# Fire resistance behaviour of lightweight framed construction

Bénichou, N.; Sultan, M. A.



**Publisher's version / Version de l'éditeur:**

*3rd Structures in Fire Conference [Proceedings], pp. 119-136, 2004-05-01*

# Fire resistance behaviour of lightweight-framed construction

**Bénichou, N.; Sultan, M.A.**

**NRCC-46891**

**A version of this document is published in / Une version de ce document se trouve dans :
Structures in Fire, Proceedings of the 3rd International Workshop,
Ottawa, Ontario, May 10-11, 2004, p. 119-136**

# FIRE RESISTANCE BEHAVIOUR OF LIGHTWEIGHT-FRAMED CONSTRUCTION

Noureddine Bénichou and Mohamed A. Sultan
National Research Council of Canada, Ottawa, Ontario, Canada
noureddine.Benichou@nrc.gc.ca
mohamed.sultan@nrc.gc.ca

## ABSTRACT

This paper presents the results of a number of full-scale fire resistance tests conducted in accordance with the CAN/ULC-S101 standard on wall and floor systems as part of the collaborative research program on the fire and acoustical performance of lightweight assemblies. Based on the test results, the effects of a number of design parameters on the fire resistance performance of assemblies have been investigated including: attachment of the gypsum board, insulation type, resilient channels, gypsum board thickness, number of gypsum board layers, stud arrangements, type of framing, resilient channel and framing spacing, sub-floor type and structural load. The results have shown that the main factors that affected the performance of stud wall assemblies were the type of insulation, the number of gypsum board layers, and attachment of gypsum board. The paper also describes how the information gathered from this study will be used to benefit practitioners, builders and regulators in choosing suitable assemblies for their designs. This includes, a discussion of the models that have been developed to predict the fire resistance of lightweight assemblies. Finally, the paper provides a brief summary of NRC's future research in the area of lightweight-framed construction.

**KEYWORDS**: behaviour, fire resistance, fire test, lightweight, models, steel, wood

## INTRODUCTION

Lightweight-framed construction is widely used in up to four-storey residential buildings. This construction includes wall and floor assemblies, which are used as fire barriers in multi-family dwellings and are required to exhibit acceptable fire resistance prescribed in the National Building Code of Canada (NBC) [1]. To satisfy these requirements, designers, architects and builders can choose fire-rated assemblies from different sources such as the listed assemblies or from the Part 9 Appendix A table of the NBC. The functions of the barriers are to contain the fire within the compartment of fire origin and to provide safety to the occupants and firefighters during evacuation and rescue operations. Aside from fire resistance, wall assemblies separating dwellings must also satisfy other requirements, including structural support, earthquake resistance and noise control between dwellings. Optimizing one factor may compromise others.

In 1990, the Sound Transmission Class (STC) between dwellings was increased from STC 45 to STC 50 in the NBC to meet public demands for better acoustic isolation. As well, construction materials and methodologies have changed over the past decade. However, with these changes, are there any concerns on the fire resistance requirements of wall and floor assemblies? To answer this question, the National Research Council of Canada (NRC), in collaboration with a number of industry and government partners, has carried out an extensive experimental program on lightweight-framed assemblies to measure the fire resistance and acoustic performance of these assemblies. The experimental studies included steel- and wood-framed wall and floor assemblies where a number of parameters have been studied, including the attachment of gypsum board to a framing or to resilient channels, types of insulation, use and location of resilient channels, gypsum board thickness, the number of gypsum board layers, stud arrangements, framing type, framing and resilient channel spacing, sub-floor type and structural load.

This paper first briefly presents the experimental studies that have been carried out on wall and floor assemblies. It then presents the effects of various parameters that influence the fire resistance performance of lightweight-framed assemblies. The paper also describes how the information gathered from this experimental program was used to: a) generate fire resistance ratings to incorporate in the National Building Code of Canada; b) develop key trends for design; and c) develop fire resistance models for designs that could provide an alternative to testing of assemblies which is both expensive and time consuming. All of this information can be useful to practitioners, builders and regulators in choosing suitable assemblies for design. In addition, a section at the end of the paper will be dedicated to providing a brief section on where NRC is going with its research in the area of lightweight-framed construction.

## EXPERIMENTAL PROGRAM

To determine the effects of various parameters on the fire resistance of wood- and steel-framed assemblies, a detailed experimental study was undertaken. The experimental program consisted of full-scale fire tests on 17 walls (see Table 1) and 23 floors (see Table 2). The systems tested were replicates of assemblies commonly used in North America and listed in the NBC [1].

Typical wall or floor assemblies are constructed with materials that include:

- Wood or steel studs or joists representing the framing and spaced at 400 mm or 600 mm.
- Layers of Type X gypsum board (GB), 12.7 or 15.9-mm thick, fixed to either resilient channels (RC) or studs or joists using screws.
- Insulation within the cavities including glass fibre, rock fibre or cellulose fibre.
- Subfloor for joist assemblies attached to the framing from the top using screws or nails.

Table 1. Wall assembly parameters and fire resistance test results [3] and [4]

| Wall No. | Stud | | | Shear Panel | Gypsum Board | | | Insulation Type | Resilient Channels | Load (kN) | Failure Time (min) | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Type | Spacing (mm) | Rows | | Type | Thickness (mm) | Exp./Unexp. | | | | | |
| 1 | SS | 406 | Single | No | X | 12.7 | 1 & 2 | *** | *** | *** | 65 | Thermal |
| 2 | SS | 406 | Single | No | X | 12.7 | 1 & 2 | Glass | *** | *** | 65 | Thermal |
| 3 | SS | 406 | Single | No | X | 12.7 | 1 & 2 | Rock | *** | *** | 100 | Thermal |
| 4 | SS | 406 | Single | No | X | 12.7 | 1 & 2 | CFI[5] | *** | *** | 62 | Thermal |
| 5 | WS | 406 | Single | No | X | 12.7 | 1 & 2 | Glass | Yes[1] | 68 | 51 | S/F |
| 6 | WS | 406 | Single | No | X | 12.7 | 1 & 2 | Rock | Yes[1] | 68 | 52 | S/F |
| 7 | WS | 406 | Single | No | X | 12.7 | 1 & 2 | Rock | Yes[2] | 68 | 58 | S/F |
| 8 | WS | 406 | Single | No | X | 12.7 | 1 & 2 | CFI[6] | Yes[2] | 68 | 56 | S/F |
| 9 | SS | 406 | Single | No | X | 12.7 | 1 & 2 | Rock[3] | *** | *** | 60 | Thermal |
| 10 | WS | 406 | Single | No | X | 15.9 | 1 & 2 | Glass | Yes[1] | 67 | 52 | S/F |
| 11 | WS | 406 | Single | No | X | 12.7 | 2 & 2 | Glass | Yes[1] | 68 | 79 | S/F |
| 12 | WS | 406 | Double[4] | No | X | 12.7 | 1 & 2 | Glass | *** | 143 | 51 | S/F |
| 13 | SS | 406 | Single | No | Reg. | 12.7 | 2 & 2 | *** | *** | *** | 63 | Thermal |
| 14 | WS | 406 | Single | No | Reg. | 12.7 | 2 & 2 | *** | *** | *** | 65 | Thermal |
| 15 | WS | 406 | Single | No | X | 12.7 | 1 & 1 | Glass | *** | 76 | 36 | S/F |
| 16 | SS | 406 | Single | No | X | 12.7 | 2 & 2 | Glass | Yes[1] | 78.4 | 56 | S/F |
| 17 | SS | 406 | Single | No | X | 12.7 | 2 & 2 | *** | Yes[1] | 78.4 | 77 | S/F |

[1] On exposed side
[2] On unexposed side
[3] Loose fit (548 mm)
[4] Staggered (single plate)
[5] Cellulose wet sprayed
[6] Cellulose dry blown
Exp. = Number of GB layers on exposed side
Unexp. = Number of GB layers on unexposed side
Reg. = Regular GB
S/F – Structural Failure
*** - Null Value
CFI = Cellulose fibre insulation
SS – Steel Stud
WS- Wood Stud

Table 2. Floor Assembly Parameters and Fire Resistance Test Results [5] and [6]

| Floor No. | Joist | | | Ceiling Finish | | | Sub-floor | | Cavity Insulation | | | Resilient Channels | | Load | Failure Time | Failure Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Type | Depth | Spacing | Type | Thick | Layers | Type | Thick | Type | Thick | Location | Orient. | Spacing | | | |
| | WJ* | (mm) | (mm) | | (mm) | | | (mm) | | (mm) | | | (mm) | (Pa) | (min) | |
| 1 | WJ | 235 | 406 | X | 12.7 | 1 | Ply | 15.5 | *** | *** | *** | Per | 406 | 3838 | 30 | Flame |
| 2 | WJ | 235 | 406 | X | 12.7 | 1 | Ply | 15.5 | *** | *** | *** | Per | 406 | 3838 | 45 | Flame |
| 3 | WJ | 235 | 406 | X | 12.7 | 1 | Ply | 15.5 | G1 | 90 | B | Per | 406 | 3838 | 36 | Flame |
| 4 | WJ | 235 | 406 | X | 12.7 | 1 | Ply | 15.5 | M1 | 90 | B | Per | 406 | 3838 | 60 | Flame |
| 5 | WJ | 235 | 406 | X | 12.7 | 1 | Ply | 15.5 | C1 | 93 | T | Per | 406 | 3838 | 59 | Flame |
| 6 | WJ | 235 | 406 | X | 12.7 | 2 | Ply | 15.5 | *** | *** | *** | Per | 406 | 3838 | 80 | Flame |
| 7 | WJ | 235 | 406 | X | 12.7 | 2 | Ply | 15.5 | G1 | 90 | B | Per | 406 | 3838 | 67 | Flame |
| 8 | WJ | 235 | 406 | X | 12.7 | 2 | Ply | 15.5 | M1 | 90 | B | Per | 406 | 3838 | 72 | Flame |
| 9 | WJ | 235 | 406 | X | 12.7 | 2 | Ply | 15.5 | C1 | 125 | T | Per | 406 | 3838 | 74 | S/F |
| 10 | WIJ | 240 | 406 | X | 12.7 | 1 | Ply | 15.5 | *** | *** | *** | Per | 406 | 4605 | 42 | S/F |
| 11 | WIJ | 240 | 406 | X | 12.7 | 1 | Ply | 15.5 | M1 | 90 | B | Per | 406 | 4653 | 46 | S/F |
| 12 | WIJ | 240 | 406 | X | 12.7 | 1 | Ply | 15.5 | C1 | 90 | T | Per | 406 | 4654 | 52 | Flame |
| 13 | WIJ | 240 | 406 | X | 12.7 | 2 | Ply | 15.5 | *** | *** | *** | Per | 406 | 3934 | 72 | S/F |
| 14 | WIJ | 240 | 406 | X | 12.7 | 2 | Ply | 15.5 | G1 | 90 | B | Per | 406 | 3982 | 64 | S/F |
| 15 | WIJ | 240 | 406 | X | 12.7 | 2 | Ply | 15.5 | M1 | 90 | B | Per | 406 | 3982 | 77 | S/F |
| 16 | WIJ | 240 | 610 | X | 12.7 | 2 | Ply | 19 | G1 | 90 | B | Per | 406 | 290 | 74 | S/F |
| 17 | WIJ | 240 | 610 | X | 12.7 | 2 | Ply | 19 | G1 | 90 | B | Per | 610 | 3120 | 65 | S/F |
| 18 | SJ | 203 | 406 | X | 12.7 | 2 | Ply | 15.5 | *** | *** | *** | Per | 406 | 2950 | 74 | S/F |
| 19 | SJ | 203 | 406 | X | 12.7 | 2 | Ply | 15.5 | G1 | 90 | B | Per | 406 | 2950 | 68 | S/F |
| 20 | SJ | 203 | 610 | X | 12.7 | 2 | Ply | 19 | G1 | 90 | B | Per | 406 | 1799 | 69 | S/F |
| 21 | SJ | 203 | 406 | X | 12.7 | 2 | Ply/Con | 15.5/38 | G1 | 90 | B | Per | 406 | 1915 | 60 | S/F |
| 22 | WJ | 235 | 406 | X | 12.7 | 2 | Ply | 15.5 | *** | *** | *** | Per | 406 | 5075 | 69 | S/F |
| 23 | WJ | 235 | 406 | X | 12.7 | 2 | Ply | 15.5 | G1 | 90 | B | Per | 406 | 5075 | 65 | S/F |

S/F – Structural Failure and Flame Penetration
Per – Perpendicular to Joists
C1 – Cellulose Fibre Insulation
WIJ – Wood-I Joist
WJ* - Screw Spacing from Gypsum Board Edges 10 mm

Ply – Plywood
T – Top
G1 – Glass Fibre Insulation
WJ- Wood Joist
X – Type X

*** - Null Value
B - Bottom
M1 – Rock Fibre Insulation
SJ- Steel Joist
Con - Concrete

The full-scale wall and floor tests were carried out by exposing one side of the assemblies to heat in a propane-fired vertical or horizontal furnace using gas fuel burners, in accordance with the CAN/ULC-S101-M89 standard [2]. The assemblies are sealed at the edges against the furnace using ceramic fibre blankets to minimize heat leakage. The furnaces can accommodate wall assemblies that are approximately 3.0 m high by 3.6 m wide and floor assemblies that are 4.8 m long by 3.9 m wide. Type K chromel-alumel thermocouples are used for measuring temperatures at a number of locations throughout an assembly. Assemblies were tested either loaded or unloaded (walls only). Loaded wall assemblies contribute to the structural load-bearing capacity of the building, while unloaded wall assemblies are used as fire barriers (partitions) and carry only their own weight. For load-bearing assemblies, the furnace has a loading device and the load is transmitted through hydraulic jacks to simulate vertical structural loads. Loads on assemblies are calculated based on the material characteristics of the assembly in accordance with CAN/ULC-S101-M89 [2]. The applied loading on the assemblies is given in Tables 1 and 2. The furnace temperature is measured by nine shielded thermocouples in accordance with CAN/ULC-S101-M89 [2]. The average of the nine-thermocouple temperatures was used to control the furnace temperature. In addition, the deflection at the unexposed surface was measured at different locations. During the tests, the furnace and assembly temperatures, deflections and the gauge pressure of the loading system were recorded at 1-minute intervals. Complete details on the construction of the wall and floor assemblies, instrumentation location and test procedures are given in references [3], [4] and [5].

The time to failure is based on failure criteria derived from CAN/ULC-S101-M89 [2], i.e.:

- Thermal failure - 140°C average temperature rise or 180°C maximum above ambient temperature on the unexposed face, or
- Integrity failure - penetration of flame and gases hot enough to ignite cotton waste, or
- Structural failure - loss of load-bearing capacity or excessive deflection of load-bearing assemblies.

## DESIGN PARAMETER INVESTIGATED

The design parameters investigated include: attachment of the gypsum board, insulation type, resilient channels (RC) use and location, gypsum board (GB) thickness, number of gypsum board layers, stud arrangements, type of framing, resilient channel and framing spacing, sub-floor type and structural load. Details of the effects of all the parameters, including the graphs showing the temperature profiles in the assemblies have been reported in other references [4]' [5] and [6]. In the following sections, a summary of the effects for each parameter is provided.

### Wall Assemblies

### Effect of insulation use and type

Tests 1 to 4 represented the effect of the use and type of insulation in (1 & 2) non-load-bearing steel-stud assemblies (1 & 2 means 1 GB layer on the exposed side and 2 GB layers on the unexposed side). The wall with glass fibre provided the same fire resistance (FR) as the assembly without any insulation (65 min). The assembly with rock fibre provided an increase of 54% in FR (100 min) while the assembly with cellulose (wet sprayed on the exposed gypsum board (GB) surface in the cavity between studs) showed a decrease of 4% in FR (62 min) compared to a non-insulated wall. The rock fibre remains in place and protects the stud and the

GB on the unexposed side when the GB on the exposed side falls off. On the other hand, when the GB on the exposed side falls off, the cellulose fibre falls off and glass fibre melts allowing the GB on the unexposed side and the studs to be exposed to heat, resulting in earlier failure. These results indicate that an assembly with rock fibre insulation provides higher fire resistance than an assembly with either glass or cellulose fibre or with no insulation in the wall cavity.

Results from fire resistance tests 5 to 8 were used to determine the effect of insulation type on (1 & 2) load-bearing wood-stud assemblies. The fire resistance is 51 min for an assembly with glass fibre (5) and 52 min with rock fibre (6). The results show that in these assemblies, the insulation type did not affect the fire resistance, as the unprotected GB vertical joints on the fire-exposed side are the dominant factor in the FR (when RCs are used, the vertical joint is not against the vertical stud), given that these are loaded assemblies and the stud edges were being attacked with the heat after failure of the GB. When resilient channels (RCs) are on the unexposed side, the fire resistance is 58 min for an assembly with rock fibre (7) and 56 min with cellulose fibre (8), and therefore also has little or no effect in this case (failure of the fire-exposed side GB is the dominant factor).

**Effect of insulation width**

Results from fire resistance tests 3 and 9 can be used to determine the effect of insulation width in non-load-bearing steel-stud assemblies. The fire resistance is 60 min for an assembly with loose-fit rock fibre (9) and 100 min for an assembly with tight-fit rock fibre (3). The results show that it is important to have the insulation installed tightly between studs since a loose fit produces gaps between stud faces and the insulation leading to an earlier failure of the assembly. When rock fibre insulation was installed tightly in non-load-bearing assemblies, it provided a 60% better fire resistance than when it was loose.

**Effect of resilient channels' use and location**

Tests 6 and 7 were conducted to investigate the effect of the resilient channels' location on the fire resistance of load-bearing wood-stud walls. The fire resistance is 52 min for an assembly with the resilient channel on the exposed side (6) and 58 min for an assembly with the resilient channel on the unexposed side (7). The results show that the location of resilient channels plays a role in FR as the assembly with RC on the double layer side provides an increase in FR of 11%. The difference in fire resistance is caused by the presence of an unprotected vertical GB joint on the fire-exposed side in the assembly when RCs are installed (when RCs are used, the vertical joint is not against the vertical stud). With direct application to the studs, joints in the GB can be aligned with the studs.

**Effect of gypsum board thickness with RCs on the exposed side**

Tests 5 and 10 were conducted to investigate the effect of GB thickness on the fire resistance of (1 & 2) load-bearing wood-stud walls. The failure of the wall assembly with 12.7-mm GB (5) occurred at 51 min while in the assembly with 15.9-mm GB (10), the failure occurred at 52 min. The results show that in (1 & 2) wall assemblies with RC installed on the fire exposed side, increasing the thickness of the gypsum board layer does not improve the FR when resilient channels are present on the single-layer side. However, the fact that the fire-resistance did not improve with the increased thickness was mainly due to the ignition of the wood studs, caused by the penetration of the hot gases through the unprotected vertical gypsum board butt joints.

The gap between the studs and the gypsum board, created by the presence of the RCs, acted as a passageway through which the flames and hot gases spread freely after entering the cavity.

**Effect of number of gypsum board layers with RCs on the exposed side**
Tests 5 and 11 were conducted to investigate the effect of the number of GB layers in load-bearing wood-stud assemblies. The failure of a wall assembly with one layer of GB (5) occurred at 51 min, while in an assembly with two layers of GB (11), the failure occurred at 79 min. The results show that the installation of a second layer of GB on the fire-exposed side (with staggered joints) increases the FR by 55% compared to an assembly with one layer of GB on the exposed side. Having a backing to the fire-exposed GB layer adds significantly to the fire resistance, as it reduces the penetration of hot gases.

**Effect of stud type**
Results from fire resistance tests 13 and 14 can be used to assess the effect of stud type in (2 & 2) non-load-bearing stud assemblies. The failure in a steel-stud wall (13) occurred at 63 min while in the wood-stud wall (14), it occurred at 65 min. The type of stud used in non-load-bearing walls is insignificant for assemblies with two layers of gypsum board on each side.

**Floor Assemblies**
**Effect of attachment of the gypsum board with RCs on the ceiling**
Floor Assemblies Nos. 1 and 2 with wood joists were tested to investigate the effect of the gypsum board screw spacing (10 mm and 38 mm) from board edges with a single layer of gypsum board ceiling finish attached to resilient channels. Assembly No. 1, with screws at 10 mm, provided 30 min of fire resistance while Assembly No. 2, with screws at 38 mm, provided 45 min. These results showed that by moving the screws away from the board edges (from 10 mm to 38 mm), the fire resistance increased by 50%. This can be explained by the fact that after the water in the board was driven off and the gypsum board core became dry, the board edges started to shrink and peel away from the screw heads. The board edges peeled away from the screw heads much faster in the assembly with screws at 10 mm, as they were located much closer to the edges, than in the assembly with screws at 38 mm. Thus, the sub-floor and joist sides were fully exposed to the furnace heat much earlier in the former assembly. This accelerated the burning of the joists and sub-floor and caused the assembly with screws at 10 mm from the board edges to fail earlier.

**Effect of insulation installation and type**
Assemblies Nos. 2 to 5 (wood joist with 1 layer of gypsum board), Nos. 6 to 9 (wood joist with 2 layers of gypsum board), Nos. 10 to 12 (wood-I-joist with 1 layer gypsum board), Nos. 13 to 15 (wood-I-joist with 2 layers of gypsum board) and Nos. 18 and 19 (C-steel joist with 2 layers of gypsum board) were tested to investigate the effect of insulation type (glass, rock and cellulose fibre) on the fire resistance.

<u>Floor Assemblies with Wood Joists</u> – The results show that, for Assemblies Nos. 1 to 5, as a result of the substantial increase in board temperature (at 27 min for assemblies with either glass or rock fibre insulation and at 35 min for an assembly with cellulose fibre insulation), the board cracked and fell off, unlike the non-insulated assembly. However, in the assembly with glass fibre insulation, the fibre melted when it was exposed to furnace heat in about 2 to 3 min after

the gypsum board had fallen off; consequently, the sub-floor and joist sides were exposed to the furnace heat and the glass fibre was unable to compensate for the earlier failure of the gypsum board and provided a negative effect in the fire resistance. The rock and cellulose fibre remained in place after the gypsum board fell off and was able to compensate for the early failure of the gypsum board as well as protect the joist and sub-floor from furnace heat and thus, both rock and cellulose fibre insulation provided a positive effect on fire resistance. The fire resistance results of Assemblies Nos. 2 to 5 given in Table 2 showed that, compared to a non-insulated assembly, which provided a 45 min fire resistance, the installation of the glass fibre reduced the fire resistance by 20% while the rock and cellulose fibre increased the fire resistance by 33% and 31%, respectively.

The results show that, for Assemblies Nos. 6 to 9, as a result of the substantial increase in board temperature, the board cracked and fell off at approximately 60 min for insulated assemblies, unlike the non-insulated assembly at 75 min. In an insulated assembly with 2 layers of gypsum board, the exposure time for indirect furnace heat (conduction through the board) was much longer than in an insulated assembly with 1 layer of gypsum board. The deteriorated glass, rock and cellulose fibre insulations were unable to compensate for the earlier failure of the gypsum board and thus, all insulations provided a negative effect on fire resistance. The fire resistance results for Assemblies Nos. 6 to 9 given in Table 2 showed that, compared to a non-insulated assembly, which provided an 80 min fire resistance, the insulation reduced the fire resistance by 16% with glass fibre, by 10% with rock fibre and by 7.5% with cellulose fibre.

<u>Floor Assemblies with Wood-I Joists</u> - The results show that, for Assemblies Nos. 10 to 12, as a result of the substantial increase in board temperature, the board cracked and fell off. However, the rock and cellulose fibre remained in place after the gypsum board fell off and was able to compensate for the early failure of the gypsum board as well as protect the joist and sub-floor from furnace heat and thus, both rock and cellulose fibre insulation provided a positive effect on fire resistance. The fire resistance results for Assemblies Nos. 10 to 12 given in Table 2 showed that the insulation increased the fire resistance by 10% in the assembly with rock fibre and by 24% in the assembly with cellulose fibre compared to an assembly with no insulation in the floor cavity. In assemblies with wood-I-joists, the rock and cellulose fibre, like in the assembly with wood joists, provided a positive effect on fire resistance.

The results show that, for Assemblies Nos. 13 to 15, as a result of the substantial increase in board temperature, the board cracked and fell off at approximately 61 min for the assembly with glass fibre, 70 min for the assembly with rock fibre and non-insulated assembly. However, in the assembly with glass fibre insulation, the fibre melted when exposed to furnace heat in about 3 min; consequently, the sub-floor and joist sides were exposed to the furnace heat and glass fibre was unable to compensate for the earlier failure of the gypsum board and provided a negative effect in the fire resistance while the rock fibre remained in place after the gypsum board fell off and was able to compensate for the early failure of the gypsum board as well as protect the joist and sub-floor from furnace heat and thus, the rock fibre insulation provided a positive effect on fire resistance. The fire resistance results for Assemblies Nos. 13 to 15 given in Table 2, showed that the insulation reduced the fire resistance by 7% in the assembly with glass fibre and increased the fire resistance by 7% in the assembly with rock fibre compared to an assembly with no insulation.

Floor Assemblies with C-Steel Joists – The results show that, for Assemblies Nos. 18 and 19, as a result of the substantial increase in board temperature, the board cracked and fell off at approximately 62 min for the assembly with glass fibre, 71 min for the non-insulated assembly. However, in the assembly with glass fibre insulation, the fibre melted when it was exposed to furnace heat in about 3 min; consequently, the sub-floor and joist sides were exposed to the furnace heat and glass fibre was unable to compensate for the earlier failure of the gypsum board and provided a negative effect in the fire. The fire resistance results for Assemblies Nos. 18 and 19 given in Table 2, showed that the installation of glass fibre insulation in the floor cavity of the assembly with a double-layer gypsum board reduced the fire resistance by 8% compared to an assembly with no insulation in the floor cavity.

**Effect of number of gypsum board layers**

Floor Assemblies with Wood Joists - Floor Assemblies Nos. 1 and 6 were tested to investigate the effect of the number of gypsum board layers on the fire resistance of non-insulated wood joist assemblies. The fire resistance of these assemblies given in Table 2, showed that the assembly with a double-layer of 12.7 mm gypsum board ceiling finish provided an increase in fire resistance of 78% compared to an assembly with a single layer of 12.7 mm gypsum board.

Floor Assemblies with Wood-I Joists - Floor Assemblies Nos. 10 and 13 were tested to investigate the effect of the number of gypsum board layers on the fire resistance of non-insulated wood-I-joist assemblies. The results given in Table 2, showed that the assembly with a double-layer gypsum board ceiling finishes provided an increase in the fire resistance of 71% compared to an assembly with a single layer of 12.7 mm gypsum board.

**Effect of joist spacing**

Floor Assemblies with Wood-I Joists - Floor Assemblies Nos. 14 and 16 were tested to investigate the effect of joist spacing (406 mm o.c. and 610 mm o.c.) on the fire resistance of wood-I-joist floor assemblies with a double layer gypsum board ceiling finish and glass fibre insulation in the floor cavity. Assembly No. 14 (with 406 mm o.c. joist spacing) provided 64 min of fire resistance while Assembly No. 16 (with 610 mm o.c. joist spacing) provided 74 min. The assembly with the wider joist spacing provided better fire resistance due to the increase in convective cooling inside the larger floor cavities created by the joists that slightly reduced the heat build-up in the gypsum board core and insulation compared to the assembly with smaller cavities.

Floor Assemblies with C-Steel Joists - Floor Assemblies Nos. 19 and 20 were tested to investigate the effect of joist spacing (406 mm o.c. and 610 mm o.c.) on the fire resistance performance of steel joist floor assemblies with a double layer gypsum board ceiling finish and glass fibre insulation in the floor cavity. Assembly No. 20 (with 406 mm o.c. joist spacing) provided 68 min, while Assembly No. 21 (with 610 mm o.c. spacing) provided 69 min. The difference in the fire resistance is within the systematic error of the test procedure. These results showed that, unlike the case with wood-I-joist assemblies, the effect of steel joist spacing on fire resistance is insignificant. For these assemblies, the joist spacing did not play a role in the fire resistance due to the heat transfer from the steel joist edges to the web.

**Effect of resilient channel spacing**

Floor Assemblies 16 and 17 were tested to investigate the effects of the resilient channel spacing (406 mm o.c. and 610 mm o.c.) on the fire resistance of wood-I-joist floor assemblies with a double-layer gypsum board ceiling finish and glass fibre insulation in the floor cavity. Assembly No. 16 (with 406 mm o.c. channel spacing) provided 74 of min fire resistance while Assembly 17 (with 610 mm o.c. channel spacing) provided 65 min. The assembly with the wider resilient channel spacing provided less fire resistance due in part to the lesser number of fasteners for the gypsum board. The more screws the assembly has, the better chance for the gypsum board to remain in place and protect the frame and thus, the better the fire resistance.

**Effect of sub-floor type**

Assemblies 20 and 21 were conducted to investigate the effect of adding concrete topping above the plywood sub-floor. Assembly 20 with no concrete topping provided 68 min of fire resistance and Assembly 21 with concrete topping provided 60 min. Adding concrete topping reduced the heat transfer across the assembly. As a result, the gypsum board temperature was higher in the assembly with concrete topping and consequently fell off earlier than the assembly with no concrete topping.

**Effect of load**

Assemblies 6, 7, 22 and 23 were conducted to determine the effect of load on the fire resistance. Assemblies 6 (no insulation) and 7 (with insulation) were tested with 75% design load and Assemblies 22 (no insulation) and 23 (with insulation) were tested with 100% design load. Assembly 6 provided 80 min and Assembly 22 provided 69 min of fire resistance. Also, Assembly 7 provided 67 min and Assembly 23 provided 65 min of fire resistance. These results showed that when the load increased by 25%, the fire resistance decreased by 14% for a non-insulated assembly and by 3% in an insulated assembly.

## HOW CAN WE USE THIS INFORMATION?

The information obtained from this experimental program can be used in 3 ways: a) development of listing tables for codes; b) key trends for design; c) development and validation of fire resistance models. These are explained in the following sections.

**Development of Listing Tables for Codes**

Fire design of wall and floor assemblies is usually carried out by reference to standard fire test results. The results of this study and a study on the acoustical performance were used as the basis for the published update Part 9 Appendix A table of the NBC [1] that included generic fire resistance ratings of hundreds of wall and floor assemblies. The list of these assemblies is on the Website (http://www.ccbfc.org/ccbfc/changes/soundfire_E.shtml). Designers can use the table for their designs, but the user can choose from any other acceptable source.

**Key Trends for Design**

The key design trends can be summarized in the following sections.

**Wall assemblies**

- Fire resistance increases considerably with an increase in the number of gypsum board layers on each side. When using multiple board layers, it is recommended to stagger joints between sheets.
- With resilient channels beneath the single gypsum board layer, increasing the thickness of the GB layer does not improve the fire resistance.
- The use of resilient channels reduces the fire resistance of stud walls, especially when fixed to a single gypsum board layer. To minimize this fire resistance reduction, resilient channels should be installed under the double gypsum board layer.
- For non-load-bearing (1&2) steel-stud walls, installing rock fibre insulation in the cavity contributes significantly to the fire resistance. To maximize the fire resistance benefits of rock fibre insulation, it is important to install the batts tightly between studs.
- For load-bearing (1&2) wood-stud walls, the cavity insulation type has no effect on fire resistance.
- For load-bearing (1&2) wood-stud walls, there is no benefit in using staggered row studs (single plate) instead of single row studs.
- The type of stud used in non-load-bearing walls has no effect on the fire resistance.

**Floor assemblies**

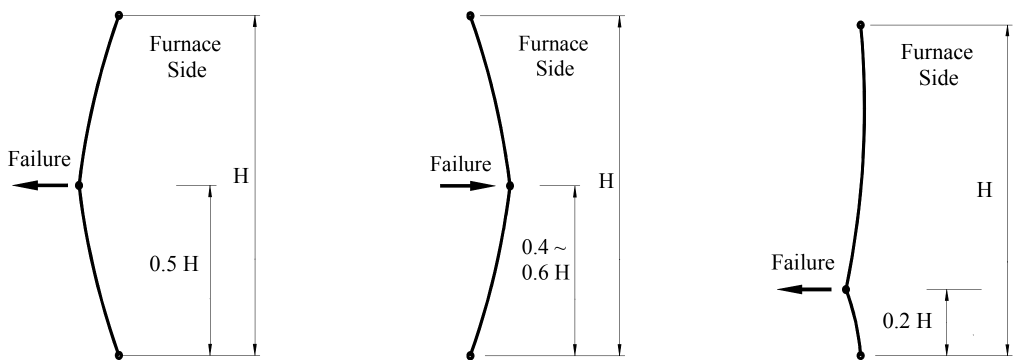
- Assemblies with screws located further away from board edges (38 mm versus 10 mm) provide higher fire resistance.
- In assemblies with wood joists and a single-layer gypsum board ceiling finish, the glass fibre reduced the fire resistance while the rock and cellulose fibre increased the fire resistance compared to a non-insulated assembly. In assemblies with a double-layer of 12.7 mm gypsum board finish, the glass, rock and cellulose fibre all reduced the fire resistance compared to a non-insulated assembly.
- For floor assemblies with wood-I-joists and a single layer of 12.7 mm gypsum board ceiling finish, the rock and cellulose fibre insulation increased the fire resistance compared to a non-insulated assembly. In assemblies with a double-layer of 12.7 mm gypsum board finish, the glass fibre reduced the fire resistance while rock fibre increased the fire resistance compared to a non-insulated assembly.
- Assemblies with two layers of 12.7 mm gypsum board with staggered joints provided a significant increase in the fire resistance compared to an assembly with one layer of 12.7 mm gypsum board.
- For wood-I joist floor assemblies with glass fibre insulation and a double-layer of 12.7 mm gypsum board, the effects of joist spacing and resilient channel spacing (406 mm o.c. and 610 mm o.c.) were significant.
- For floor assemblies with C-steel joists and a double-layer of 12.7 mm gypsum board ceiling finish, glass fibre insulation reduced the fire resistance compared to a non-insulated assembly and the effect of joist spacing (406 mm o.c. and 610 mm o.c.) was insignificant.
- Adding concrete topping to a plywood sub-floor reduced the fire resistance.
- The increase in structural load decreases fire resistance.

**Development of Fire Resistance Models**

Although beneficial, test methods have drawbacks, including high costs and time, limitations of specimen geometry and loading, and repeatability. To overcome these drawbacks, there is a need to develop calculation methods for assessing the fire resistance of lightweight-frame assemblies. The calculation methods would also help in designing an experimental program, improve products manufacturing, and assist the industry in taking full advantage of the opportunities offered by performance-based codes, as these methods would facilitate a faster design process. To develop a fire resistance model for assemblies that replicate test results, the fire resistance behaviour from the experimental program must be carefully observed. In the following sections, two models for predicting the fire resistance of stud wall assemblies are presented. A third model for predicting steel-joist floor assemblies was also developed but will not be presented in this paper because of space limitation.

**Wall Models**

During the tests, the behaviour of wood- and steel-stud wall assemblies was observed and Figure 1 shows schematic representations of the failure modes of wood- and steel-stud wall assemblies.




a) wood studs b) non-insulated steel studs c) insulated steel studs

Figure 1. Schematic representations of failure modes for wood- and steel-stud walls.

**Description of the Wood-Stud Wall Fire Resistance Model**

NRC, in collaboration with Forintek Canada Corp. (FCC), has developed an analytical model for predicting the fire resistance of wood-stud wall assemblies. The model couples a thermal response sub-model and a structural response sub-model. The thermal response sub-model, called WALL2D [7], predicts the temperature profile inside the wood-stud wall and the time to insulation failure. The thermal response is predicted using a finite difference heat transfer sub-model developed by FCC. The sub-model determines the temperature distribution in the wall as a function of time, taking into account the heat absorbed in the dehydration of gypsum and wood, and in the pyrolysis of wood, without considering mass transfer. The heat transfer, through gypsum boards and wood studs, is described using an enthalpy formulation. The sub-model assumes that heat transfer occurs mainly in the cross-section of the wall assembly and that heat flow in the vertical direction can be ignored. The finite difference mesh considers symmetry of the wall, with a mesh refinement in proximity of the wood stud and larger spacing within the gypsum board far from the wood stud. The structural fire performance of wood-frame assemblies is affected by the rate of charring, degradation of the mechanical properties of the wood at elevated temperatures and the load sustained by assemblies. To determine the structural response, a buckling load sub-model is implemented with WALL2D. The sub-model uses the temperature distribution predicted by WALL2D as an input, then calculates the deflection and the critical elastic buckling load for a wood-stud wall. The buckling of the wood studs is restricted to the strong axis because of the lateral support by the gypsum board. The critical elastic buckling-load, assuming both ends of the studs are pinned, is:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \tag{1}$$

where $P_{cr}$ is the elastic buckling-load (N), E is the modulus of elasticity of the resisting member (MPa), I is the moment of inertia ($mm^4$), and KL is the effective stud length (mm), with K = 1 in this case. The values of the moment of inertia and modulus of elasticity change with time. For the moment of inertia, the temperature profile and pre-set charring temperature provide an estimation of the remaining cross-section of the stud, thus allowing for calculation of the time-dependent moment of inertia. For the modulus of elasticity, the change with temperature is obtained from the literature [4]. Structural failure is assumed to occur when the load applied on the wall exceeds the buckling load. The stud's out-of-plane deflection is estimated using the theory of elasticity. The deflection of the stud, as predicted for a hinged-hinged eccentric column, can be calculated by considering the stud as a beam-column structure. The out-of-plane deflection, y, at any height x on the stud at any time, is:

$$y(x) = \frac{M_0 L^2}{8EI}\left[\frac{2\cos\left(\Psi - \frac{2\Psi}{L}x\right) - \cos(\Psi)}{\Psi^2 \cos(\Psi)}\right] \text{ with } \Psi = \frac{\pi}{2}\sqrt{\frac{P}{P_{cr}}} \text{ and } M_0 = P(e_c - e_p) \tag{2}$$

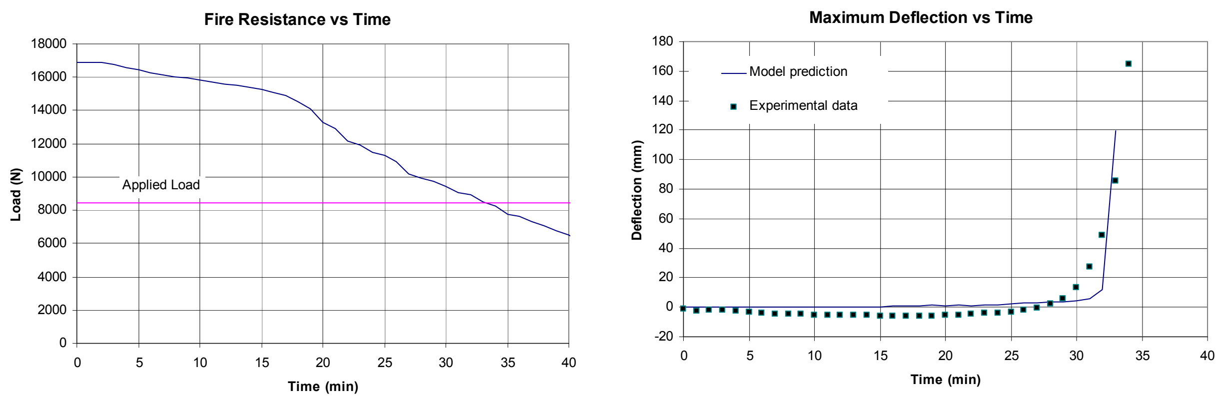
where L is the length of the stud (mm), $e_c$ is the eccentricity of the centroid of the resisting member (mm), and $e_p$ is the applied load eccentricity (mm). The maximum deformation occurs at mid-height.

A fire resistance test for assembly No. 15 was used to evaluate the predictions by the fire resistance model. The predictions of time-temperature curves generated by the heat transfer have been used to calculate the reduction in load-carrying capacity of the studs and the degradation in the modulus of elasticity, which was assumed to be equal to 7000 MPa at ambient temperature. Temperatures on the unexposed sides did not reach the insulation failure criterion, as the assembly failed by structural instability at 36 min. Table 3 summarizes the model predictions and experimental results. The model predicts conservatively the onset of charring, with a difference of about 10%.

Table 3. Comparison between tests results and model predictions

| Test No. | Onset of Char (min) | | | Insulation Failure (min) | | Structural Failure (min) | | |
|---|---|---|---|---|---|---|---|---|
| | Test | Model | Difference | Test | Model | Test | Model | Difference |
| 15 | 19.0 | 17.0 | 10% | N/A | 48.0 | 36.0 | 33.0 | 8% |

Figure 2a illustrates the critical elastic buckling load versus time as predicted by the structural response sub-model. The fire resistance decreases with increasing time because the value of the modulus of elasticity decreases with time and the cross-section of the studs reduces after charring. The intersection of the horizontal line, at the level of the applied load (8.45 kN), with the elastic buckling-curve, represents the theoretical time to structural failure of the wall. The time is 33 min for the assembly, while the time to structural failure measured experimentally is 36 min. Therefore, the model predictions are very close to the test results, with the analytical time to structural failure underestimated by 8%. The maximum mid-height deflections are also plotted versus time for both the analytical predictions and the test results (see Figure 2b). As shown in this figure, the deflection is very small in the first 30 min. After this, the model predictions and the test measurements start increasing at a faster rate. The rate of increase in the model predictions is similar to that of the test results. The rate in the model, however, starts a few minutes later. The model slightly overestimates the deflection at 33 min.




(a) (b)

Figure 2. Fire resistance determination and deflection comparisons.

**Description of the Steel-Stud Wall Fire Resistance Model**

As part of a joint research effort between NRC and the Canadian Steel Construction Council (CSCC), a numerical model for predicting the fire resistance of steel-stud wall assemblies was developed. The model couples a thermal response sub-model and a structural response sub-model. The thermal response sub-model, called TRACE [8], predicts the temperature history across a section of a wall assembly using a finite-difference method to solve the one-dimensional heat transfer governing equations. The model can be used to predict the temperature distribution across the assembly using any defined design fire time-temperature relationship. The structural fire performance sub-model, called STUD [8], models the stud-frame assembly as a single stud with initial imperfection, subjected to eccentric tributary load P. The model assumes: a) steel stress-strain relationships at elevated temperatures are linear up to the yield strength; b) flexural-torsional and weak axis buckling failure modes are prevented by adequate lateral restraints (bridging and blocking); c) the stud is hinged at the ends, as the load eccentricity in part models rotational end restraints; d) there is no temperature variation in the vertical direction along the stud; however, the temperature varies across the stud section from $T_H$ at the hot flange to $T_C$ at the cold flange. The total lateral deflection, y(x), of the stud is given by the following equation:

$$y(x) = y_1(x) + y_2(x) = (\varphi\,\beta^{-2} - e)\,[\tan(0.5\beta H)\sin(\beta x) + \cos(\beta x) - 1] \quad \text{with} \quad \beta^2 = P / (E\,I^*) \qquad (3)$$

where, $\varphi$ = stress-free thermal bowing curvature, H is the height of the wall, P is the load applied in the stud, I* = elasticity-modulus-weighted moment of inertia of the unreduced stud section about the neutral axis parallel to flanges [8], E = steel modulus of elasticity at room temperature, $y_1(x)$ is the stress-free initial imperfection caused by thermal bowing, and $y_2(x)$ is the secondary lateral deflection caused by the vertical load, P acting with an eccentricity, e given by Equation (4) below.

$$e = (1 - K_R)\, \varphi\, \beta^{-2} \tag{4}$$

where $K_R$ is a reduction coefficient. The structural failure of studs can be predicted using formulas for members subjected to combined compression and bending [8], adjusted to account for the deterioration of the mechanical properties of steel at elevated temperatures. For insulated walls, a critical section near stud ends must be checked for the compressive failure of the hot flange, using the following failure criterion:

$$f_H = n_H \left( \frac{P}{A_e^*} + \frac{P\,[e - y(0.2H)]}{S_{eH}^*} \right) \;\geq\; F_{yH} \tag{5}$$

where, $f_H$ = compressive stress at the extreme fibre of the hot flange, $n_H$ = reduction factor for temperature $T_H$ (given as $E_{TH}/E$), $F_{y\,H}$ = yield strength of steel at temperature $T_H$ [8], $A^*_e$ = elasticity-modulus-weighted effective stud section area in compression, and $S^*_{eH}$ = elasticity-modulus-weighted effective stud section modulus in bending that causes compression of hot flange [8]. For non-insulated walls, a critical section at (or near) the stud mid-height must be checked for the compressive failure of the cold flange, using the following failure criterion:

$$f_C = n_C \left( \frac{P}{A_e^*} + \frac{P\, y(0.4H)}{S_{eC}^*} \right) \;\geq\; F_{yC} \tag{6}$$

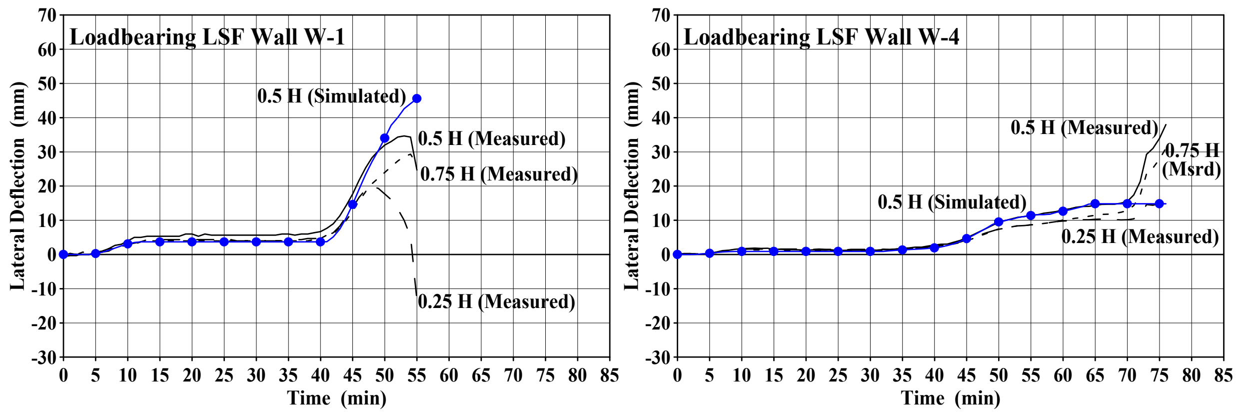
where, $f_C$ = compressive stress at the extreme fibre of the cold flange, $n_C$ = reduction factor for temperature $T_C$ (given as $E_{TC}/E$), $F_{yC}$ = yield strength of steel at temperature $T_C$ [8], and $S^*_{eC}$ = elasticity-modulus-weighted effective stud section modulus in bending that causes compression of cold flange [8].

Table 4 lists predictions for Tests 16 and 17 based on measured temperature histories, and also, based on histories obtained from heat transfer simulations [8]. Predictions for non-insulated wall 17 show a reasonable agreement with test structural failure times. For insulated wall 16, predicted failure times agree well with the initiation of structural failure in central studs.

Table 4. Comparison of Predicted Failure Times with Test Results.

| Assembly number | Fall-off time of gypsum board on exposed side (min) | | Structural failure time in test (min.) | Initiation of failure in central studs in test (min.) | STUD predictions based on measured temperatures (min.) | STUD predictions based on simulated temperatures (min.) |
|---|---|---|---|---|---|---|
| | Face layer | Base layer | | | | |
| 16 | 50 | in place | 56 | 49 | 50 | 51 |
| 17 | 58 | in place | 77 | N/A | 77 | 73 |

Simulated mid-height lateral deflection histories for Tests 16 and 17 are presented in Figure 3. For these simulations, average HF and CF temperatures measured in the central part of wall specimens were used for $T_H$ and $T_C$ input, respectively. For all test simulations, the value of $K_R$ = 0.6 proved to produce a reasonably good agreement of simulated and measured deflections until the initiation of structural failure mechanisms in central studs. More details on the validation of the model are found in other references [8].




(a) Test No. 16 (b) Test No. 17

Figure 3. Measured and Simulated Histories of Lateral Deflection (H = wall height)

## SUMMARY AND CONCLUSIONS

To evaluate the impact of changes in code requirements and building construction materials, an extensive experimental program has been undertaken to investigate the effects of a number of design parameters including attachment of the gypsum board, insulation type, resilient channels, gypsum board thickness, number of gypsum board layers, stud arrangements, type of framing, resilient channel and framing spacing, sub-floor type and structural load on the fire performance of wall and floor assemblies. The results have shown that the main factors that affected the performance of assemblies are the attachment of gypsum board, type of insulation, and the number of gypsum board layers. The data gathered from this study was used to produce key design trends, to propose generic ratings for possible incorporation in the appendices of the National Building Code of Canada, and to develop fire resistance models for wood and steel wall assemblies. This information is of great benefit to practitioners, builders and regulators in choosing suitable assemblies for their design.

## FUTURE RESEARCH

As a next step, the models presented here will be validated against more experimental data that include exposure to both standard and non-standard fires. A new model to predict the fire resistance of wood-joist floor assemblies will be developed. Further, a sensitivity analysis on the models on different effects such as mechanical and thermal properties, length factors, and load factors, will be carried out. Furthermore, all the models will be put under the same platform so that the designers have access to all the tools from the same menu. Finally, design equations will be developed for potential incorporation in codes and standards.

## ACKNOWLEDGEMENTS

This research was funded by NRC and industry partners that included the Canadian Wood Council, Canadian Home Builders Association, Canadian Sheet Steel Building Institute, Forintek Canada Corp., Owens-Corning Canada, Roxul Inc., Gypsum Manufacturers of Canada. The authors are grateful to John Latour, Patrice Leroux, Roch Monette, Jocelyn Henrie and Richard Rombough for assisting in constructing the assemblies and conducting the tests.

## REFERENCES

[1] Canadian Commission on Building and Fire Codes (1995), National Building Code of Canada, Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada

[2] CAN/ULC-S101-M89 (1989) Standard Methods of Fire Endurance Tests of Building Construction and Materials, Underwriters' Laboratories of Canada, Scarborough, Canada

[3] M. A. Sultan and G. D. Lougheed, Results of Fire Resistance Tests on Full-Scale Gypsum Board Wall Assemblies, Internal Report (in press), Institute for Research in Construction, National Research Council, Ottawa, Canada

[4] N. Bénichou, and M.A. Sultan, Design considerations for fire resistance performance of lightweight-framed assemblies, CSCE 2003 Annual Conference, Moncton, NB, pp. 567-1 - 567-10, 2003

[5] M.A. Sultan, Y.P. Séguin, P. Leroux, Results of Fire Resistance Tests on Full-Scale Floor Assemblies, Internal Report No. 764, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, 1998

[6] M.A. Sultan and N. Bénichou, Fire resistance performance of lightweight floor assemblies, Designing Structures for Fire Conference, Baltimore, MD, U.S.A., pp. 203-214, 2003

[7] H. Takeda and J.R. Mehaffey, WALL2D: A Model for Predicting Heat Transfer through Wood-Stud Walls Exposed to Fire," Fire and Materials, 22: 133-140, 1998

[8] F. Alfawakhiri and M.A. Sultan, Numerical modelling of steel members subjected to severe thermal loads, Fire & Materials 2001 Conference, San Francisco, U.S.A., pp. 483-494, 2001