated FED (based on temperature and CO measurements).

The main conclusions of the study were as follows:

For Unprotected Assemblies with an Open Basement Doorway

- The estimated time to reach untenable occupant conditions in the tests using the engineered floor systems was similar to that in the test using the solid wood joist floor system. The change in floor construction basically did not change the estimated time to reach incapacitation for occupants. Data analysis indicated that tenability conditions and the time to reach untenable conditions due to smoke and gaseous products of combustion appear to be the critical factors affecting occupant life safety under the fire scenario tested.

- The failure of unprotected floor assemblies in the test fire scenario did not appear to be the critical issue affecting occupant life safety since the tenability limits were reached before the structural failure of the test floor assemblies.

For Unprotected Assemblies with a Closed Basement Doorway

- The presence of the closed door to the basement reduced the fire growth rate and restricted the transport of combustion products from the basement to the upper storeys. The closed door prolonged the time available for occupant escape (from within the basement and from upper floors in the house) and the time for the test assemblies to reach structural failure since the fire was less severe.
- The times available for escape before the onset of untenable (incapacitation) conditions were roughly doubled and the times to reach structural failure were about 50-60% longer than with the open basement doorway scenario.
- Several experiments were conducted with the closed basement doorway scenario, one with the solid wood joist assembly and two with selected engineered floor assemblies. One engineered floor assembly (Test UF-08), which had the shortest time to reach structural failure in the open basement doorway scenario, failed structurally in the closed basement doorway scenario before the tenability limits were reached for healthy adults of average susceptibility (FED=1). Because the floor failed structurally before the tenability limits (FED = 1.0) were reached, this would represent a risk factor for some of the occupants.

For Protected Assemblies with an Open Basement Doorway

- For the experiments using the test assemblies with gypsum board protection, the chronological sequence of the fire events was the same as the experiments with unprotected assemblies, i.e., fire initiation, smoke alarm activation, onset of untenable conditions for occupants, and structural failure of the test assemblies.
- The incapacitation (untenable) conditions were reached shortly after smoke obscuration. Compared to the experiments using the same floor assemblies without gypsum board protection, the times during which tenable conditions were maintained were similar or only slightly improved whilst the structural performance was improved significantly with the gypsum-board-protection.
- The times taken to reach structural failure for the gypsum-board-protected ceiling/floor assemblies were much longer than those for the unprotected assemblies. The results indicated that all of the test assemblies that were protected by a gypsum board ceiling achieved similar structural fire endurance under the experimental fire scenario.
- The experiment with a suspended ceiling (Test PF-05) followed the same sequence of fire events and similar tenability conditions compared with the gypsum-board-protected assemblies. The benefit of the suspended ceiling as a protection measure was very

minimal - the structural collapse of the test assembly was only delayed by 2 min 28 s, compared to the same test assembly without protection.

- For the experiments with residential sprinkler-protected assemblies (Tests PF-03, PF-03B and PF-06), the residential sprinkler systems protected the structural integrity of the test assemblies and effectively suppressed the fire. No ignition, structural failure or damage occurred with the test assemblies during the experiments and tenability conditions remained below threshold values throughout the experiments.

For all Scenarios

- An early alert to a fire appears to be the key to occupant life safety. The smoke alarm located in the basement compartment consistently took 30-50 s to activate. The experimental results highlighted the importance of the NBC requirements for interconnected smoke alarms houses.
- The times to reach structural failure for the wood I-joist, steel C-joist, metal-plate and metal-webbed wood truss assemblies were 35-60% less than that for the dimensional lumber joist assemblies.
- Untenable conditions were not reached, for the duration of the tests, in the second storey bedroom where the door to the bedroom was closed.
- Further research on the required egress times from single-family houses was recommended.

Evacuation Study

- The required safe egress times (RSET), for a single family two-storey house, were estimated to vary from 2 min to 16 min 10 s based on the information that was available at the time of the study. The variation is wide and largely dependent on the characteristics of each person, the building design and the fire scenario. Further research was recommended to enhance the accuracy of the evacuation time estimates. In the worst-case scenario, assuming that the smoke alarms were interconnected and sounded simultaneously on each floor of the house, with the basement door opened, occupants in the 2nd floor bedroom would have about 2 min to escape before the smoke obscuration threshold and about 2.5 min before untenable conditions on the 1st floor. This is for the experiments with the shortest time to the attainment of the respective smoke obscuration or tenability thresholds on the first floor. With the basement door closed, the time before the smoke obscuration threshold is over 4 min and untenable conditions on the 1st floor are reached at around 7 min for less susceptible individuals (FED = 1).

3 Literature Review of Fire Tests involving Residential Floor Assemblies

It has long been recognized that floor and roof assemblies constructed with engineering structural elements, i.e., joists and trusses, sometimes exhibit different fire endurance compared to traditional dimensional lumber assemblies. In this regard, the main concern is the reduction in fire performance that results in unprotected engineered assemblies experiencing structural failure earlier than dimensional lumber assemblies. This has been of particular concern to the fire services, especially in the United States where a number of firefighter injuries and deaths have been attributed to the unexpected structural collapse of floor and roof assemblies [18,19]. Therefore, many of the earliest reported research and demonstration tests concerning the performance of engineered floor assemblies were conducted in the United States.

There are numerous experiments involving unprotected and protected floor assemblies in the published literature in North America, dating as far back as the 1970s. The literature review identified at least 50 fire experiments (excluding the 16 tests conducted at NRC in the FPH study that is summarized in Section 2) that have been conducted with floor assemblies for houses, since 1973, within the context of the impact of the introduction of engineered floor joist assemblies and the evolution of fuel loads on fire safety in houses. In addition to dimensional lumber joists, the following six types of engineered joists were covered: wood I-joists, steel C-joists, metal-plate connected wood truss, finger jointed (glued) wood truss and metal-plate steel web truss. The tests reviewed can be grouped in two main categories: standard and non-standard, defined by the type of fire exposure. Standard tests are conducted in a fire resistance furnace using the temperature-time exposure and procedures defined by the ASTM E119 or CAN/ULC S101 test methods, although in some cases the loading and furnace operating conditions deviate from the requirements in the standard test methods. Non-standard tests seek to simulate actual compartment fires using combustible fuel loads and the tests are often conducted in structures that are constructed with representative construction materials. Non-standard tests also included tests that are conducted in fire resistance furnaces without following the ASTM E119 or CAN/ULC S101 standard temperature-time exposure; such tests usually attempt to simulate temperature conditions that are consistent with data from compartment fires. Although many of the reported non-standard compartment tests were well instrumented for temperature, heat flux and gas concentration measurements, none of the tests included a tenability analysis (as was undertaken in the NRC FPH Phase 1 series of tests), and were limited to reporting on the structural failure of the tested floor assemblies.

Experiments in which the floor assembly was protected by an automatic fire sprinkler were excluded from this review since previous research has shown that properly installed sprinklers were very effective in extinguishing fires and thereby preventing structural collapse in the experiments reviewed [15,20].

The fire experiments (both standard and non-standard) that were found in the literature are presented in Table 8. The experiments were largely focused on evaluating the fire endurance of floor assemblies with the structural failure (typically floor collapse) as the critical end point.

3.1 Non-standard fire experiments

Figure 9 shows the results of the time to structural failure for all of the non-standard experiments conducted with unprotected and protected assemblies. The results from the NRC FPH project are also included in Figure 9 to give a complete picture of all of the available data. There are variations in the results obtained for similar assemblies due to the many experimental variables that were used. One of the key variables that has a strong influence on the time to structural failure is the live load applied to the test assemblies. Other main variables in non-standard compartment fire tests included ventilation conditions and the fire load (quantity and composition), which creates differences in fire severity. However, the fire performance trends for the various assemblies and effect of protection measures are clearly discernible. For dimensional lumber assemblies, the lowest time to structural failure was 6.9 min (Test 7-3 in Table 8). The test was conducted in a fire resistance furnace using a non-standard temperature-time exposure that was derived from compartment fire tests, in which the same assemblies had a failure time of 12 min (Test 6-2 in Table 8). This result is similar to that obtained in the NRC FPH project (failure time of 12.5 min in Test UF-01) although the live load was different. Another FPH test (UF-02) with the same assembly had a failure time of about 20 min under the reduced fire severity resulting from reduced ventilation when the basement door was closed.

The results shown in Figure 9 also collaborate the findings in the FPH study, which found that assemblies using trusses and steel C joists had significantly reduced structural fire endurance compared to dimensional assemblies. The lowest preforming assemblies in the tests presented in Table 8 were a steel C-joist and metal-plate connected truss with failure times of 2.6 min (Test 7-10) and 3.5 min (Test 10-10), respectively. The effect of adding ceiling protection (typically 12.7 mm regular gypsum board) is also evident in the results.

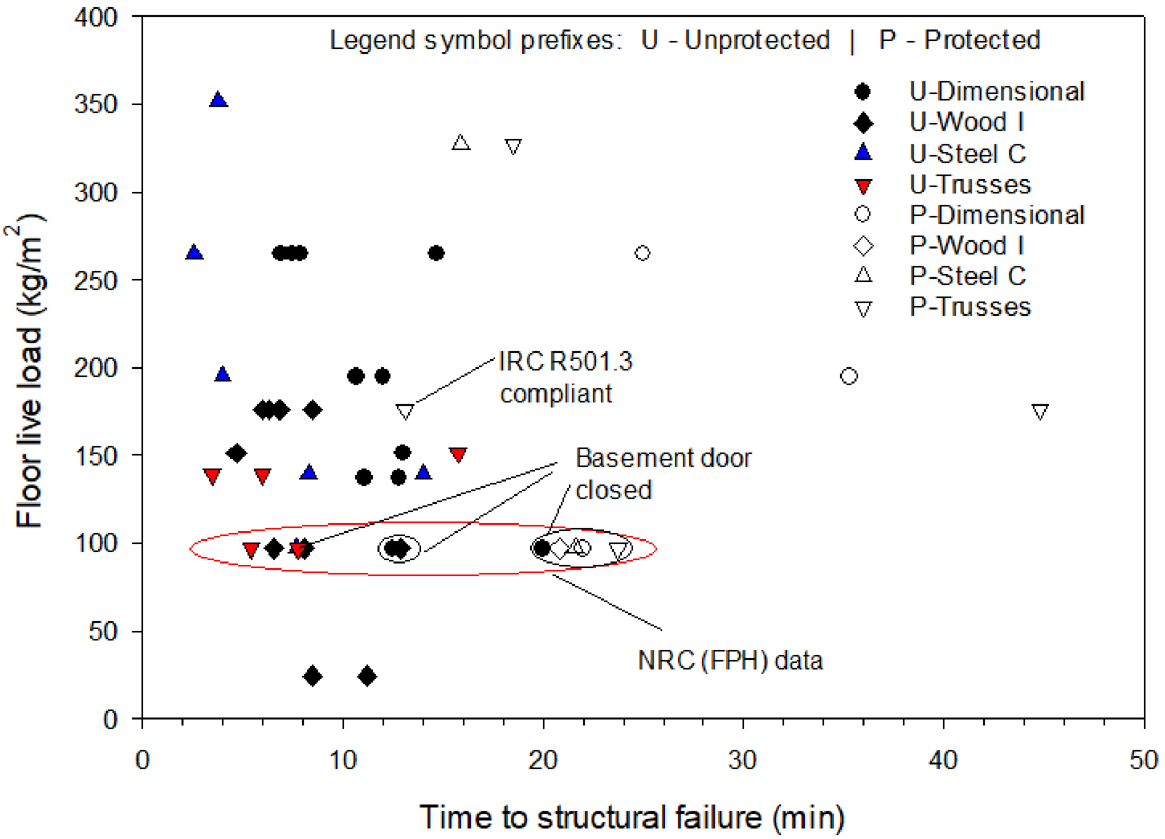

Figure 9: Non-standard experiments

Figure 9 also shows the performance of a test (No. 11-4) which evaluated the performance of a metal-plate connected truss assembly that complied with the new provisions that were introduced in the International Residential Code (IRC) in the USA that essentially required unprotected engineered assemblies to demonstrate fire performance equivalent to dimensional lumber assemblies. In the USA, the main codes are the International Building Code or International Residential Code, electrical codes and plumbing, and mechanical codes. It is reported that about fifty states have adopted the I-Codes at the state or jurisdictional level. Since 2012, the International Residential Code Section R501.3 "Fire protection of floor", required floor assemblies that are not required to be fire-resistance rated to be provided with a 12.7 mm gypsum membrane, 15.9 mm (5/8 in.) wood structural panel membrane or equivalent on the underside of the floor framing. In the 2015 and 2018 IRC, the provision was moved from Section R501.3 to Section R302.13 and new language was added to allow for penetrations or openings in the fire-protection membrane. Therefore, the 2018 IRC R302.13 reads as follows:

R302.13 Fire protection of floors. Floor assemblies that are not required elsewhere in this code to be fire-resistance rated, shall be provided with a 1/2-inch (12.7 mm) gypsum wallboard membrane, 5/8-inch (16 mm) wood structural panel membrane, or equivalent on the underside of *the floor framing member. Penetrations or openings for ducts, vents, electrical outlets, lighting, devices, luminaires, wires, speakers, drainage, piping and similar openings or penetrations shall be permitted.*

Exceptions:

1. *Floor assemblies located directly over a space protected by an automatic sprinkler system in accordance with Section P2904, NFPA 13D, or other approved equivalent sprinkler system.*
2. *Floor assemblies located directly over a crawl space not intended for storage or for the installation of fuel-fired or electric-powered heating appliances.*
3. *Portions of floor assemblies shall be permitted to be unprotected where complying with the following:*
    1. *The aggregate area of the unprotected portions does not exceed 80 square feet (7.4 m^2) per story.*
    2. *Fire blocking in accordance with Section R302.11.1 is installed along the perimeter of the unprotected portion to separate the unprotected portion from the remainder of the floor assembly.*
4. *Wood floor assemblies using dimension lumber or structural composite lumber equal to or greater than 2-inch by 10-inch (50.8 mm by 254 mm) nominal dimension, or other approved floor assemblies demonstrating equivalent fire performance.*

The IRC code change stated that it was intended to address concerns for firefighters' safety and incidents of injury or death to firefighters while fighting residential fires due to the collapse of floors. The application of gypsum wallboard or another approved material was intended to provide some protection to the floor system against the effects of fire and delay the collapse of the floor assembly.[1]

Test No. 11-4 (labelled "IRC R503.1 compliant" in Figure 9) evaluated the performance of an assembly with an unprotected aggregate area complying with IRC R302.13, i.e., not exceeding 7.4 m^2. The structural fire endurance of the assembly was 13.1 min, representing almost double that obtained with an unprotected assembly (6.1 min with Test 10-9).

In reviewing the test results presented in Table 8, it is worth discussing a project undertaken by NIST, which is similar to the NRC FPH Phase 1 project since it sheds some light on the implications of non-standard furnace tests conducted with a non-standard temperature-time exposure. NIST undertook a project [21,22] to develop a fire endurance test for residential floor assemblies, which better represented the rapid growth and higher severity of fires in residential buildings compared to the ATSM E119 fire exposure. It was noted that the ASTM E119 fire exposure is characterized by a slow rate of temperature rise that did not represent actual fire conditions created in fires involving real furnishings in residential dwellings. This research also

---

[1] The derivation of the area limitation was not provided.

stated the following additional drawbacks of the ASTM E119 test method, which made it unsuitable for evaluating the performance of assemblies in real fire conditions:

1. The shielded thermocouples prescribed in the ASTM E119 tests method had longer response time, which made it difficult to control the furnace temperature when simulating the short-duration growth phase exhibited by actual room fires;
2. The furnace operates under negative or neutral pressure, which is not representative of room fires.

The first part of the project involved seven experiments (see Tests 6-1 to 6-7 in Table 8) with floor assemblies that were conducted in a simulated basement room with actual furnishings. In the second part of the project, 10 experiments (Tests 7-1 to 7-10 in Table 6) were conducted in a standard fire resistance furnace using two different fire exposures: the ASTM E119 temperature-time exposure and a non-standard temperature-time exposure (see Figure 10) that was developed using the temperature data from the experiments in the first part of the project. An additional variable introduced in the furnace tests was the excess air, which was controlled to simulate the limitation in ventilation that occurs in post-flashover room fires.

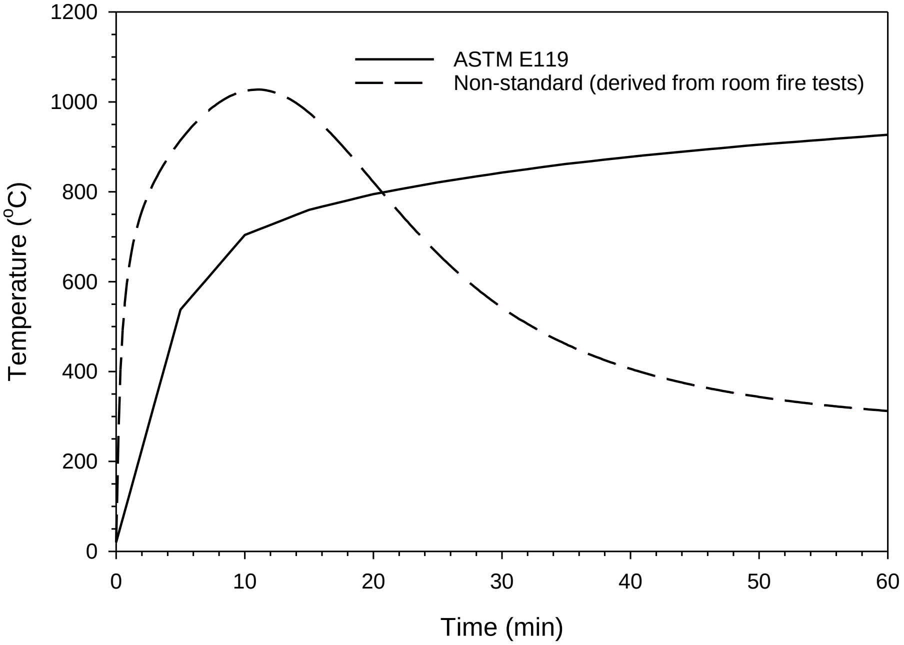

Figure 10: Non-standard temperature-time curve developed using data from full-scale room tests [22] compared with the ASTM E119 curve.

The results showed that the fire endurance time, based on the passage of flames to the unexposed side of the floor assemblies with unprotected dimensional lumber joists, varied from 6 to 9 min when tested with the experimentally-derived temperature-time curve (Figure 10) and 16 to 18 min when tested in accordance with the ASTM E119 fire exposure. Under similar fire exposure (non-standard furnace fire with less excess air), the unprotected steel-C assembly failed in about 4.5 min compared to 9 min for the unprotected dimensional wood joist floor assembly. The assemblies with wood components tested in the furnace had a shorter fire endurance than those tested in the compartment fire scenarios. This was attributed to the possibility of accelerated rate of charring and additional the heat contribution from the combustion of the floor assembly, and the presence of excess air in the furnace.

A review of the test data present in Table 8 found that there were no experiments conducted with a similar live load to that used in the NRC FPH study (95 kg/m^2), which makes it difficult to compare results on the same basis although the trends are similar. However, there were a few tests (see Table 6) that were conducted using a comparable live load to that indicated in Part 9 of the 2015 NBC (i.e. maximum of 1.9 kPa (194 kg/m^2)). In the FPH study a 38 x 235 mm (nominal 2 x 10) dimensional lumber assembly (UF-01; 95 kg/m^2 live load) had a failure time of 12 min 20 s compared to 10 min 43 s for Test 6-1, while a Steel C assembly had a failure time of 7 min 42 s compared to 3 min 59 s in Test 6-6.

Table 6. Non-standard floor tests conducted with a live load of 195 kg/m^2.

Test ID	Joist Type	Joist Spacing (mm)	Ceiling Finish	Failure time (mm:ss)
6-1	Dimensional (38 x 184)	406	None	10:43
6-2	Dimensional (38 x 184)	610	None	12:00
6-6	Steel C	406	None	3:59
6.3	Dimensional (38 x 184)	406	XGB[1]	35:18 No collapse

[1] Type X gypsum board

3.2 Experiments based on the ASTM-119 temperature-time exposure

Fewer standard tests have been conducted with unprotected and protected floor assemblies compared to non-standard tests. UL conducted one of the most extensive series involving seven fire tests (see Tests 8-1 to 8-7 in Table 8) with floor assemblies using a standard floor furnace [23] following the standard ASTM E119 time-temperature exposure. The performance of floor assemblies constructed with engineered wood I-joists, metal gusset trusses and finger joint trusses were compared with that of an assembly constructed with traditional 38 x 235 mm (nominal 2 x 10) dimensional lumber joists. Two tests were conducted with unprotected assemblies (without a ceiling installed) while the remaining five tests were conducted with protected assemblies. The research concluded that the fire endurance of a combustible floor assembly constructed with dimensional lumber joists was 18 min, which was used as the benchmark performance for comparison with other assemblies. A wood I-joist floor assembly recorded a fire endurance that was 12 min less than the bench mark (Test 8-2 vs Test 8-1). Addition of a 12.7 mm thick regular board ceiling to the wood I-joist assembly increased its fire performance by 8 minutes above the benchmark value (Test 8-4 vs Test 8-1).

Figure 11 shows the results of structural failure times for 15 experiments (including the seven UL tests discussed previously) that were conducted with the floor assemblies subjected to the standard ASTM E119 temperature-time exposure. As was the case with the non-standard tests, the applied load affects the structural fire endurance of the assembly. The one test with an unprotected steel C-joist assembly recorded the lowest failure time of 3.75 min. A wood I-joist assembly also had a relatively short time to failure of 6 min under an applied load of 97 kg/m^2. The effect of the applied load is clear from results for the dimensional lumber assembly; the failure time was as short as 6.5 min under a high applied load of 387 kg/m^2, while this was significantly extended to 18.8 min at a loading on 97 kg/m^2, which is similar to the live load that was applied in the NRC FPH fire tests. As previously found in the non-standard tests, the application of a ceiling protection resulted in a significant improvement in structural fire endurance. Two tests are highlighted in Figure 11, in which the failure time was greatly increased (beyond 40 min) likely due to the type of ceiling, sub-floor and finish materials (19 x 140 mm (1 x 6) subfloor, (19 x 89 mm (1 x 4) floor finish and 12.7 mm regular gypsum board in one case; and 19 mm plasterboard in the second case).

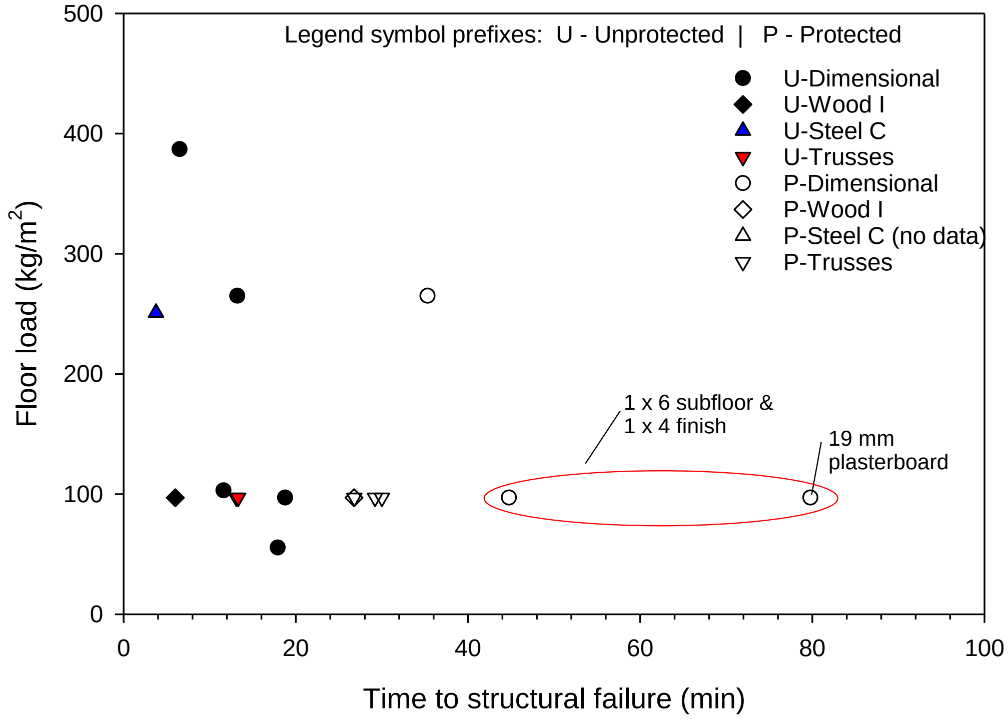

Figure 11. Failure time of 15 experiments based on the ASTM E-119 standard test method

Table 7 shows selected results of test assemblies with a comparable live load to that (95 kg/m^2) used in the FPH study. Note that there were no standard tests conducted in the FPH study. This comparison is provided to give an indication of how some types of assemblies tested in the FPH study performed in standard tests found in the literature. With the exception of Test 8-2 (unprotected Wood-I joist assembly), comparable assemblies recorded longer times to failure in the standard tests compared to those obtained in the FPH study due to the expected greater fire severity in the non-standard fire scenarios used in the FPH study and the fact that some of the assemblies in the standard tests included floor finish materials, e.g. Test 8-1 was constructed with a 19 x 140 mm (1 x 6 in) tongue and groove subfloor and a 19 x 89 mm (1 x 4 in.) floor finish whereas the FPH assembly in Test UF-01 only had a 15.1 mm thick OSB subfloor.

Table 7. Selected standard floor tests conducted with a live load of 97 kg/m^2.

Test ID	**Joist Type**	**Joist Spacing (mm)**	**Ceiling Finish**	**Failure time (mm:ss)**	**FPH failure time (mm:ss)****
8-1	Dimensional (38 x 235)	406	None	18:45	12:20 (Test UF-01, 406 mm spacing)
8-2	Wood-I	610	None	6:03	8:10 (Test UF-03, 406 mm spacing) 6:22 (Test UF-06, 406 mm spacing)
8-5	MPCW	610	GB	29:15	No FPH data
8-6	Wood-I	610	GB[1]	26:45	20:47 (Test PF-04, 406 mm spacing)
9-3	MPCW	610	None	13:20	7:49 (Test UF-05, 406 mm spacing)

[1] 12.7 mm regular gypsum board

** FPH study only performed non-standard room tests

Table 8. Summary of unsprinklered fire experiments of residential floor assemblies constructed with dimensional lumber, steel and engineered wood joists

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
1-1	Dimensional 38 x 184 mm 406 mm. o.c.	NBS (NIST) / 1973 [24]	12.7-mm plywood	ASTM E119	None	103	11:38	- Loading was 40% less than required in the standard.
2-1	Steel C (6 x 1 3/4”) 610 mm. o.c.	NBS (NIST) / 1973 [25]	19-mm plywood with carpet	ASTM E119	None	251	3:45	
3-1	Dimensional 38 x 235 mm 406 mm o.c.	Forest Products Laboratory / 1983 [26]	18.3-mm plywood	ASTM E119	None	55.4	17:54	- Furnace dimensions: 3.56 m wide x 4.57 m length. - 55.4 kg/m^2 represented domestic live load from survey results [27], hence deviated from the standard - Average of 5 tests (standard deviation 48 s) - Time to failure of the first joist
3-2	Dimensional 38 x 235 mm 406 mm o.c.	Forest Products Laboratory / 1983 [26]	18.3-mm plywood	ASTM E119	None	387	6:30	- Furnace dimensions: 3.56 m wide x 4.57 m length.

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
								- Average of 5 tests (standard deviation 44 s) - Time to failure of the first joist
4-1	Dimensional 38 x 235 mm 406 mm. o.c.	Illinois Fire Service Institute / 1986 [28]	2.4 x 4.9 m / 19-mm OSB	Non-standard	None	151	>13:00	- Fire load: Diesel fuel - Demonstration tests
4-2	Wood-I 406 mm. o.c.	Illinois Fire Service Institute / 1986 [28]		Non-standard	None	151	4:40	
4-3	MPCW[1] truss 406 mm. o.c.	Illinois Fire Service Institute / 1986 [28]		Non-standard	None	151	15:45	
4-4	MWW[2] truss 406 mm. o.c.	Illinois Fire Service Institute / 1986 [28]		Non-standard	None	151	N/A	
4-5	TJL[3] truss 406 mm. o.c.	Illinois Fire Service Institute / 1986 [28]		Non-standard	None	151	9:45	
5-1	Wood I 302 mm. deep 610 mm. o.c.	Tyco / 2008 UL [20]	4.9 m x 4.9m / Plywood finished with carpet	Non-standard	None	24.4	Test #1 11:10 Test # 2 8:34	- Fuel load: Residential furnishings. - Fuel load: 23 kg/m^2 - Joist installed 24 in. O.C. - Floor live load: 581 kg (24.4 kg/m^2) consisting of 136 kg firefighter

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
								mannequins and concrete blocks.
6-1	Dimensional 38 x 184 mm 406 mm. o.c.	NIST / 1980 [21]	3.3 m x 3.3 m / 15.9-mm Plywood finished with carpet	Non-standard	None	195.0	10:43	- Fuel load: Residential living room furnishings (including upholstered sofas) - 7 tests in the series - Span of all joists was 3.25 m - Instrumentation: Temperatures, deflection, heat flux, static pressure, air velocity at doorway, smoke optical density, gas concentrations (O_2, CO, CO_2)
6-2	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1980 [21]	3.3 m x 3.3 m / 18.3-mm plywood finished with carpet	Non-standard	None	195.0	12:00	
6-3	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1980 [21]	3.3 m x 3.3 m / 18.3-mm.plywood finished with carpet	Non-standard	XGB[4]	195.0	35:18 (N.C.)[7]	
6-4	Steel C 184 mm deep 610 mm. o.c.	NIST / 1980 [21]	3.3 m x 3.3 m / 15.9-mm plywood	Non-standard	None	352.0	3:47	

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
			finished with carpet					
6-5	Steel C 184 mm deep 610 mm. o.c.	NIST / 1980 [21]	3.3 m x 3.3 m / 18.3-mm plywood finished with carpet	Non-standard	GB[5]	327.0	15:58 (N.C.)	
6-6	Steel C 184 mm deep 810 mm. o.c.	NIST / 1980 [21]	3.3 m x 3.3 m / 19.1mm plywood finished with carpet	Non-standard	None	195.0	3:59	
6-7	MPCW truss 184 mm deep 610 mm. o.c.	NIST / 1980 [21]	3.3 m x 3.3 m / 18.3mm plywood finished with carpet	Non-standard	GB	327.0	18:34	
7-1	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]	18.3 mm. plywood finished with carpet (for all tests)	Non-standard (furnace fire)	XGB	265	N.C. (flame through at 20:06)	- Tests conducted using a standard fire resistance furnace measuring 2.95 m long x 2.44 m wide x 2.85 m high. - Furnace temperature controlled to follow ASTM E119 and Non-standard (in-house) exposure in some tests.

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
								- Specimen dimensions: 2.44 m wide x 3.05 m long. - High furnace excess air
7-2	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]		ASTM E119	XGB	265	35:20 (flame through at 34:00)	- High furnace Excess air
7-3	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]		Non-standard (furnace fire)	None	265	6:53 (flame through at 6:04)	
7-4	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]		Non-standard (furnace fire)	None	265	7:52 (flame through at 6:07)	
7-5	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]		Non-standard (furnace fire)	None	265	7:36 (flame through at 7:00)	- High furnace excess air
7-6	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]		Non-standard (furnace fire)	None	265	14:42 (flame through at 16:08)	- Low furnace excess air
7-7	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]		ASTM E119	None	265	13:10 (flame through at 17:35)	
7-8	Dimensional 38 x 184 mm	NIST / 1982 [22]		Non-standard	XGB	265	24:59	- Low furnace excess air #2

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
	610 mm. o.c.			(furnace fire)			(flame through at 24.22)	
7-9	Dimensional 38 x 184 mm 610 mm. o.c.	NIST / 1982 [22]		Non-standard (furnace fire)	None	265	8:48 (flame through at 9:09)	- Low furnace excess air #2
7-10	Steel C 184 mm deep 610 mm. o.c.	NIST / 1982 [22]		Non-standard (furnace fire)	None	265	2:38 (flame through 4:38)	- Low furnace excess air #2
8-1	Dimensional 38 x 235 mm 406 mm. o.c.	UL / 2008 [23]	19 x 140 mm (1 x 6) subfloor & (19 x 89 mm (1 x 4) floor finish	ASTM E119	None	97	18:45 (flame through 18:30)	- Nine fire tests conducted in the project with seven different residential floor assemblies and two roof assemblies (not reported here) - Non-standard load: 195 kg/m^2 along two of the four edges and two 136 Kg (fire fighter mannequins) concentrated loads near the center - Total live load: 2,282 kg (approx. distributed load: 97 kg/m^2

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
8-2	Wood-I 305 mm deep 610 mm. o.c.	UL / 2008 [23]	18.3-mm OSB with carpet	ASTM E119	None	97	6:03 (flame through 6:00)	
8-3	Dimensional 38 x 235 mm 406 mm. o.c.	UL / 2008 [23]	19 x 140 mm (1 x 6) & (19 x 89 mm (1 x 4) floor finish	ASTM E119	GB	97	44:45 (flame through 44:15)	
8-4	Wood-I 305 mm deep 610 mm. o.c.	UL / 2008 [23]	18.3-mm OSB with carpet	ASTM E119	GB	97	26:45	
8-5	MPCW truss 356 mm deep 610 mm. o.c.	UL / 2008 [23]	18.3-mm OSB with carpet	ASTM E119	GB	97	29:15 (flame through 28:40)	
8-6	FJCW[6] truss 356 mm deep 610 mm. o.c.	UL / 2008 [23]	18.3-mm OSB with carpet	ASTM E119	GB	97	26:45 (insulation failure 24:15)	
8-7	Dimensional 38 x 235 mm 406 mm. o.c	UL / 2008 [23]	19 x 140 mm (1 x 6) subfloor & (19 x 89 mm (1 x 4) floor finish	ASTM E119	19 mm plaster	12	79:45 (flame through 26:00)	-
9-1	MPCW truss 356 mm deep 610 mm. o.c.	UL / 2009 [29]	18.3-mm OSB with carpet	ASTM E119	GB	12	30:08 (flame through 26:00)	- Assembly included bottom cord splices, can lights and duct work - Non-standard load: 195 kg/m^2 along two of the four edges and two

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
								136 Kg (fire fighter mannequins) concentrated load near the center
9-2	FJCW[6] truss 356 mm deep 610 mm. o.c.	UL / 2009 [29]	18.3-mm OSB with carpet	ASTM E119	None	97	13:06 (insulation failure 11:15)	- Non-standard load: 195 kg/m^2 along two of the four edges and two 136 Kg (fire fighter mannequins) concentrated load near the center
9-3	MPCW truss 356 mm deep 610 mm. o.c.	UL / 2009 [29]	18.3-mm OSB with carpet	ASTM E119	None	97	13:20 (insulation failure 5:00)	- Non-standard load: 195 kg/m^2 along two of the four edges and two 136 Kg (fire fighter mannequins) concentrated load near the center
10-1	Dimensional 38 x 286 mm (2 x 12) 406 mm. o.c	UL / 2012 [28]	6 x 11 m 18.3-mm OSB sub-floor	Non-standard (maximum ventilation)	None	137	11:09	- Test setup: Field experiments simulated a house with a basement and one storey above - Fuel load mass: 430 kg of wood pallets and polystyrene trays

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
								- Floor loading: water filled steel barrels to provide 65% of allowable load - Assemblies selected to be representative of residential construction, continuity with previous experiments and need to optimize the span - Ventilation settings: - Maximum: all openings open
10-2	Dimensional 38 x 286 mm (2 x 12) 406 mm. o.c	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (Sequenced ventilation)	None	137	12:45	- Sequenced ventilation: openings opened to simulate fire department operations.
10-3	Wood I 305 mm deep 406 mm. o.c	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (maximum ventilation)	None	176	6:00	
10-4	Wood I 305 mm deep 406 mm. o.c	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (No ventilation)	None	176	6:49	- Sequenced ventilation: openings opened to simulate fire

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
								department operations.
10-5	Wood I 305 mm deep 406 mm. o.c	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (No ventilation)	None	176	8:27	- Modified fuel load - Sequenced ventilation: openings opened to simulate fire department operations.
10-6	Wood I 305 mm deep	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (sequenced ventilation)	None	176	6:49	- Modified fuel load: 195 kg/m2 along two of the four edges and two 136 Kg barrels to simulate fire fighters at the center of the floor - Sequenced ventilation: openings opened to simulate fire department operations. - Modified fuel load: No polystyrene.
10-7	Steel C 305 mm deep	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (maximum ventilation)	None	139	8:15	
10-8	Steel C 305 mm deep	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard	None	139	14:04	- Sequenced ventilation: openings opened

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
				(sequenced ventilation)				to simulate fire department operations.
10-9	MPCW truss 356 mm deep	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (No ventilation)	None	139	6:08	- Sequenced ventilation: openings opened to simulate fire department operations.
10-10	MPCW truss 356 mm deep	UL / 2012 [28]	18.3-mm OSB sub-floor	Non-standard (maximum ventilation)	None	139	3:28	
11-1	Wood I 305 mm deep 406 mm. o.c	UL / 2012 [28]	6 x 11 m / 18.3-mm OSB	Non-standard	None	176	6:20	- Set of four large-scale tests conducts in the UL test facility - Test setup only simulated the basement compartment (without first floor) and used similar dimensions to previously conducted filed experiments with the same ventilation opening - Stairwell to first floor, but doorway

Test No.	Type of Joist	Organization and date of testing	Assembly Dimensions / Sub-floor	Fire Exposure	Ceiling	Load (kg/m^2)	Structural Failure (min:sec)	Additional Details
								was open to outside. - Same fuel load and floor load as that used in field experiments - Maximum ventilation for all tests. - Test 1 was a repeat of filed test #3. - Floor load: 65% of design stress
11-2	Wood I 305 mm deep 406 mm. o.c	UL / 2012 [28]		Non-standard	None	176	31:25	- Fire started by igniting center of floor assembly (underside) Ignited with a propane torch, resulting in delayed fire spread to main fuel load
11-3	MPCW truss 356 mm deep 406 mm. o.c	UL / 2012 [28]		Non-standard	GB	176	44:46	- Ceiling void ignition (two igniters in floor void space) - Ceiling penetrations: Ten recessed lights
11-4	MPCW truss 356 mm deep 406 mm. o.c	UL / 2012 [28]		Non-standard	GB	176	13:10	- Ceiling finish: with 7.43 m2 (80 ft^2) exposed, as required in the

Test No.	**Type of Joist**	**Organization and date of testing**	**Assembly Dimensions / Sub-floor**	**Fire Exposure**	**Ceiling**	**Load (kg/m^2)**	**Structural Failure (min:sec)**	**Additional Details**
								2012 International Residential Code Section R501.3 - Ceiling penetrations: Recessed lights

[1] MPCW truss: Metal-plate connected wood truss; [2] MWW truss: Metal-webbed wood truss; [3] TJL: Trus joist L-series (outdated)

; [4] XGB - 16-mm type X gypsum board; [5] GB - 12-mm regular gypsum board; [6] FJCW: Finger jointed connected wood truss.

[7] N.C. – No Collapse: Joists did not collapse (failure determined by excessive deflection)

3.3 Fire Fighting Implications

Recent research undertaken at UL sought to understand the changes in residential room fires that has occurred over the past several decades and the resulting impact on the structural fire endurance of residential floor and roof assemblies [18,30]. The changes discussed included larger homes, different home geometries, increased synthetic fuel loads, and changing construction materials. Several room fire experiments were conducted to compare the impact of changing fuel loads in residential houses. These experiments showed that living room fires had flashover times of less than 5 min when they used to be in the order of 30 min [30] decades ago. Similar and even shorter times to flashover have also been observed in experiments conducted at NRC [31] in which a relatively strong (> 9 kW) flaming ignition source was used. Other experiments conducted at UL demonstrated that the failure time of wall linings, windows and interior doors has decreased over time, which also impacts fire growth and firefighting tactics. Each of these changes alone may not be significant but the all-encompassing effect of these developments on residential fire behavior has changed the incidents that the fire services are responding to.

One of the test series that is not included in Table 8, which was conducted at UL [18], was driven by the need to inform firefighting operations. Table 9 provides a summary of the results of the UL tests. The assemblies did not include a ceiling and were considered unprotected floor assemblies representative of a basement. Two of the assemblies were coated with a topical treatment to assess its ability to provide fire protection to enhance structural integrity. These experiments were part of a larger project that examined residential floor systems in different scales of experiments, examining several variables to provide information to the fire service to add to their knowledge of basement fire dynamics and collapse hazards. Floor collapse times ranged from 2 min 20 s to 18 min 05s. Three fire service tactical considerations were identified and several IRC code implications were discussed. The tactical considerations concerned the following:

1) The timeframe for collapse of unprotected floor assemblies with regards to the operational timeframes of the fire service;
2) Procedures used to determine the structural integrity of floor assemblies, and;
3) The use of thermal imaging cameras.

The results of these experiments were combined with a series of experiments conducted by UL in 2008 [23], which took place in the same floor furnace. It was highlighted that the collapse of all unprotected floor systems, including dimensional lumber, happened well within the potential operational timeframe of the fire services. This timeframe was considered to be less than 11 minutes, which was the 90th percentile value based on a study that was conducted by the United States Fire Administration (USFA) [32]. It was also highlighted that some procedures used by firefighters to determine the structural integrity of floor assemblies during actual fire incidents may not be reliable, e.g., sounding of the floor and the use of thermal imaging cameras.

Table 9. Summary of ASTM E119 experimental results for seven floor assemblies

Assembly	**Time of 121ºC avg. temperature rise of surface of floor (min:sec)**	**Time of 163ºC max. temperature rise of surface of floor (min:sec)**	**Flame passage through floor (min:sec)**	**Time of structural failure (min:sec)**
Wood I-joist (with openings) (~ 40% load)	NR[1]	NR	18:10	18:10
Wood metal hybrid truss (~ 40% load)	NR	NR	5:30	5:30
Wood I-joist with intumescent coating (~ 40% load)	NR	NR	15:10	17:50
Wood I-Joist (100% load)	NR	NR	2:20	2:20
Wood I-joist with fire retardant coating (~ 40% load)	NR	NR	8:40	8:40
38 x 235 mm dimensional lumber (2 x 10) (100 % load)	NR	NR	7:04	7:40
38 x 184 mm dimensional lumber (2 x 8) (100% load)	15:40	14:20	15:45	18:05

[1] Not Reached.

Another study was conducted by UL in 2012 [28], involving 14 non-standard fire tests of unprotected floor assemblies (See Tests 10-1 to 11-4 in Table 8), with one of the tests representing a more severe fire scenario where the fire was provided with sufficient ventilation to achieve a faster growth and higher peak temperatures. It was concluded that although dimensional lumber floor assemblies outperformed engineered assemblies, they could not be considered to provide a sufficient level of safety for responding firefighters since the two floor systems constructed with 38 x 286 mm (2 x 12) dimensional lumber joists collapsed at 11 min 9 s and 12 min and 45 s for the first and second tests, respectively, in view of the findings of USFA on structural fire response times [32]. With regards to the 2012 IRC R501.3 provision, exception No. 4, which effectively set the fire performance of dimensional 38 x 235 mm (2 x 10) as the benchmark, the study argued that the code provisions needed further clarification since the structural fire endurance of 7 min 40 s obtained in this study (Table 9) implied compliance with the code although it did not provide adequate time for the fire service operations. A similar result was obtained in earlier tests conducted at the Forest Products Laboratory (See Test 3-2, in Table 8); the average failure time of five assemblies that were conducted by applying the maximum load of 387 kg/m^2, in accordance with the ASTM E119 test method, was 6.5 min with a coefficient of variation of 11.6%. Additional observations from this UL research were:

1. The assemblies treated with the spray applied fire retardants or intumescent coatings were unable to provide the fire endurance required by the new IRC code provision. Therefore, applying a 12.7 mm layer of gypsum provided better performance.
2. The older 38 x 184 mm (2 x 8) dimensional lumber assembly had a vastly superior fire endurance of 18 min compared to 7 min for the newer 38 x 235 mm (2 x 10) assemblies due to the differences in the applied load, which was significantly higher for the 38 x 235 mm assemblies as per the standard test method..

The second observation raised some questions regarding the test parameters on which the IRC R501.3 code provision was based since previous tests conducted at UL (See Table 8, Test 8-1) showed that a similar 38 x 235 mm (2 x 10) assembly did not fail until 18 min 35, albeit using a wood material as the floor finish on top of a 19 x 140 mm (1 x 6) sub-floor. However, it is noted that the failure time of 7 min for the 38 x 235 mm wood joist was obtained at the maximum design load and therefore, it is the opinion of the authors of this report that the result may be inconsequential given that the IRC equivalence fire resistance time of 15.5 min (see Section 4 for more details) only requires 50% of the design load.

4 US Regulatory Developments and Test Methods

In light of the 2015 or 2018 IRC R302.13 requirements for the fire protection of residential floor assemblies, the Wood I-Joist Manufacturers Association (WIJMA) in the USA developed guidelines for a test methodology [33] intended to demonstrate equivalent fire performance of structural floor joists to the unprotected 38 x 235 mm (2 x 10) dimension lumber that is required in the IRC. The guidelines were developed by a task group setup up by WIJMA, which consisted of testing labs and product manufacturers and certification agencies. The guidelines were intended to be also applicable to factory-applied or field-applied treatments or materials used to provide fire resistance to a floor joist, which includes fire-resistive paints, coatings or chemical treatments, or mechanically-attached fire protection materials.

4.1 The WIJMA test method

The test method prescribes the use of a standard fire resistance floor furnace to subject a test specimen to the ASTM E119 temperature-time exposure. While the ASTM E119 test protocol is not followed entirely, elements of the test method relating to temperature measurement are retained while relaxing the allowable temperature deviations in light of the difficulty of controlling the furnace temperature given that unprotected wood components of the test specimens contribute additional fuel. Some of the main details of the test method are as follows:

1. **Load:** Each floor joist is required to support 50% of its full allowable stress design (ASD) bending design load. (Note: This is the service load, similar to that used in the NRC FPH project)
2. **Deflection:** Measured at the mid-span as directed in the guide.
3. **Test Duration:** Continued until a floor joist can no longer support the applied load. Further details on how to determine failure are provided in the guide.
4. **Condition of Acceptance:** The test duration shall be at least 15 minutes and 30 seconds, which was calculated using a methodology specified in Chapter 16 of the American Wood Council (AWC) National Design Specification (NDS) for Wood Construction assuming unprotected solid-sawn 38 x 235 mm (2 x 10) dimension lumber or equal sized structural composite lumber floor joists.
5. **Test Specimen Design:** Permits the use of test specimen that is less than full-scale with single or multiple floor joists, and floor sheathing is permitted for lateral support of the joist, but should not provide any vertical support.

The guide contains vast information on various fire protection aspects relating to fire resistive paints, coatings and chemical treatments that can be applied to joists or other components.

The Engineered Wood Association (APA), WIJMA and AWC [12] discussed the basis of the 2018 IRC provisions in Section R302.13, indicating that the intent of the provisions was to ensure a minimum level of fire performance for floors in one- and two-family dwellings that were previously not required to be fire-resistance rated. The document stated that part of the rationale for selecting the 12.7 mm regular gypsum board sheathing for protecting framing members was because building codes already recognized that it provided approximately 15 minutes of added fire endurance under the standard ASTM E119 exposure conditions. The 38 x 235 mm (2 x 10) dimensional lumber joist was selected as a benchmark since the fire service indicated that fewer problems had been experienced in the many decades that it was used in homes with unfinished basements (note that NBC 2020 does not require a ceiling finish for any floors in houses). As stated earlier, the means to benchmark the fire performance of 38 x 235 mm (2 x 10) lumber joist does not rely on an actual test, but rather a calculation that is contained in

Chapter 16 of the AWC National Design Specification for Wood Construction (NDS). The result of the calculation yields a fire resistance time of 15.5 min (time to failure) for a single dimension lumber joist subjected to the ASTM E119 temperature-time exposure with a load ratio of only 50% of the design capacity. Coincidentally, the calculated fire resistance of 15.5 min is essentially the same as that assumed for 12.7 mm regular gypsum board. The applied load is in accordance with procedures described in the ICC ES AC 14 [34] and is based on the conservative assumption of the actual load ratio for residential floor loads during a fire, i.e., part of the live load is absent following the escape of occupants. Apparently, the NDS method for calculating fire resistance times for wood assemblies is permitted in the 2015 International Building Code (IBC)[2] . Part of the rationale for selecting a reduced load ratio appears to have been an intent to extend the time that framing members were exposed to high temperatures under the ASTM E119 exposure. As was seen from the literature review of standard ASTM E119 tests with unprotected assemblies, the failure time of a 38 x 235 mm (2 x 10) wood joist can be substantially reduced to as low as 6.5 min when the full design load is applied according to the standard test method.

5 Summary

Research into the performance of residential floor assemblies constructed with innovative engineered components, particularly joists, has been motivated by the long-held notion that floor and roof assemblies constructed with engineering structural elements exhibit reduced structural fire endurance compared to dimensional lumber assemblies. In this regard, the main concern is that the possibility of engineered assemblies experiencing structural failure earlier than dimensional lumber assemblies could have an adverse impact on the safety of occupants and first responders. This has resulted in engineered floor assemblies being the focus of a number of research efforts, in Canada and the US, aimed at developing technical information that can be used to develop solutions to address the resulting fire safety challenges. In Canada, this concern was brought to the CCCME by CCMC, especially as the NBC 1995 did not require floors to be protected from underneath, for all floors in a house. To this end, NRC undertook the FPH Project phase 1, in 2004, in response to a request from the CCBFC and the CCCME. In addition, other organizations [21,28] have also carried out similar research to the FPH study.

This report summarized the results of Phase 1[3] of the FPH research that was undertaken at NRC and an extensive literature review of various other related research and regulatory

---

[2] It should be noted that method of using char rate to determine the reduced cross-section of the wood member is similar to the T.T. Lie method in 2015 NBC Appendix D2.1. A similar method for large (heavy/mass) timber elements is described in informative Annex B of CSA 086, but it is not recognized in the NBC 2015. However, it will be recognized in the 2020 NBC.

[3] Phases 2 and 3 were planned to focus on the fire performance of innovative wall assemblies and foundations, which have also been outlined by CCMC in 1995 as being a source of concern for innovative product for walls and foundations in houses. However, the work was not undertaken due to the closure of the NRC large-scale fire research laboratory in 2006.

developments in the published literature, in the US and Canada, to assist the work of the CCBFC Joint Task Group on Fire Performance of Floor Assemblies in Houses.

5.1 Fire Performance of Houses Research

The FPH research developed a wealth of information on the fire performance of a range of engineered floor systems, constructed with wood I-joists, steel C-joists, metal-plate and metal-webbed wood trusses, under two fire scenarios (door to the basement either open or closed) and where the joists were either unprotected or protected. The FPH research established that the time to structural failure for the engineered floor assemblies tested was 35-60% shorter than that for the dimensional lumber assemblies and that the failure of the unprotected floor assemblies in the fire scenarios used did not appear to be the critical issue affecting occupant life safety since the tenability limits were reached before the structural failure of the test floor assemblies occurred in all but one experiment. For the tests with unprotected floor assemblies that were conducted with the basement door open, the time to structure failure ranged from 5 min 25 s (metal-webbed wood truss assembly) to 12 min 20s (dimensional lumber assembly). Closing the basement doorway extended the time to structure failure for the three assemblies tested since the lower ventilation reduced the intensity of the fire. Under this scenario, the times to structure failure of the dimensional lumber, metal-webbed wood truss and wood I-joist A increased by 7 min 40 s, 2 min 29 s and 4 min 48 s, respectively. It was also concluded that an early alert to a fire played a significant role in enhancing occupant life safety. The smoke alarm located in the basement compartment consistently took 30-50 s to activate. The experimental results highlighted the importance of the NBC requirements for interconnected smoke alarms in houses.

In four experiments with the floor assemblies that were protected with a gypsum board ceiling, the period during which tenable conditions were maintained, was similar to or slightly improved than that obtained in the tests with unprotected assemblies. However, only the assemblies with a gypsum board ceiling exhibited a significant improvement in the structural fire endurance, for instance the dimensional lumber assemblies improved by 9 min 40 s while the lowest performing unprotected assembly (metal-webbed wood truss) achieved the highest improvement of 18 min 19 s.

For the experiments with residential sprinkler-protected assemblies, the residential sprinkler systems protected the structural integrity of the test assemblies and effectively suppressed the fire. No ignition, structural failure or damage occurred with the test assemblies during the experiments and tenability conditions remained viable throughout during the experiments.

5.2 Literature Review

An extensive literature review was undertaken, which covered in excess of 50 fire experiments (excluding the 16 tests conducted at NRC in the FPH research) conducted since 1973 and that were relevant to the objectives of this study. In addition to dimensional lumber joists, the following six types of engineered joist were covered: wood I-joists, steel C-joists, metal-plate connected wood truss, finger jointed (glued) wood truss and metal-webbed truss. The tests reviewed were grouped in two main categories, standard and non-standard, defined by the type of fire exposure. Non-standard tests seek to simulate actual compartment fires using combustible fuel loads and the tests are typically conducted in structures that are constructed with representative construction materials. Non-standard tests also included tests that are conducted in fire resistance furnaces without following the ASTM E119 and CAN/ULC S-101 temperature-time exposure; such tests usually attempt to simulate temperature conditions that are consistent with compartment fires. Although many of the non-standard compartment tests were very well instrumented for temperature, heat flux and gas concentration measurements, none of the tests other than the NRC FPH research conducted any tenability analysis.

5.2.1 Non-Standard Tests

The results demonstrated that one of the key variables that had a strong influence on the structural fire endurance for identical assemblies was the live load that was applied to the test assemblies, which is a known factor. Other main variables in non-standard compartment fire tests included ventilation conditions and the fire load (quantity and composition), which creates differences in fire severity. In addition, there were also variables associated with construction materials, such as the sub-floor and floor finish. This resulted in unprotected dimensional lumber assemblies exhibiting a wide range of failure times, from about 6 min under high loading to about 20 min under lower loads and less severe fire conditions. For unprotected floor assemblies, the range of failure times for specific engineered floor assemblies were as follows (live load is given in parenthesis):

- Steel C-joist assemblies: 2.6 min (265 kg/m^2) to 7.7 min (97 kg/m^2)
- Wood I-joist assemblies: 4.7 min (151 kg/m^2) to 12.9 min (97 kg/m^2)
- Trusses (mostly metal-plate connected wood): 3.5 min (139 kg/m^2) to 6 min (139 kg/m^2)

The addition of a 12.7 mm regular gypsum ceiling to protect the assemblies resulted in a significant increase in the structural fire endurance for all assemblies, extending the failure time by more than 10 min in many cases. For all of the tests in which a protective ceiling membrane was installed, the failure time ranged from 13.1 min (for a metal-plate connected wood truss assembly) to 44.8 min (again for a metal-plate connected wood truss assembly), with other assemblies, including dimensional lumber, producing values in between.

5.2.2 Tests using the Standard ASTM E119 and CAN/ULC S-101 Temperature Exposure

There were fewer standard tests that have been conducted with unprotected and protected floor assemblies compared to non-standard tests, with none of the tests conducted at NRC in the FPH research. The effect of the applied load is demonstrated by looking at results of dimensional lumber assemblies. It is noted that there were no other significant variables in standard tests other than minor variations due to differences in test and specimen preparation procedures and materials at different laboratories. In tests with unprotected floor assemblies, the failure time was as short as 6.5 min under a high (maximum) applied of 387 kg/m^2, while it was significantly extended to

18.8 min at a lower loading of 97 kg/m^2. For unprotected floor assemblies, the range of failure times for specific engineered floor assemblies were as follows (superimposed load is given in parenthesis):

- Steel C-joist assemblies: 3.8 min (251 kg/m^2) - one data point
- Wood I-joist assemblies: 6 min (97 kg/m^2) - only one data point
- Trusses (mostly metal-plate connected wood): 13.1 min (139 kg/m^2) and 13.3 min (139 kg/m^2) – Two data points

As was the case with non-standard tests, the addition of a ceiling membrane (typically 12.7 mm gypsum board) resulted in a significant improvement in structural fire endurance, with failure times ranging from 26 min to 80 min (for instance, structural failure time of a dimensional lumber joist assembly increased from 18 min 45 s to 44 min 45 s; other assemblies were as follows: Wood-I joist - 6 min 3 s to 26 min 45s; metal-plate connected truss joist – 13 min 20 s to 30 min 8 s). The assembly with the highest failure time of 79 min 45 s was constructed with 38 x 235 mm dimensional lumber joists, 19 mm plaster board ceiling and subjected to a low applied load of only 12 kg / m^2.

5.2.3 US Regulatory Developments

Since 2012, the International Code Council (ICC) International Residential Code in the US introduced a code change that required residential floor assemblies that are not required to be fire resistance rated to meet specified performance requirements. The Code (2012 IRC Section R501.3 and 2018 Section R302.13) requires floor assemblies to be provided with a 12.7-mm gypsum membrane, 15.9-mm wood structural panel membrane or equivalent on the underside of the floor framing with the four exceptions (R302.13 (4)), one of which essentially required non-dimensional lumber assemblies to demonstrate fire performance equivalent to that of 38 x 235 mm (2 x 10) dimensional lumber. Another exception (R302.13 (3.1)) permits floor assemblies to have a total unprotected ceiling area of 7.4 m^2 (80 ft^2) per storey. The equivalent fire resistance time of the reference joist was determined to be 15.5 min based on a calculation method contained in Chapter 16 of the AWC National Design Specification for Wood Construction assuming ASTM E119 fire exposure and a 50% design load.

One instance of an industry-developed technical guide / test protocol that was developed by WIJMA of Canadian and US manufacturers of I-joists and the CCMC Test Protocol has been harmonized with this WIJMA Protocol. The test method utilizes the ASTM E119 or CAN/ULC S101 temperature-time exposure and the test specimen can be less than full scale and constructed with as few as one joist. This is likely due to the approach used to determine the fire resistance time of the 38 x 235 mm (2 x 10) dimensional joist, i.e., the calculation was carried out for one structural member based on char rate and residual cross-section.

5.3 Further Research

The literature review revealed that many non-standard and standard fire experiments have been conducted with floor assemblies constructed using various types of floor joists. There are many variables that were found to have an influence on the fire performance of floor assemblies. One variable that had a significant impact on structural fire performance, for both standard and non-standard tests, is the live load that is applied to the floor assembly. Other variables in non-standard tests include parameters that have a direct influence on the severity of the fire, such as fuel load (quantity and type), compartment size and lining materials, ventilation conditions and method of fire initiation. Other factors that impact structure fire performance include floor construction details and materials (e.g. floor finish materials).

The available data shows that the structural fire endurance of unprotected engineered floor joist assemblies underperforms that of dimensional lumber assemblies as detailed in this report. Although the data provides valuable insight into the performance of various floor assemblies under standard and non-standard fire exposures, it was found that there was a lack of uniformity in test variables, which makes it difficult to draw firm conclusions and to use the data in subsequent research.

The NRC FPH study developed a test method for evaluating the fire performance of floor assembly under real fire conditions in a simulated house structure. However, the high cost of non-standard tests, such as those conducted in the FPH study, makes them less feasible for routine regulatory testing. Therefore, there is a need to develop less costly test methods that utilize established standard test facilities, such as the floor furnace that is used in the CAN/ULC S101 test method.

In view of the lack of uniformity in test variables that was found in the published literature that is presented in this report and an effort to build on the FPH study, NRC-Construction Fire Safety is planning to undertake an experimental program with input from the Joint Task Group (JTG) on Fire Performance of Floor Assemblies in Houses. The research will be helpful in developing a consistent set of test data that addressees parameters, such as live load, that are relevant to NBC requirements for floor assemblies in houses. The scope of the proposed research is as follows:

1) Develop a modified furnace test method to simulate the temperature conditions obtained in the NRC FPH study. This will provide a cost-effective means of evaluating the effect of identified variables on the structural fire performance of floor assemblies that can be related to real fire performance.
2) Develop test data on the performance of selected floor assemblies (e.g. those tested in the FPH study) using the standard CAN/ULC S101 test method with the live load used in the FPH study. Note that none of the standard tests found in the literature had the same applied load and floor assembly designs that were directly comparable to the FPH assemblies.
3) Explore the feasibility of developing a correlation to predict structural fire performance of floor assemblies between the standard tests (2) and simulated FPH tests (1).

6 References

1. Grundahl, K., National Engineered Lightweight Construction Fire Research Project – Technical Report: Literature Search & Technical Analysis, 1992, National Fire Protection Research Foundation, USA.
2. Su, J.Z.; Bénichou, N.; Bwalya, A.C.; Lougheed, G.D.; Taber, B.C.; Leroux, P.; Kashef, A.; Thomas, J.R., Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Summary Report. Research Report IRC-RR-252, Institute for Research in Construction, National Research Council Canada: Ottawa, Canada; 2008.
3. Su, J.Z.; Bénichou, N.; Bwalya, A.C.; Lougheed, G.D.; Taber, B.C.; Leroux, P.; Kashef, A.; Thomas, J.R., Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Part 2 - Results of Tests UF-03 and UF-09 (Wood I-Joists A), Research Report RR-247, Institute for Research in Construction, National Research Council Canada, Ottawa, 2009.
4. Su, J.Z.; Bénichou, N.; Bwalya, A.C.; Lougheed, G.D.; Taber, B.C.; Leroux, P.; Kashef, A.; Thomas, J.R., Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Part 3 - Results of Test UF-04 (Light-Gauge Steel C-Joists), Research Report RR-248, Institute for Research in Construction, National Research Council Canada, Ottawa, 2009.
5. Su, J.Z.; Bénichou, N.; Bwalya, A.C.; Lougheed, G.D.; Taber, B.C.; Leroux, P.; Kashef, A.; Thomas, J.R., Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Part 4 - Results of Test UF-05 (Metal-Plate Connected Wood Trusses), Research Report RR-249, Institute for Research in Construction, National Research Council Canada, Ottawa, 2009.
6. Su, J.Z.; Bénichou, N.; Bwalya, A.C.; Lougheed, G.D.; Taber, B.C.; Leroux, P.; Kashef, A.; Thomas, J.R., Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Part 5 - Results of Tests UF-06, UF-06R and UF-06RR (Wood I-Joists B), Research Report RR-250, Institute for Research in Construction, National Research Council Canada, Ottawa, 2009.
7. Su, J.Z.; Bénichou, N.; Bwalya, A.C.; Lougheed, G.D.; Taber, B.C.; Leroux, P.; Kashef, A.; Thomas, J.R., Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Part 6 - Results of Tests UF-07 and UF-08 (Metal-Webbed Wood Trusses), Research Report RR-251, Institute for Research in Construction, National Research Council Canada, Ottawa, 2009.
8. Su, J.Z.; Bénichou, N.; Bwalya, A.C.; Lougheed, G.D.; Taber, B.C.; Leroux, P.; Kashef, A.; Thomas, J.R., Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Part 1 - Results of Tests UF-01 and UF-02 (Solid Wood Joists), Research Report RR-246, Institute for Research in Construction, National Research Council Canada, Ottawa, 2009.

9. ASTM E119-20, Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, 2020, www.astm.org.
10. CAN/ULC-S101-14. Standard Methods of Fire Endurance Tests of Building Construction and Materials., 5th Ed., Underwriters' Laboratories of Canada, Scarborough, Ontario, 2014
11. Cooper, L. Y; Steckler, K. D., Methodology for Developing and Implementing Alternative Temperature-Time Curves for Testing the Fire Resistance of Barriers for Nuclear Power Plant Applications, NISTIR 5842, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, USA, 1996.
12. APA; WIJMA; AWC, Basis of IRC Membrane Protection Provisions, The Engineered Wood Association, Wood I-Joist Manufacturer's Association, American Wood Council, https://i-joist.org/wp-content/uploads/2018/05/Basis-of-IRC-Membrane-Protection-Provisions-07-22-15.pdf , Date Accessed: 29 August 2020.
13. ISO 13571, Life-threatening Components of Fire - Guidelines for the Estimation of Time Available for Escape Using Fire Data., International Organization for Standardization, Geneva, 2002.
14. The SFPE Handbook of Fire Protection Engineering, 3rd ed., Society of Fire Protection Engineers (SFPE) NFPA International, Bethesda, USA, 2002.
15. Su, J. Z.; Taber, B. C.; Leroux, P.; Bénichou, N.; Lougheed, G. D.; Bwalya, A. C., Experiments of Sprinkler Protected Ceiling/Floor Assemblies in a Basement Fire Scenario. Research Report IRC-RR-308, Institute for Research in Construction, National Research Council Canada, Ottawa, Canada, 2011.
16. Proulx G.; Cavan, N. R.; Tonikian, R., Egress Times from Single Family Houses, Research Report, National Research Council of Canada Ottawa, Canada, 2006.
17. Proulx G., Evacuation from a single family house, The 4th International Symposium on Human Behaviour in Fire, Robinson College, Cambridge, UK, 2009.
18. Kerber, Steve; Samuels, Matthew; Backstrom, Bob; Dalton, James, Matthew; Backstrom, Bob; Dalton, James. Fire Service Collapse Hazard Floor Furnace Experiments, UL, USA, 2012.
19. Madrzykowski, D. M., Jonathan, L. . *Examination of the Thermal Conditions of a Wood Floor Assembly above a Compartment Fire.* Technical Note (NIST TN) – 1709, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, USA, 2011.
20. Avila M., A Technical Analysis: The Performance of Composite Wood Joists Under Realistic Fire Conditions. Tyco Fire Suppression and Building Products, USA, 2008.
21. Fang, J. B., Fire Performance of Selected Residential Floor Constructions Under Room Burnout Conditions, Interim Report NBSIR 80-2134, National Engineering Laboratory, National Bureau of Standards, Washington, DC, USA, 1980.

22. Fang , J. B., Fire Endurance Test of Selected Residential Floor Constructions, NBSIR 82-2488, National Engineering Laboratory, National Bureau of Standards, Washington, DC, USA, 1982.
23. Izydorek, Mark S.; Zeeveld, Patrick A.; Samuels, Matthew D.; Smyser, James P.; Berhinig, Robert M., Structural stability of engineered lumber in fire conditions, Project Number: 07CA42520, File Number: NC9140, Underwriters Laboratories, Northbrook, IL, USA, 2008.
24. Son, B. C., Fire Endurance Tests of Unprotected Wood-Floor Constructions for Single Family Residences, NBSIR 73-263, Center for Building Technology - Institute for Applied Technology, National Bureau of Standards, Washington, DC, USA;1973.
25. Son, B. C., Fire Endurance of Plywood on Steel Joist Floor Assemblies, With and Without Ceiling, NBSIR 73-14-1, Center for Building Technology - Institute for Applied Technology, National Bureau of Standards, Washington, DC, USA;1973.
26. White, R. H.; Schaffer, E. L., Woeste, F. E., Replicate fire endurance tests of an unprotected wood joist floor assembly, Wood and Fiber Science. Vol 16, pp. 374 – 390, 1984
27. Issen, L, A., Single-Family Residential Fire and Live Loads Survey, NBSIR 80-2155, National Engineering Laboratory, National Bureau of Standards, Washington, DC, USA, 1980.
28. Kerber, S. B., Robert; Dalton, James; Madrzykowski, Daniel. Full-Scale Floor System Field and Laboratory Fire Experiments. NIST; 2012/10/01 2012. 1572-8099.
29. Izydorek, Mark S.; Zeeveld, Patrick A.; Samuels, Matthew D.; Smyser, James P.; Gandhi, Pravinray D.; Backstrom, B., Structural Stability of Engineered Lumber in Fire Conditions, NC10412, Underwriters Laboratories, Northbrook, IL, USA, 2009.
30. Kerber S., Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes, Fire Technology, 2012, 48(4), 865-891.
31. Bwalya. A. C.; Gibbs, E.; Lougheed, G.; Kashef, A., Characterization of Fires in Multi-Suite Residential Dwellings: Final Project Report. Part 2 - Analysis of the Results of Post-Flashover Room Fire Tests, Research Report No. 350, Construction Portfolio, National Research Council Canada, Ottawa, Canada; 2012.
32. USFA, Structure Fire Response Times, United States Fire Administration, National Fire Data Center, Emmitsburg, Maryland, 2006. http://www.usfa.fema.gov/inside-usfa/nfdc/pubs/tfrs.shtm
33. Establishing fire equivalency for floor framing members to unprotected 2x10 dimension lumber or equal-sized structural composite lumber, Wood I-Joist Manufacturers Association, USA, 2009, https://i-joist.org/wp-content/uploads/2019/01/1_14_19-Final-Policy.pdf, Date Accessed: 29 August 2020.
34. ICC ES, AC14 - Acceptance Criteria for Prefabricated Wood I-Joists., International Code Council (ICC) Evaluation Service (ES), 2019.