



Fire Resistance of Exterior Wall Assemblies for Housing and Small Buildings

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Abstract. This paper presents the fire resistance results of 6 full-scale exterior wall assemblies study conducted at the National Research Council of Canada jointly with the North American construction industry and other Canadian government departments. The parameters investigated include: cavity insulation types (rock, glass and cellulose fibre) in exterior wall assemblies with oriented strand board sheathing; cavity insulation types (glass fibre and cellulose fibre) in exterior wall assemblies with Type X gypsum glass mat sheathing; and assemblies with different screw spacing of standard 400 mm o.c. and non-standard 200 mm o.c. for attaching the Type X gypsum board on the fire-exposed side and glass mat sheathing board on unexposed side to wood studs using glass fibre insulation in wall cavity. The impact of the investigated parameters on the fire resistance of exterior wall assemblies is discussed. Also, Further research recommendations on design changes to enhance the fire resistance of exterior wall assemblies are proposed. Results of the parameters studied showed that the effect of insulation types on the fire resistance of exterior wall assemblies with OSB sheathing can be considered significant when gypsum board on the fire-exposed side is attached to wood studs with screws spaced at 406 mm o.c., however, the effect insulation types on fire resistance when the gypsum board on fire-exposed side and gypsum glass mat sheathing are attached to wood studs with screw spaced at 203 mm o.c. can be considered insignificant. Also, results showed the use of non-standard screw spacing at 203 mm o.c. for attaching the gypsum board on the fire-exposed side increased the fire resistance by 37% compared to screw spacing at 406 mm o.c. Therefore, the effect of screw spacing on the fire resistance of exterior wall is significant.

Keywords: Fire resistance, Exterior walls, Wood stud, OSB, Glass mat, Rock, Glass, Cellulose

1. Introduction

In designing exterior wall assembly to comply with the building code requirements for fire resistance ratings, the construction industry has some options for considerations such as conducting a fire resistance test to show compliance with code

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requirements or selecting an assembly from testing laboratories listing directories or selecting an assembly from the National Building Code of Canada (NBC) [1] Part 9 buildings tables. The NBC's Table 9.10.3.1-A on walls lists over 400 walls and Table 9.10.3.1-B on floors lists over 700 floor assemblies with fire resistance ratings (FRR), loaded and non-loaded, and sound transmission classification (STC) ratings for assemblies constructed with generic materials. These listings of walls and floors assemblies are based on results of tests and engineering judgements and only for use in NBC Part 9 housing and small buildings. The current 2015 NBC code lists exterior walls assemblies constructed with wood studs and either rock or glass fibre insulations in wall cavity. There are needs to examine the exterior wall listed assemblies with 45-min and 1-h fire resistance ratings to insure the ratings comply with the current construction industry practices and available materials and also to add a new set of exterior wall assemblies with cellulose fibre insulation to provide the users with insulation options. These needs warranted the initiation of a new Joint Research Project (JRP) in 2017 between NRC, the North American construction industry and other Canadian government departments. The research goal was to generate experimental data on the effect of different design parameters on the fire resistance performance of exterior walls to support possible 2020 code changes in NBC Part 9 on Housing and Small Buildings.

2. Parameters Investigated

To develop data to support 2020 NBC code changes for exterior walls, this study focused on the parameters that could affect the fire resistance performance of exterior walls assemblies such as the type of insulation for exterior wall assemblies with either OSB sheathing and screws spaced at 406 mm o.c. or gypsum glass mat sheathing with screws spaced at 203 mm o.c. and the screw spacing methods for attaching the gypsum board to wood studs.

The design parameters investigated in this study are as follows:

1. Effect of wall cavity insulation types: glass fibre, rock fibre and sprayed cellulose fibre (water-adhesive-based mixture) on the fire resistance of exterior wall assemblies using standard screw spacing of 406 mm o.c. for attaching one layer of Type X gypsum board, 15.9 mm thick, on the fire-exposed side to wood studs and standard screw spacing of 300 mm o.c. in the board field and 150 mm o.c. along board edges for attaching one layer of Oriented Strand Board (OSB) sheathing, 11.1 mm thick, on unexposed side to wood studs (Assemblies 1, 3 and 5),
2. Effect of wall cavity insulation types: glass fibre and dry-blown cellulose fibre on the fire resistance of exterior wall assemblies using a non-standard screw spacing of 203 mm o.c. for attaching both one layer of Type X gypsum, 15.9 mm thick, on the fire-exposed side and one layer of Type X gypsum glass mat sheathing, 15.9 mm thick, on unexposed side to wood studs (Assemblies 4 and 6), and

3. Effect of screw spacing: non-standard of 203 mm o.c. versus standard of 406 mm o.c. on the fire resistance of exterior wall assemblies for attaching both one layer of Type X gypsum board on the fire-exposed side and one layer of Type X gypsum glass mat sheathing, 15.9 mm thick, on unexposed side to wood studs (Assemblies 2 and 6).

3. Assemblies' Materials

Type X gypsum board, 15.9 mm thick, conforming to requirements of the ASTM C1396/C1177M-17 standard [2] was used on the fire-exposed side of all assemblies with an average board density of 690 kg/m^3 . Two types of sheathings were considered: OSB boards 11.1 mm nominal thick and density of 572.1 kg/m^3 was used on the unexposed side in Assemblies 1, 3 and 5 conforming to the CAN/CSA O324-07 standard [3] and Type X gypsum glass mat sheathing boards 15.9 mm nominal thick and density of 762.9 kg/m^3 was used on the unexposed side in Assemblies 2, 4 and 6 conforming to the ASTM C1177/C1177M-17 standard [4]. The wood studs used were S-P-F select No. 2- KD-HT nominal $2 \times 4 \text{ s}$ (38 mm thick by 89 mm deep) conforming to the CAN/CSA O141-05 [5] standard. The moisture content for wood studs was measured using Delmhorst BD 2100 moisture meter with two 8 mm long pins penetrate through the wood studs. This device can measure the wood moisture content in the range of 6% to 60%. Three measurements were taken for each wood stud: one at each end and one in the middle and the average of these three measurements was considered the moisture content of the stud. The studs used measured an average moisture content of 10.3%. Three types of insulations were considered: glass fibre insulation (GFI) conforming to the requirements of CAN/ULC-S702 standard [6] was used in Assemblies 1, 2 and 6 with a density of 11 kg/m^3 , rock fibre insulation (RFI) conforming to the requirements of CAN/ULC-S702 standard [6] was used in Assembly 3 with a density of 32.8 kg/m^3 and dry blown cellulose fibre insulation (CFI) with a density of 49.1 kg/m^3 conforming to CAN/ULC-S703-09 standard [7] was used in Assembly 4, and sprayed wet cellulose fibre insulation (water-adhesive-based mixture) with a stabilized density of 36 kg/m^3 conforming to CAN/ULC-S703-09 standard [7] was used in Assembly 5.

4. Description of Test Assemblies

Six full-scale wall assemblies measured 3048 mm high by 3658 mm wide were constructed in accordance to the CAN/CSA-A82.31-M91 standard [8]. Full description of the tested assemblies are given in Ref. [9], however, a brief description of exterior full-scale wall assemblies is provided below. Also, construction details of the 6 exterior wall assemblies are given in Figs. 1, 2, 3 and Table 1. These details are of importance to those researchers who are developing mathematical model to predict fire resistance of exterior walls.

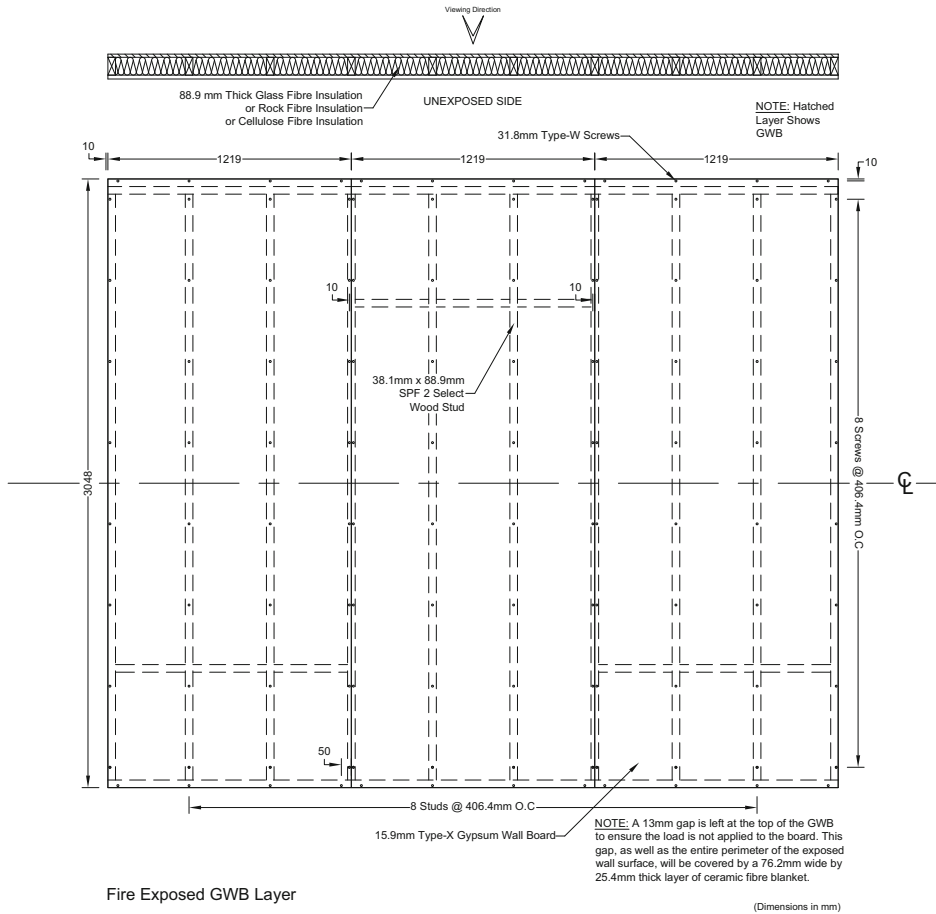


Figure 1. Construction details for assemblies No. 1 (glass fibre insulation), 3 (rock fibre insulation) and 5 (cellulose fire insulation) with OSB sheathing and screws spaced at 406 mm o.c.

4.1. Assemblies 1, 3 and 5

The assemblies 1, 2 and 3 were similar in construction, however, the wall cavities were filled with different types of insulation. Details on design parameters for these assemblies are given in Table 1 and Fig. 1. Assembly 1 was constructed with glass fibre insulation batts in wall cavity, Assembly 3 was constructed with rock fibre insulation batts in wall cavity and Assembly 5 was constructed with cellulose fibre insulation sprayed wet with water-adhesive mixture in wall cavity. The assemblies were constructed with wood studs (38 mm by 89 mm) spaced at 406 mm o.c. On the fire-exposed side, one layer of Type X gypsum boards 15.9 mm thick, without horizontal joints, was attached vertically to wood studs with screws spaced at 406 mm o.c., however in practice, the boards can be applied either vertically or horizontally. The results of a separate study conducted at NRC

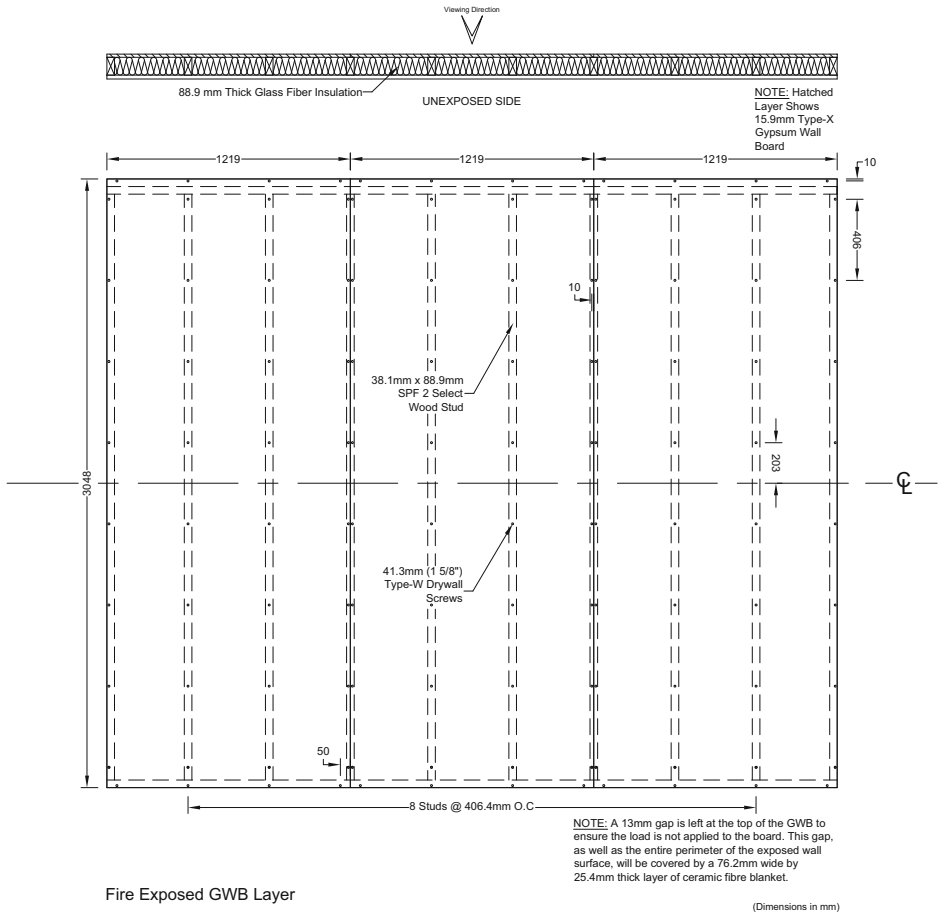


Figure 2. Construction details for Assembly No. 2 (glass fibre insulation) with glass mat sheathing and screws spaced at 406 mm o.c.

[9] on the effect of gypsum board orientation on fire resistance showed that, the installation orientation (vertical vs. horizontal) has little effect on the fire resistance and also, the ULC 308 [10] design for exterior wall permits the use of either horizontal or vertical application to comply with the fire resistance rating of 1 h. On the unexposed side, one layer of OSB sheathing, 11.1 mm thick, was installed vertically with three horizontal joints as shown in Fig. 1 and backed on the cavity side with wood pieces (38 mm by 89 mm) and sheathing was attached to wood studs with screws spaced at 200 mm o.c. in the board field and 150 mm o.c. along the board edges in accordance with CAN/CSA O325-07 standard [3].

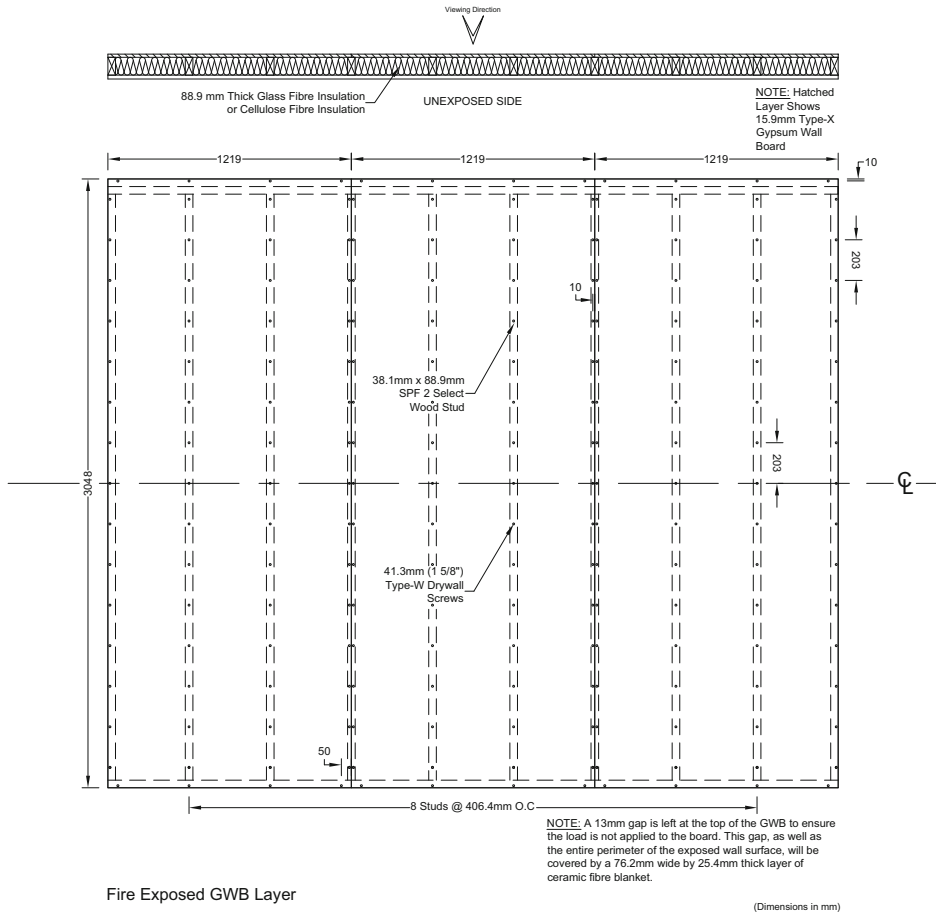


Figure 3. Construction details for Assemblies No. 4 (cellulose fibre insulation) and No. 6 (glass fibre insulation) with glass mat sheathing and screws spaced at 203 mm o.c.

4.2. Assemblies 2, 4 and 6

Details on design parameters for assemblies 2, 4 and 6 are given in Table 1 and Figs. 2 and 3. Assembly 2 was constructed with one layer of Type X gypsum board, 15.9 mm thick, installed vertically without horizontal joints on the fire-exposed side and one layer of Type X gypsum glass mat sheathing, 15.9 mm, installed vertically without horizontal joints on the unexposed side and both boards were attached to wood studs with screws spaced of 406 mm o.c. maximum allowed as per NBC [1] and the wall cavity was filled with glass fibre insulation batts as shown in Fig. 2. Assemblies 4 and 6 were similar in construction as Assembly 2 with the Type X gypsum board on the fire-exposed side and Type X gypsum glass mat sheathing on the unexposed side were attached to wood studs with non-standard screws spaced at 203 mm o.c. In Assembly 4, the wall cavity

Table 1
Design Parameters and Results of Fire-Resistance Tests

Test no.	Stud type	Stud size	Stud spacing	Membrane on fire-exposed side	Membrane on non-exposed side (sheathing)	Membrane fastener spacing
1	Wood	38 mm × 89 mm	406 mm o.c.	15.9 mm Type X Interior Gypsum Board	11.1 mm OSB (all joints backed)	406 mm o.c. on exposed side; 305 mm o.c. in the field and 152 mm o.c. along edges on non-exposed sheathing side ^a
2	Wood	38 mm × 89 mm	406 mm o.c.	15.9 mm Type X Interior Gypsum Board	15.9 mm Type X Gypsum Sheathing	406 mm o.c. on exposed and non-exposed sheathing sides ^a
3	Wood	38 mm × 89 mm	406 mm o.c.	15.9 mm Type X Interior Gypsum Board	11.1 mm OSB (all joints backed)	406 mm o.c. on exposed side; 305 mm o.c. in the field and 152 mm o.c. along edges on non-exposed sheathing side ^a
4	Wood	38 mm × 89 mm	406 mm o.c.	15.9 mm Type X Interior Gypsum Board	15.9 mm Type X Gypsum Sheathing	203 mm o.c. on exposed and non-exposed sheathing sides
5	Wood	38 mm × 89 mm	406 mm o.c.	15.9 mm Type X Interior Gypsum Board	11.1 mm OSB (all joints backed)	406 mm o.c. on exposed side; 305 mm o.c. in the field and 152 mm o.c. along edges on non-exposed sheathing side ^a
6	Wood	38 mm × 89 mm	406 mm o.c.	15.9 mm Type X Interior Gypsum Board	15.9 mm Type X Gypsum Sheathing	203 mm o.c. on exposed and non-exposed sheathing sides

Table 1
continued

Test no.	Insulation type and thickness	Applied load (kN)	Time to failure (min:s)	Gypsum board fall-off time (min:s)	Mode of Assembly Failure
1	GFI 89 mm	75.1	45:40	44:46	Flame Penetration due to deflection
2	GFI 89 mm	75.1	41:00	41:00	Structural
3	RFI 89 mm	75.1	55:11	51:49	Structural
4	CFI 89 mm	75.1	59:12	56:45	Structural
5	CFI** 89 mm	75.1	46:35	44:00	Flame Penetration Through unexposed OSB
6	GFI 89 mm	75.1	56:10	55:00	Flame Penetration due to deflection

Flame penetration failure—the appearance of flame on the unexposed side (failure criteria in Sect. 6.4, CAN/ULC S-101 standard [10])

Structural failure—the assembly is unable to sustain the applied load during the fire test (failure criteria in Sect. 6.4, CAN/ULC S-101 standard [10])

GFI glass fibre insulation, RFI rock fibre insulation, CFI dry-blown cellulose fibre insulation, CFI** sprayed cellulose fibre insulation (water-adhesive-based mixture)

*Maximum spacing permitted by Part 9 of 2015 NBC and Gypsum Board Application Standards

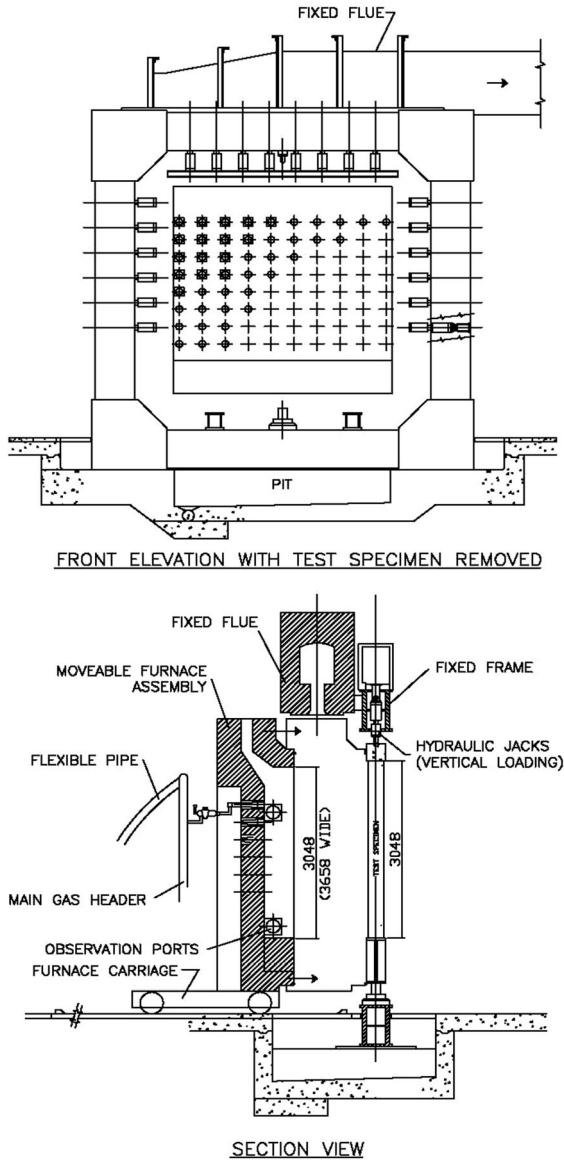
was filled with dry-blown cellulose fibre insulation and in Assembly 6, the wall cavity was filled with glass fibre insulation batts. The construction details of these assemblies are shown in Fig. 3.

5. Test Conditions and Procedures

In Canada, the exterior walls are required to be tested for fire resistance by exposing the interior face of gypsum wall board to furnace heat, however, in the USA exterior walls are required to be tested for fire resistance by exposing the wall exterior face to furnace heat. Hose stream tests were not considered in this study as the research goal was to provide data on the fire resistance performance of exterior walls for use by the NBC Part 9 Standing Committee on Houses and Small Buildings for possible code changes in 2020 code.

The fire resistance tests were carried out using the NRC wall furnace shown in Fig. 4 by exposing the fire-exposed surface of the test assembly to heat in a propane-fired vertical furnace. The furnace was lined with fire brick, covered with a 2.5 cm thick ceramic fibre insulation blanket. The assemblies were sealed at the edges against the furnace with 2.5 cm thick ceramic fibre blankets. The furnace temperature was measured by nine, 20 gauge, shielded thermocouples in accordance with CAN/ULC-S101-14 standard [11]. The average of the nine thermocouple temperatures was used to control the furnace temperature during the fire resistance test. Type K (20 gauge) chromel–alumel thermocouples, with a thickness of 0.91 mm, were used for measuring temperatures at a number of locations inside the test assemblies: six thermocouples at the interface between the gypsum board and the wood studs on the fire-exposed side and another six thermocouples on the back side of the unexposed sheathing facing the wall cavity (i.e. between the cavity insulation and sheathing). Locations of thermocouple are given, as an example, in Fig. 5. An additional nine thermocouples (located under the insulated pads) were installed on the unexposed side facing ambient, as per CAN/ULC-S101-14 standard. Nine deflection gauges were installed on the unexposed side facing ambient to measure the assembly deflection. Details on locations of the thermocouples and deflection gauges for each assembly are also given in Ref. [12]. The loadbearing device used to apply the superimposed load on the wall assemblies is illustrated also in Fig. 4 and the details of this device are given in Ref. [13]. The loading system consisted of two steel frames, located at the top and bottom of the wall assembly. Eight hydraulic jacks were used to provide a vertical superimposed load on the wall assembly via a steel frame; however, the gypsum board edges were not touching the steel frame. The applied superimposed load for each assembly are given in Table 1. Details on the design load calculations are given in Ref. [12].

The failure criteria below for the full-scale tests were derived from CAN/ULC-S101-14 standard [11] in Sect. 6.4 “Determination of Fire Endurance Period” as follows:



(Dimensions are in millimetres)

Figure 4. NRC full-scale wall furnace.

1. Transmission of heat through the test specimen throughout the fire endurance test shall not raise the average temperature measured by stationary thermocouples on its unexposed surface more than 140°C above its initial average temper-

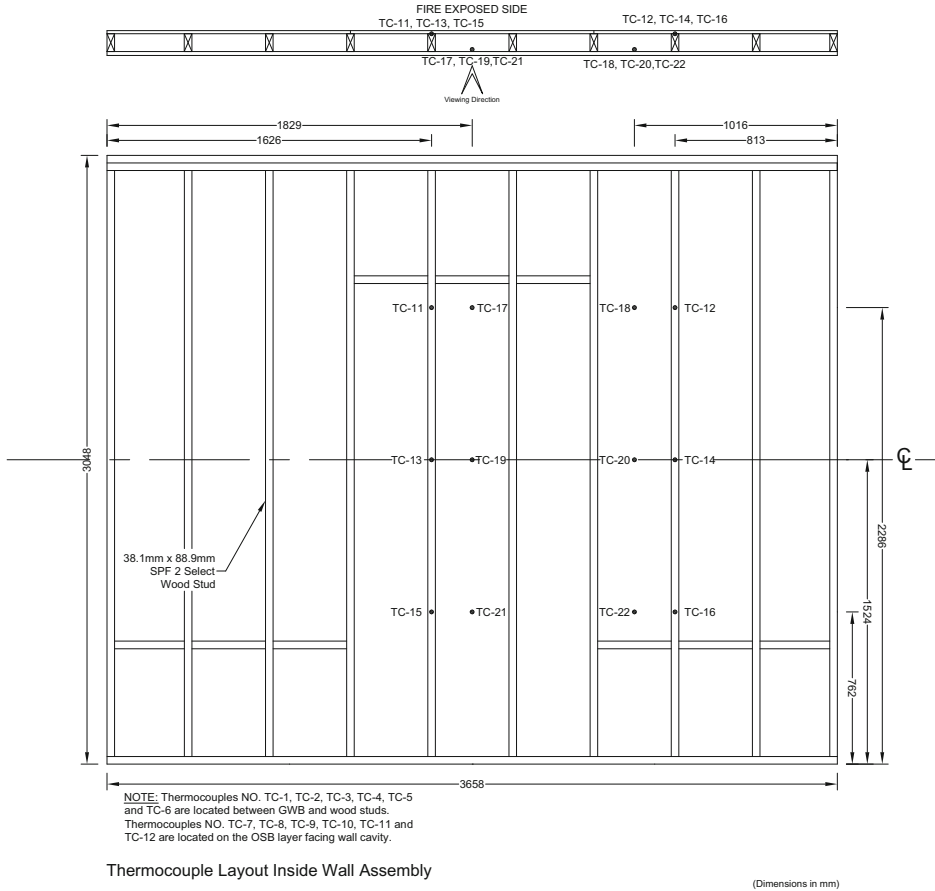


Figure 5. Thermocouple location inside test assemblies.

ature; nor shall the temperature rise at any individual point exceed 180°C including a temperature measured by the roving thermocouple.

2. The test specimen shall have sustained the applied load throughout the fire endurance test without passage of flame or passage of gasses hot enough to ignite cotton pads.

6. Results and Discussion

The design parameters, applied load, time to failure, fire-exposed gypsum board fall-off time and mode of failure are given for each assembly in Table 1. The standard time–temperature curve, average measured furnace temperature, average unexposed surface temperature, average temperature measured at interface between the gypsum board and wood studs (Stud Avg), average measure tempera-

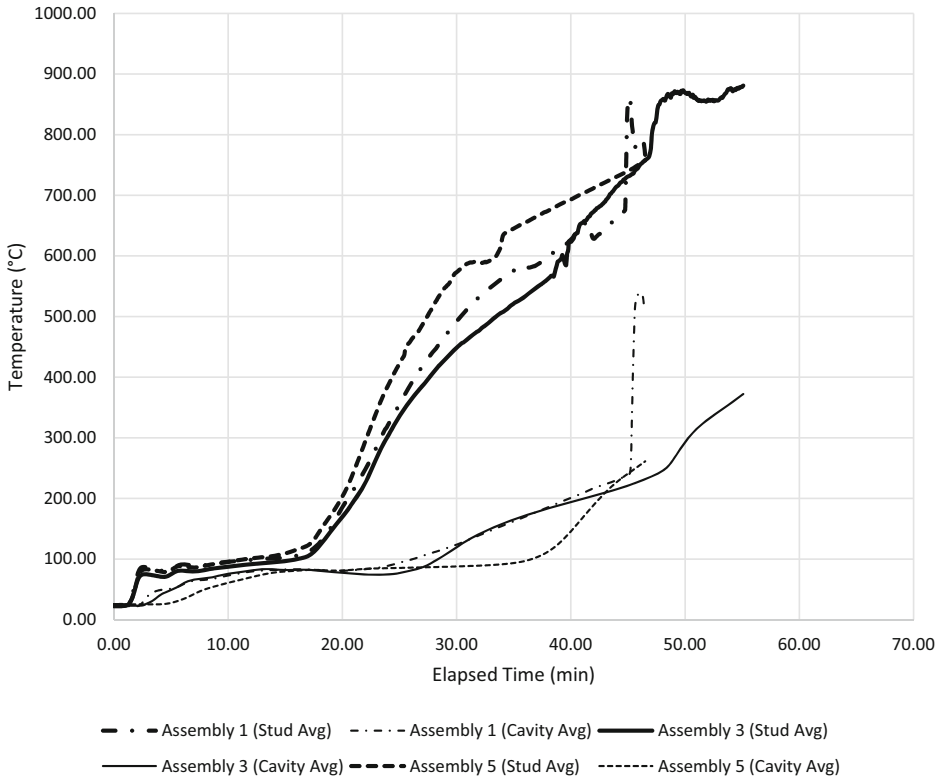


Figure 6. Temperature distributions for Assemblies No. 1 (glass fibre insulation), 3 (rock fibre insulation) and No. 5 (cellulose fibre insulation).

ture at the interface between the insulation and gypsum board on the unexposed side (Cavity Avg), the average of nine thermocouples under insulating pads on the unexposed surface and measured maximum deflection for wall Assemblies are given in References [12, 14]. The measured temperature and deflection results of the assemblies studied are provided in Figs. 6, 7, 8, 9, 10 and 11 which are also useful for those researchers who need to validate their fire resistance models for exterior walls.

The fire resistance standards such as the CAN/ULC S101 and ASTM E119 [15], doesn't specify the number of tests required for determining the assembly fire resistance rating, however, the repeatability of fire resistance test is an issue, however, the repeatability of tests was not considered in this study. However, the NRC have conducted in a separate study [16] fire resistance tests on two identical wood framed wall assemblies to examine the test repeatability and results showed that only 1 min difference in the fire resistance (see wall assembly F-14 with 52 min and wall assembly F-14B with 51 min).

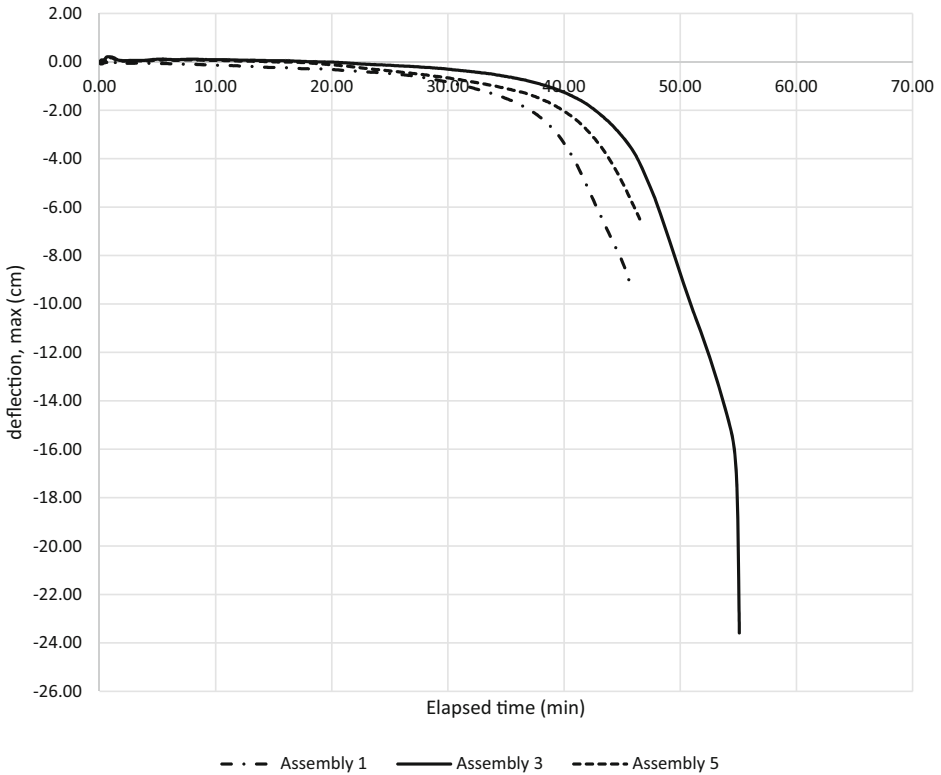


Figure 7. Maximum deflection distributions for Assemblies No. 1 (glass fibre insulation), 3 (rock fibre insulation) and 5 (cellulose fibre insulation) with screws spaced at 406 mm o.c.

Comparisons of the three investigated parameters mentioned above on the fire resistance performance of exterior wall assemblies are presented as follows:

1. Effect of wall cavity insulation types: glass fibre, rock fibre and sprayed cellulose fibre (water-adhesive-based mixture) on the fire resistance of exterior wall assemblies using standard screw spacing of 406 mm o.c. for attaching one layer of Type X gypsum board, 15.9 mm thick, on the fire-exposed side to wood studs and standard screw spacing of 300 mm o.c. in the board field and 150 mm o.c. at board edges for attaching one layer of Oriented Strand Board (OSB) sheathing, 11.1 mm thick, on unexposed side to wood studs.

Assemblies 1 (glass fibre insulation), 3 (rock fibre insulation) and 5 (sprayed cellulose fibre insulation with water-adhesive-based mixture) were tested to investigate the effect of insulation type on the fire resistance of exterior wall assemblies with one layer of Type X gypsum board on fire-exposed side attached to wood studs with screws spacing of 406 mm o.c. and one layer of OSB sheathing attached to wood studs on unexposed side with screw spacing of 200 mm o.c. in the board

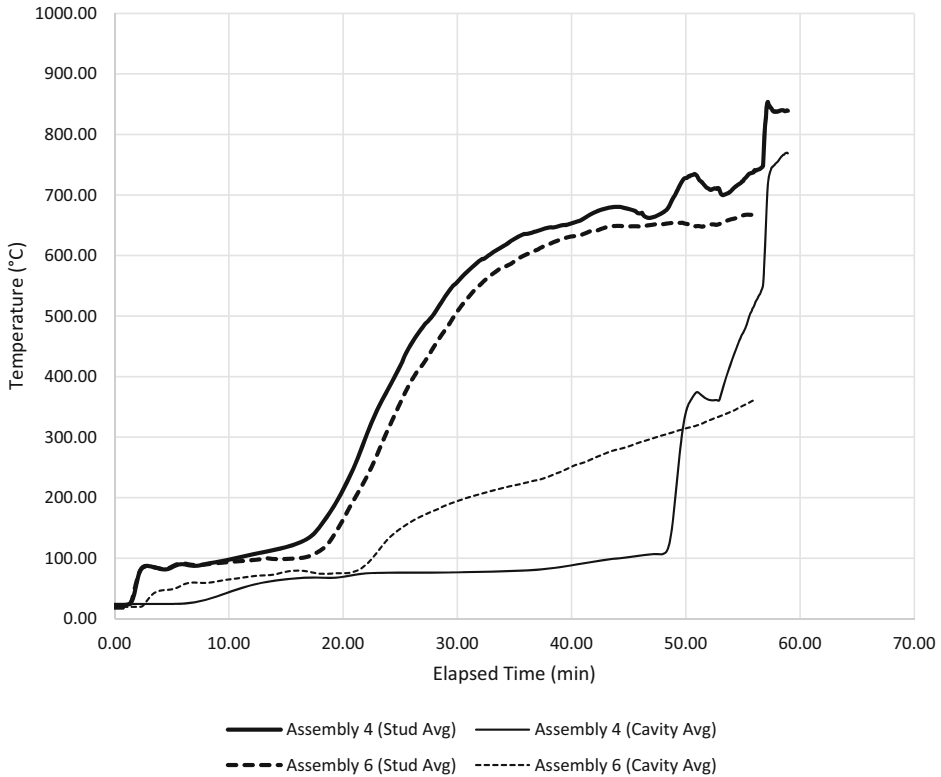


Figure 8. Temperature distributions for Assemblies No. 4 (cellulose fibre insulation) and 6 (glass fibre insulation) with screws spaced at 203 mm o.c.

field and 150 mm o.c. along the board edges. The average temperature measured at interface between the gypsum board and wood studs (Stud Avg) on fire-exposed side and average temperature measured at the interface between the insulation and facing wall cavity on the unexposed-side (Cavity Avg) as well as maximum deflection measured for Assemblies 1, 3 and 5 are presented in Figs. 6 and 7, respectively.

Comparison of the temperature results presented in Fig. 6 shows that for Assembly 1, there is a sharp increase in the average temperature measured between studs and gypsum (Stud Avg) on fire-exposed side at 45 min which consistent with the observed gypsum board fell-off time at 44 min 46 s. When the gypsum board fell-off, the glass fibre insulation in wall cavity was exposed to furnace heat and as results, the insulation degraded rapidly. This is also shown by the rapid increase in temperature measured between the insulation and back surface of OSB board facing wall cavity (Cavity Avg) at 45 min. Assembly 1 failed due to flame penetration on the unexposed side joints at 45 min 40 s, however, the failure occurred in less than 1 min after the gypsum board on the fire-exposed side

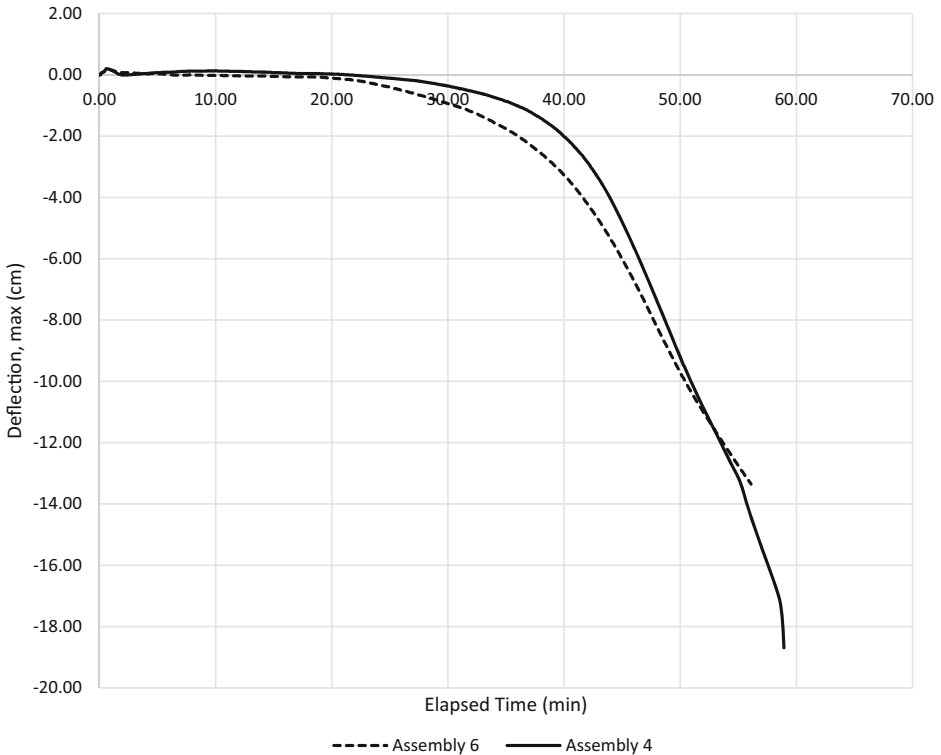


Figure 9. Maximum deflections distributions for Assemblies Nos. 4 and 6.

fell-off. Test observations for Assembly 3 with rock fibre insulation showed that the gypsum board joint became wide open at 47 min and the board fell-off at 51 min 49 s. Figure 6 also shows that there is an increase in the measured temperature at the interface between the gypsum board and wood studs at about 47 min. Unlike the glass fibre insulation in Assembly 1, the rock fibre insulation did not deteriorate and had protected the sides of wood studs for a few minutes extra until the studs deteriorated due to furnace heat exposure and deflected out-of-plan away from the furnace due to fall-off of the gypsum board. The Assembly 3 was unable to sustain the applied load at 55 min 11 s. Test observation for Assembly 5 with sprayed cellulose fibre insulation with water-adhesive-based mixture showed that the gypsum board joints on the fire-exposed side were wide open and gypsum board fell-off at 44 min and the cellulose fibre insulation was exposed to furnace heat. Figure 6 shows that the average measured temperature at the interface between the gypsum board and wood studs (Stud, avg) increased rapidly at 44 min which is consistent with the fell-off of the gypsum board on the fire-exposed side and the assembly failed on flame penetration through the OSB sheathing at 46 min 35 s.

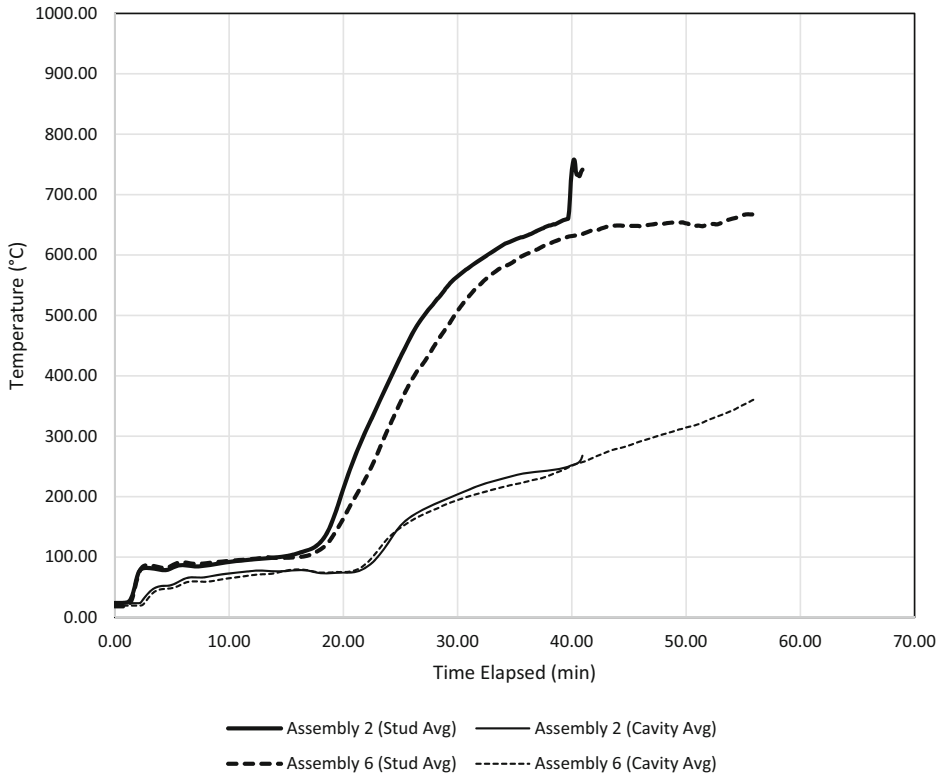


Figure 10. Temperature distributions for Assemblies Nos. 2 and 6.

Comparisons of the maximum deflection results in Fig. 7 for Assemblies 1, 3 and 5 showed an increase in deflection up to 40 min and then followed by a rapid deflection, as results of gypsum board fell-off, until the failure occurred.

In exterior wall assembly protected with one layer of Type X gypsum board, 15.9 mm thick on the fire-exposed side and one layer of OSB, 11 mm thick, sheathing board on the unexposed side and both boards were attached to wood studs with screw spacing at 406 mm o.c., the Assembly with rock fibre insulation protected the wood studs sides and OSB sheathing longer than the glass or cellulose fibre insulation and that resulted in provided approximately 10 min more fire resistance in assembly with rock fibre insulation than in the assemblies with either cellulose or glass fibre insulation, therefore, the effect of insulation types on the fire resistance can be considered significant.

- Effect of wall cavity insulation types: glass fibre and dry-blown cellulose fibre on the fire resistance of exterior wall assemblies using a non-standard screw spacing of 203 mm o.c. for attaching both the Type X gypsum, 15.9 mm thick, on the fire-exposed side and Type X gypsum glass mat sheathing, 15.9 mm thick, on unexposed side to wood studs.

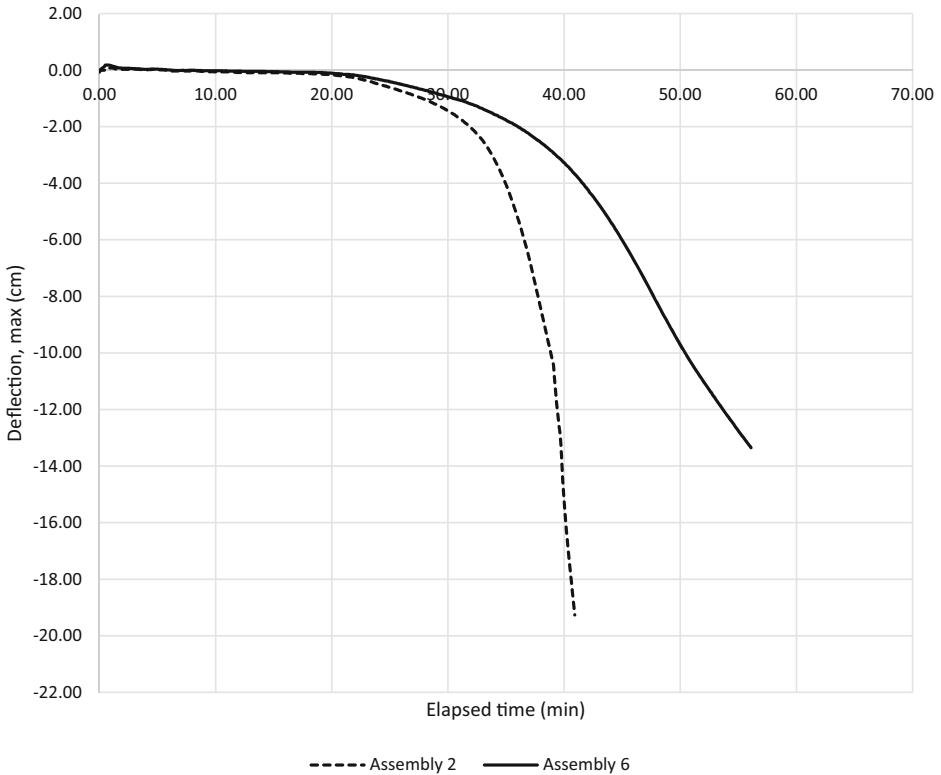


Figure 11. Maximum deflection distributions for Assemblies Nos. 2 and 6.

Assembly 4 with dry-blown cellulose fibre insulation and Assembly 6 with glass fibre insulation were tested to investigate the effect of insulation types on the fire resistance of exterior wall assemblies with one layer of Type X gypsum board on fire-exposed side and one layer of gypsum glass mat sheathing on the unexposed side and both boards were attached to wood studs with screw spaced at 203 mm o.c. The average temperature measured at interface between the gypsum board layer and wood studs (Stud Avg), average measure temperature at the interface between the insulation and gypsum board on the unexposed side (Cavity Avg) as well as maximum deflection measured for Assemblies 4 and 6 are presented in Figs. 8 and 9, respectively.

Comparison of the temperatures (stud Avg) and (Cavity Avg) presented in Fig. 8, for Assembly 4 with cellulose fibre insulation show, that there are two sharp increases in temperatures at 47 min and 56 min due to 5 cm wide of gypsum board joint opening and the gypsum board fell-off, respectively. The second sharp temperature rise at 56 min is consistent with test observations where the gypsum board fell-off at 56 min 45 s. The Assembly 4 was unable to sustain the applied load at 59 min 10 s and test was terminated. For Assembly 6, with glass

fibre insulation, the temperature at the interface between the gypsum board and wood studs (Stud Avg) presented in Fig. 8 show that there is an increase in temperature at 17 min, followed by gradual temperature increase of up to 40 min, due to the furnace heat penetration into wall cavity via gypsum board joint opening with more time exposure, and then the temperature became more or less the same till the end of test. The temperature (Cavity Avg) results show that, there is an increase in temperature at the interface between the unexposed gypsum mat sheathing and at 22 min followed by a gradual temperature increase reached 370°C at the end of test due to furnace heat penetration into the wall cavity via the gypsum board joint opening. The Assembly 6 was unable to sustain the applied load at 56 min 10 s and test was terminated.

Comparisons of the maximum deflection results presented in Fig. 9 for Assemblies No. 4 and 6 showed that the walls had a slight deflection as gypsum board joints opened and followed by an increase in deflection as board joints became wide open due to the deterioration of glass fibre insulation and wood studs and then followed by a rapid out-of-plan deflection away from the furnace when the gypsum board fell-off until the failure occurred.

Table 1 shows that, the time difference between the fire-exposed gypsum board fall-off and time to failure for Assemblies 4 and 6 is less than 2.45 min, therefore, the use of a reduced screw spacing at 203 mm o.c. shows that the gypsum board fell-off on the fire-exposed side is controlling the fire resistance of the assembly and, therefore, the insulation type whether glass fibre or cellulose fibre did not provide much contribution to the fire resistance.

In exterior wall assembly protected with one layer of Type X gypsum board, 15.9 mm thick, on the fire exposed side and one layer of gypsum glass mat, 15.9 mm thick, sheathing on the unexposed side and both boards attached to wood studs with screw spacing at 203 mm o.c., the Assembly with cellulose fibre insulation provided 3 min slightly more fire resistance than the assembly with glass fibre insulation, therefore, the effect of insulation types glass versus cellulose fibre on fire resistance the assembly can be considered insignificant as the fire resistance was controlled by the stay-in-place for the gypsum board on the fire-exposed side.

3. Effect of screw spacing: non-standard of 203 mm o.c. versus standard of 406 mm o.c. on the fire resistance of exterior wall assemblies for attaching both the Type X gypsum board on the fire-exposed side and Type X gypsum glass mat sheathing, 15.9 mm thick, on unexposed side to wood studs.

Assembly 2 with standard screw spacing at 406 mm o.c. and Assembly 6 with non-standard reduced screw spacing at 203 mm o.c. were tested to investigate the effect of screw spacing for attaching the Type X gypsum board to wood studs on fire-exposed side and Type X glass mat sheathing on the unexposed side to wood studs. The average temperature measured at interface between the gypsum board layer and wood studs (Stud Avg), average measure temperature at the interface between the insulation and gypsum board on the unexposed side (Cavity Avg) as well as maximum deflection measured for Assemblies 2 and 6 are presented in

Figs. 10 and 11, respectively.

Test observations for Assembly 2 with standard screw spacing at 406 mm o.c. showed that the gypsum board joints started to open at 18 min and flame appeared at the joints and joints became wide open at 35 min and board fell-off at 41 min. Comparison of the temperatures (Stud Avg and Cavity Avg) presented in Fig. 10 shows that there was an increase in temperature 18 min as the gypsum board joints started to become open followed by a more increase in temperature as the joints became wide open due to the deterioration of the glass fibre insulation and then followed by a sharp increase in temperature between the gypsum board and wood studs at the fire-exposed side (Stud Cav) at 40 min and this is consistent with the observed board fell-off. The Assembly 2 was unable to sustain the applied load at 41 min and test was terminated. Test observations for Assembly 6, with non-standard screw spacing at 203 mm o.c., showed the gypsum board joints started to open at 18 min and flame appeared at the joints and flame appeared stronger as the joints became wider opening until the gypsum board fell off at 55 min. Comparison of the temperature (Stud Avg and Cavity Avg) presented also in Fig. 10 shows that there was an increase in temperature at 18 min followed by gradual temperature increase of up to 40 min, due to the furnace heat penetration into wall cavity as the gypsum board joint became more open, and then the temperature was more or less the same till the end of test. The temperature (Cavity Avg) results show that, there is an increase in temperature at the interface between the unexposed gypsum mat sheathing and at 23 min followed by a gradual temperature increase that reached 370°C at the end of test due to also furnace heat penetration into the wall cavity via the gypsum board joint opening. The Assembly 6 was unable to sustain the applied load at 56 min 10 s and test was terminated.

Comparisons of maximum deflection results in Fig. 11 for Assemblies 2 and 6 showed that the walls had a slight deflection first as results of gypsum board joints open up and furnace heat penetrated the wall cavity followed by an increase in deflection at 30 min as board joints became wide open due to the deterioration of glass fibre insulation and wood studs and then followed by a rapid out-of-plan deflection, as results of gypsum board fell-off, until the failure occurred.

Table 1 shows that, the time difference between the gypsum board fall-off and time to failure and time difference of the gypsum board fell-off for Assemblies 2 and 6 is less than 1.17 min. Also, the gypsum board fell-off time for assemblies 2 and 6 is 14 min. These results clearly indicate that there is two key findings: first, the gypsum board on the fire-exposed side is controlling the fire resistance of the assembly and second, the longer for the gypsum board on fire-exposed side stays-in-place using the reduced screw spacing at 203 mm o.c., the more fire resistance of 15 min than when screw is spaced at 406 mm o.c.

In exterior wall assembly protected with one layer of Type X gypsum board, 15.9 mm thick, on the fire exposed side and one layer of Type X gypsum board glass mat, 15.9 mm thick, sheathing on the unexposed side, the assembly with reduced screw spacing of 203 mm o.c. provided approximately 15 min more fire resistance than the assembly with maximum allowed NBC screw spacing at 406 mm o.c. Therefore the effect of screw spacing (203 mm o.c. vs. 406 mm o.c.)

for the gypsum board attached to wood studs on the fire exposed side is significant.

7. Proposed Further Research Recommendations

Further research recommendations to enhance the fire resistance of the studied exterior wall Assemblies 1, 3 and 6 to achieve 1-h fire resistance rating are proposed below.

Assembly 1, fire resistance of 45 min 40 s, with design modifications such as reducing the screw spacing on the fire-exposed gypsum board field from 406 mm o.c. to 203 mm o.c. and along the edges from 406 mm o.c. to 150 mm o.c. and that may lead the Assembly 1 with rock fibre insulation to achieve 1-h fire resistance rating. Assembly 3, fire resistance of 55 min 11 s, with design modifications such as reducing the screw spacing from 406 mm o.c. to 203 mm o.c. at the gypsum board on the fire-exposed side edges and that may lead the Assembly 3 to achieve fire resistance rating of 1-h. Assembly 6, fire 56 min 10 s, With design modifications such as reducing the screw spacing on the gypsum board edges from 203 mm o.c. to 150 mm o.c. may lead to achieve 1-h fire resistance rating. The further research mentioned above need to confirm the fire resistance rating of the assemblies based on the proposed design modifications.

8. Conclusions

The followings are key findings summary:

1. The effect of insulation types on fire resistance exterior wall assembly with standard screw spacing of 406 mm o.c. (1st investigated parameter), results showed that, the installation of rock fibre insulation in wall cavity provided significant increase of 10 min (20%) fire resistance compared to a similar assembly but with either glass fibre insulation or sprayed cellulose fibre insulation, therefore the effect of insulation type on the fire resistance can be considered significant.
2. The effect of insulation types on fire resistance exterior wall assembly with standard screw spacing of 203 mm o.c. (2nd investigated parameter), results showed that, the effect of types of insulation (glass fibre vs. cellulose fibre) on fire resistance is insignificant as the fire resistance was controlled by the stay-in-place for the gypsum board on the fire-exposed side.
3. The effect of screw spacing of 406 mm o.c. versus 203 mm o.c on the fire resistance (3rd investigated parameter) results showed that reducing the screw spacing from 400 mm o.c. to 203 mm o.c. increased the stay-in-place for the gypsum board on the fire-exposed side by 14 min and, thus increased the fire resistance by 15 min (37%), therefore, the effect of screw spacing on the fire resistance is significant.
4. Test repeatability of one min can move the Assembly 4 with fire resistance of 59 min 12 s, to 1-h fire resistance rating.

5. Further research recommendations on the design changes to enhance the fire resistance of Assemblies 1, 3 and 6 to achieve 1-h fire resistance rating are proposed. This further research need to confirm the fire resistance rating of 1-h for these assemblies.

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