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Review of the NRC Canada Studies on Fire Resistance of Walls: Results, Research Gaps and Design Guidelines

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Abstract. The National research council Canada conducted three major fire resistance studies on the interior party walls, interior fire separation walls and exterior walls. The fire resistance results of these studies were published over the past three decades and the publications were short in suggesting design guidelines for practioners' use and gaps for future research. This paper summaries the fire resistance results of 35 full-scale wall tests, suggests design guidelines and identifies future research gaps for interior party walls, interior fire separation walls and exterior walls. The result summary includes the effect of different design parameters on the fire resistance performance of wall assemblies such as the stud type and spacing, number of stud rows, number of gypsum board layers and thickness, mid-height blocking, resilient channels installation and spacing, screws spacing for attaching gypsum board to either wall faming or resilient channels, insulation type and exterior wall sheathing type on the fire resistance of loadbearing and non-loadbearing wall assemblies. The summary results was used as the basis for suggesting design guidelines for practioners' use and identifying gaps for future research to improve the fire resistance performance of wall assemblies. For example, the use of a reduced screw spacing from 406 mm o.c. to 203 mm o.c. in the gypsum board field and from 406 mm o.c. to 150 mm o.c. at the board joints was suggested for future research to keep the protective gypsum board layer attached to studs or resilient channels longer for a better fire resistance performance of wall assemblies. Also, fire resistance design guidelines are suggested, for examples, the use of rock fibre insulation for non-load bearing interior party walls to achieve 1.5-h fire resistance, the use of cellulose fibre insulation for loadbearing fire separation walls to achieve 2-h fire resistance rating and the use of reduced screw spacing in attaching the gypsum board to wall framing from 406 mm o.c. to 203 mm o.c. for loadbearing exterior wall assembly with gypsum board glass mat sheathing to expand the fire resistance rating from non-useful 30-min to a useful code compliance 45-min fire resistance rating assembly. Additional suggested examples for future research gaps and design guidelines are also provided.

Keywords: Fire resistance, Party walls, Fire separation walls, exterior walls, Research gaps, Design guidelines

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1. Introduction

Light-weight framed wall constructions are widely used across Canada and the USA and required to exhibit acceptable fire resistance ratings (FRR) and sound transmission classification (STC) ratings prescribed in Part 9 and Part 5 of the National Building Code (NBC). The fire resistance requirements are prescribed as fire barriers/separation to contain the fire within the compartment of fire origin and also to provide safety for the occupants and firefighters during the evacuation and rescue operations, respectively. In designing walls to comply with the FRR requirements, the construction industry has a few options for considerations such as conducting fire resistance tests to show code compliance, selecting assemblies from the listing laboratories' directories or selecting assemblies from the NBC Part 9 tables. In the1990 NBC Edition [1], the STC rating between multi-family dwellings was increased from 45 STC to 50 STC to meet public demands for better sound isolation across dwellings party wall. The NBC 1990 Edition, Part 9 Appendix A listed only 13 wall assemblies with FRR and STC for users to choose from. In 1992, there were needs not only to expand the wall listed assemblies and provide more wall design options, but also to confirm some of the FRR ratings and STC ratings due to the changes in building materials and construction methodologies/practices. To meet these needs, the National Research Council Canada (NRC) in partnership with 14 North America construction industries and other government department's partners carried out three major joint research projects (JRP) on the fire resistance and sound transmission performance of wall assemblies. The fire resistance studies included: Walls-I project [2] that was conducted to determine the fire resistance for interior party walls for loadbearing wood and non-loadbearing steel studs assemblies in multi-family dwellings with 45-min and 1-h FRR, Walls-II project [3] that was conducted to determine the fire resistance for interior party walls in multi-family dwellings with loadbearing steel studs assemblies with 45-min, 1-h and 1.5-h FRR and the Fire Resistance Performance of building Assemblies (FRPBA) project [4] that was conducted to determine the fire resistance of wood studs interior fire separation wall assemblies with 1.5-h and 2-h FRR and wood studs exterior wall assemblies with 45-min and 1-h FRR. Walls-I and Walls-II projects were conducted in parallel with two major studies on the acoustic isolation for party wall assemblies. The summary results of fire resistance tests conducted in the period of 1992 to 2019 are presented in this paper, however, the results of sound transmission studies are giving in Refs. [5, 6]. The sound transmission studies demonstrated that, the major factor to consider in construction walls, to control sound transmission, was the isolation of the gypsum board layers from the studs on each side of wall. These studies also reported other important design parameters, to improve the sound reduction across walls, such as the construction with double studs (wood or steel), stagger studs, resilient channels installation, more number of gypsum board layer on each side, bigger wall cavity depth, studs and resilient channels installation spaced at 610 mm o.c., however, it was reported that, the insulation type, unlike for fire resistance performance of wall assembles, had a relatively minor effect on the ability of wall to control sound transmission. The objectives of the joint research projects were to generate knowledge on the fire resistance of loadbearing and non-loadbearing wood and steel studs wall assemblies as well as on the sound isolation of different designs wall assemblies constructed with generic materials for the purpose of assigning FRR and STC ratings in future NBC Part 9 tables' development. During the fire resistance and sound performance studies for wall assemblies, the results showed that, some design parameters enhances the FRR but had counter effect on the STC ratings. In these cases, the research conducted jointly with the NRC acoustics laboratory was geared to find out design parameters solutions that work to enhance both the fire resistance and acoustics performance of wall assemblies. The generated knowledge from the JRPs were instrumental in successful number of code change proposals for updating the wall tables in NBC Part 9 in 2000 [7], 2005 [8] and 2020 [9] Editions and as results of these code changes, the number of wall assemblies was increased from 13 in 1990 NBC Edition to over 400 wall assemblies in 2020 NBC Edition so that, the builders, architects, and design engineers have more wall design options in the NBC tables to select from without the need for conducting expensive and time consuming fire resistance tests, and also the listed assemblies with FRR and STC ratings facilitate building approvals process. Prior to 2005, the NBC adopted the prescriptive code approach that uses standards requirement for constructing assemblies, however, in 2005, the NBC adopted the objective-based approach to facilitate innovations and cost effectiveness for assemblies that show performance at least the same or better to the prescriptive code approach. Walls-I and Walls-II were conducted for prescriptive code approach development, however, the FRPBA project, was conducted with a mix use of standard and non-standard construction requirements for the use in objective-based code designs approach. As the JRP studies mentioned above targeted the Canadian code changes development, the available literature with similar design such as the use of maximum design load, resilient channels installation and use of generic materials was limited for comparison purposes, however, the Underwriters' Laboratories of Canada (ULC) published listings for 1-h FRR: design W308 [10] on exterior walls with glass mat gypsum board sheathing and design U356 [11] on exterior walls with Oriented Strand Board (OSB) sheathing where both listings were based on restricted load of 82% of maximum design load while the FRPBA study on exterior walls [4] was conducted using the maximum design load and results provided 45-min FRR for both assemblies with either gypsum board glass mat or OSB sheathings. The fire resistance results of the studies mentioned above [2–4] were published over the past three decades and publications were short in identifying gaps for future research or suggesting design guidelines for practioners' use. To accomplish these short fall, the summary results presented in this paper was instrumental in suggesting design guidelines for practioners' used and identifying future research gaps to improve the fire resistance of wall assemblies for cost effective design purposes.

2. Test Conditions and Procedures

The fire resistance tests in the above mentioned studies were carried out in accordance with CAN/ULC-S101 standard [12]. Details on the loadbearing device used to apply the superimposed load on the wall assemblies are given in Ref. [13]. Unlike, the interior fire separation and exterior walls, the party wall assemblies were instrumented with additional thermocouples and deflection gauges other than those required by the standard to provide data for fire resistance mathematical modeling development calibration. Superimposed load for each assembly studied are given in Tables 1, 2 and 3 and the load calculations were based on the maximum design load capacity required by the fire resistance standard [12]. Fire resistance tests were carried out until the structural failure occurred and the failure criteria used in assemblies testing were derived from the standard [12] in Sect. 6.4 "Determination of Fire Endurance Period".

3. Description of Wall Assemblies

Details on the materials, construction of assemblies and instrumentation are given in Tables 1, 2 and 3 below and in References [2–4, 14]. Three types of insulation in wall cavity were considered: glass fibre (GFI), rock fibre (RFI) and cellulose fibre (CFI).

4. Brief Summary Results, Gaps for Future Research and Design Guidelines

To facilitate readability navigation, this paper is presented in three main sections titled: brief summary results, design guidelines and gaps for future research where each section is subsequently divided into three subsections: interior party walls, interior fire separation walls and exterior walls.

4.1. Brief Summary Results

Brief summary results for interior party walls, interior fire separation and exterior walls assemblies: 1-PW to 22-PW, 1-FS to 7-FS and 1-EW to 6-EW, respectively, are presented below, however, details results analysis are also provided in References [2–4, 15, 16]. This summary was necessary to be provided in this paper as it was instrumental in the development of future research gaps and design guidelines.

4.1.1. Interior Party Walls Twenty-two interior party wall assemblies were studied 30 years ago, the temperature and deflection measurements row data was not available in a format that can be used in parametric comparison purposes. Also, the party walls studies were conducted purposely for the prescriptive approach of NBC code development changes and, therefore, comparison with available literature was limited. Two types of the gypsum board arrangements were studied for interior party walls: asymmetrical (1 $\times$ 2) with one layer of gypsum board on one

Table 1
Design Parameters and Fire Resistance Test Results for Interior Party Wall Assemblies

Test no.	Stud type	Stud size	Stud spacing	Membrane(s) on fire-exposed side	Membrane(s) on non-exposed side	Resilient channels
1-PW	Steel	38 mm × 90 mm	610 mm o.c	One-layer 12.7 mm type × gypsum board	Two-layers 12.7 mm Type × gypsum board	–
2-PW	Steel	38 mm × 90 mm	610 mm o.c	One-layer 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	–
3-PW	Steel	38 mm × 90 mm	610 mm o.c	One-layer 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	–
4-PW	Steel	38 mm × 90 mm	610 mm o.c	One-layer 12.7 mm Type × gypsum board	Two-layers 12.7 mm Type × gypsum board	–
5-PW	Steel	38 mm × 89 mm	610 mm o.c	One-layer 12.7 mm type × gypsum board	Two-layers 12.7 gypsum Board	–
6-PW	Steel	38 mm × 90 mm	406 mm o.c	Two-layers 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	Exposed side spaced at 406 mm o.c
7-PW	Steel	38 mm × 90 mm	406 mm o.c	Two-layers 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	Exposed side spaced at 406 mm o.c
8-PW	Steel	38 mm × 90 mm	406 mm o.c	Two-layers 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	Exposed side spaced at 406 mm o.c
9-PW	Steel	38 mm × 90 mm	406 mm o.c	Two-layers 12.7 mm Type × gypsum board	Two-layers 12.7 mm Type × gypsum board	Exposed side spaced at 406 mm o.c
10-PW	Wood	38 mm × 89 mm	406 mm o.c	One-layer 12.7 mm type × gypsum board	2 layers 12.7 mm type × gypsum board	Exposed side spaced at 406 mm

Table 1 continued

Test no.	Stud type	Stud size	Stud spacing	Membrane(s) on fire-exposed side	Membrane(s) on non-exposed side	Resilient channels
11-PW	Wood	38 mm × 89 mm	406 mm o.c	One-layers 12.7 mm type × gypsum board	2 layers 12.7 mm type × gypsum board	Exposed side spaced at 406 mm o.c
12-PW	Wood	38 mm × 89 mm	406 mm o.c	One-layer 12.7 mm Type × gypsum board	Two-layers 12.7 mm Type × gypsum board	Unexposed side spaced at 406 mm o.c
13-PW	Wood	38 mm × 89 mm	406 mm o.c	One-layer 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	Unexposed side spaced at 406 mm o.c
14-PW	Steel	38 mm × 90 mm	406 mm o.c	Two-layers 12.7 mm Type × gypsum board	Two-layers 12.7 mm Type × gypsum board	–
15-PW	Wood	38 mm × 89 mm	406 mm o.c	One-layer 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Exposed side spaced at 406 mm o.c
16-PW	Wood	38 mm × 89 mm	406 mm o.c	Two-layers 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	Exposed side spaced at 406 mm o.c
17-PW	Steel	Double row 38 mm × 90 mm	406 mm o.c	Two-layer 12.7 mm type × gypsum board	2 layers 12.7 mm type × gypsum board	–
18-PW	Wood	Double row 38 mm × 89 mm	406 mm o.c	One-layers 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	–
19-PW	Steel	38 mm × 90 mm	610 mm o.c	Two-layers 12.7 mm type × gypsum board	Two-layers 12.7 mm type × gypsum board	Exposed side spaced at 406 mm o.c

Table 1
continued

Test no.	Stud type	Stud size	Stud spacing	Membrane(s) on fire-exposed side	Membrane(s) on non-exposed side	Resilient channels
20-PW	Steel	38 mm × 90 mm	406 mm o.c	Two-layers 12.7 mm regular gypsum board	Two-layers 12.7 mm regular gypsum board	–
21-PW	Wood	38 mm × 89 mm	406 mm o.c	Two-layers 12.7 mm regular gypsum board	Two-layers 12.7 mm regular gypsum board	–
22-PW	Steel	Double row 38 mm × 89 mm	406 mm o.c	Two-layer 12.7 mm type × gypsum board	2 layers 12.7 mm type × gypsum board	–

Test no.	Stud type	Insulation type and thickness	Applied load (kN)	Time to failure (min)	Mode of assembly failure
1-PW	Steel	–	–	65	Thermal
2-PW	Steel	GFI 89 mm	–	65	Flame/structural
3-PW	Steel	RFI 89 mm	–	100	Flame/structural
4-PW	Steel	CFI* 89 mm	–	62	Flame/structural
5-PW	Steel	RFI* 89 mm	–	60	Thermal
6-PW	Steel	–	78.4	77	Thermal
7-PW	Steel	CFI 89 mm	78.4	71	Thermal
8-PW	Steel	GFI 89 mm	78.4	56	Thermal
9-PW	Steel	RFI 89 mm	78.4	59	Thermal
10-PW	Wood	GFI 89 mm	68.0	51	Structural

Table 1
continued

Test no.	Stud type	Insulation type and thickness	Applied load (kN)	Time to failure (min)	Mode of assembly failure
11-PW	Wood	RFI 89 mm	68.0	52	Structural
12-PW	Wood	CFI* 89 mm	68.0	56	Structural
13-PW	Wood	RFI 89 mm	68.0	58	Structural
14-PW	Steel	–	78.4	83	Structural
15-PW	Wood	GFI 89 mm	67.0	52	Structural
16-PW	Wood	GFI 89 mm	68.0	79	Structural
17-PW	Steel	–	156.7	100	Structural
18-PW	Wood	GFI 2x89 mm	156.7	51	Structural
19-PW	Steel	RFI 89 mm	52.4	74	Structural
20-PW	Steel	–	–	63	Thermal
21-PW	Wood	–	–	65	Thermal
22-PW	Steel	–	156.7	102	Structural

GFI glass fibre insulation, *RFI* rock fibre insulation 615 mm wide, *RFI** rock fibre insulation 548 mm wide, *CFI* dry-blown cellulose fibre insulation, *CFI** water base wet spray cellulose fibre insulation

Table 2
Design Parameters and Fire Resistance Test Results for Interior Fire Separation Wall Assemblies

Test no.	Stud type	Stud size	Stud spacing	Membrane(s) on fire-exposed side	Membrane(s) on non-exposed side	Membrane fastener spacing	Resilient channels	Insulation type and thickness	Applied load (kN)	Time to failure (min:s)	Mode of assembly failure
1-FS	Wood	38 mm × 89 mm	610 mm o.c	2 layers 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Base layer at 610 mm o.c. and face layer at 305 mm o.c. on exposed and non-exposed sides*	Exposed side spaced at 610 mm	GFI 89 mm	49.5	103:45	Structural
2-FS	Wood	38 mm × 89 mm	610 mm o.c	2 layers 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Base layer at 610 mm o.c. and face layer at 305 mm o.c. on exposed and non-exposed sides*	Exposed side spaced at 610 mm	RFI 89 mm	49.5	109:50	Structural
3-FS	Wood	Double row of 38 mm × 89 mm (Blocked)	610 mm o.c	2 layers 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Base layer at 610 mm o.c. and face layer at 305 mm o.c. on exposed and non-exposed sides*	Exposed side spaced at 610 mm	RFI 89 mm in both rows	99.5	113:54	Structural
4-FS	Wood	38 mm × 89 mm (Blocked)	610 mm o.c	2 layers 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Base layer at 610 mm o.c. and face layer at 305 mm o.c. on exposed and non-exposed sides*	Exposed side spaced at 610 mm	RFI 89 mm	49.5	119:28	Structural
5-FS	Wood	Double row of 38 mm × 89 mm (Blocked)	406 mm o.c	2 layers 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Base layer at 610 mm o.c. and face layer at 305 mm o.c. on exposed and non-exposed sides*	Exposed side spaced at 406 mm	RFI 89 mm in both rows	150.2	117:28	Structural

Table 2 continued

Test no.	Stud type	Stud size	Stud spacing	Membrane(s) on fire-exposed side	Membrane(s) on non-exposed side	Membrane fastener spacing	Resilient channels	Insulation type and thickness	Applied load (kN)	Time to failure (min:s)	Mode of assembly failure
6-FS	Wood	Double row of 38 mm × 89 mm (Blocked)	406 mm o.c	2 layers 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Base layer at 610 mm o.c. and face layer at 305 mm o.c. on exposed and non-exposed sides*	Exposed side spaced at 406 mm	CFI** Full Cavity 203 mm	150.1	132:12	Structural
7-FS	Wood	Double row of 38 mm × 89 mm	406 mm o.c	2 layers 15.9 mm type × gypsum board	2 layers 15.9 mm type × gypsum board	Base layer at 610 mm o.c. and face layer at 305 mm o.c. on exposed and non-exposed sides*	Exposed Side Spaced at	406 mm	CFI** Full		Cavity 203 mm
150.1		130.50	Structural								

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

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

Table 3
Design Parameters and Fire Resistance Test Results for Exterior Walls

Test no.	Stud type	Stud size	Stud spacing	Membrane on fire-exposed side	Membrane on non-exposed side (sheathing)	Membrane fastener spacing	Insulation type and thickness	Applied load (kN)	Time to failure (min:s)	Gypsum board fall-off time (min:s)	Mode of assembly failure
1-EW	Wood	38 mm × 89 mm	406 mm o.c	15.9 mm type × 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*	GFI 89 mm	75.1	45:40	44:46	Flame Penetration due to deflection
2-EW	Wood	38 mm × 89 mm	406 mm o.c	15.9 mm type × interior gypsum board	15.9 mm type × Gypsum Sheathing	406 mm o.c. on exposed and non-exposed sheathing sides*	GFI 89 mm	75.1	41:00	41:00	Structural
3-EW	Wood	38 mm × 89 mm	406 mm o.c	15.9 mm type × 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*	RFI 89 mm	75.1	55:11	51:49	Structural
4-EW	Wood	38 mm × 89 mm	406 mm o.c	15.9 mm type × interior gypsum board	15.9 mm type × gypsum sheathing	203 mm o.c. on exposed and non-exposed sheathing sides	CFI 89 mm	75.1	59:12	56:45	Structural

Table 3 continued

Test no.	Stud type	Stud size	Stud spacing	Membrane on fire-exposed side	Membrane on non-exposed side (sheathing)	Membrane fastener spacing	Insulation type and thickness	Applied load (kN)	Time to failure (min:s)	Gypsum board fall-off time (min:s)	Mode of assembly failure
5-EW	Wood	38 mm × 89 mm	406 mm o.c	15.9 mm type × 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*	CFI** 89 mm	75.1	46:35	44:00	Flame Penetration Through unexposed OSB
6-EW	Wood	38 mm × 89 mm	406 mm o.c	15.9 mm type × interior gypsum board	15.9 mm type × Gypsum Sheathing	203 mm o.c. on exposed and non-exposed sheathing sides	GFI 89 mm	75.1	56:10	55:00	Flame Penetration due to deflection

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

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]) side and two layers on the other and symmetrical (2 × 2) with two layers of gypsum board on each side of the walls. In the asymmetrical (1 × 2) wall assembles studied, the reason for the use of two layers of gypsum board on one side was to improve the STC ratings. However, for building code purposes, the fire resistance of asymmetrical wall assemblies was determined on the basis of subjecting the less number of gypsum board, conservative fire resistance approach, to furnace heat, therefore, the single gypsum board layer side was considered as the fire exposed side. The parameters investigated for interior party walls and their effect on the fire resistance performance are provide below.

- Effect of insulation type on the fire resistance in non-loadbearing asymmetrical gypsum board (1 × 2) wall assemblies with steel stud spaced at 610 mm o.c. and without resilient channels installation

Four asymmetrical (1 × 2) wall assemblies were studied to investigate the effect of insulation type on the fire resistance. Assemblies: 1-PW was without insulation in wall cavity, 2-PW was with GFI, 3-PW was with RFI and 4-PW was with water base spray CFI. Design details of these assemblies are given in Table 1 and Ref. [2]. The Assembly 1-PW provided 65 min fire resistance, Assembly 2-PW also provided 65 min fire resistance, Assembly 3-PW provided 100 min fire resistance and Assembly 4-PW provided 62 min fire resistance. In non-loadbearing asymmetrical (1 × 2) steel studs spaced at 610 mm o.c. assemblies, the installation of FRI in wall cavity had increased significantly the fire resistance by 54% compared to assembly without insulation or assembly with either GFI or CFI. Additional results analysis can be found in Ref. [2]. The assembly with RFI is a good example that shows the installation of RFI in wall cavity can achieve a substantial increase in fire resistance and possibly also an increase in sound isolation.

- Effect of insulation type on the fire resistance of loadbearing symmetrical gypsum board (2 × 2) wall assemblies with steel studs and resilient channels spaced at 406 mm o.c. installed on the fire exposed side

Four symmetrical (2 × 2) wall assemblies were studied to investigate the effect of insulation type on the fire resistance. Assembly 6-PW was without insulation in wall cavity while Assembly 7-PW was with CFI dry-blown, Assembly 8-PW was with GFI and Assembly 9-PW was with RFI. Details on the construction design are given in Table 1 and Ref. [3]. The Assembly 6-PW provided 77 min fire resistance, Assembly 7-PW provided 71 min fire resistance, Assembly 8-PW provided 56 min fire resistance and Assembly 9-PW provided 59 min fire resistance. While having insulation in wall cavity improves the sound isolation, the installation of insulation in symmetrical (2 × 2) wall assemblies did reduce the fire resistance by 27%, 8% and 23%, respectively, in comparison to an assembly without insulation in wall cavity. Additional results analysis are provided in Ref. [3].

- Effect of insulation type, GFI vs RFI, on the fire resistance of loadbearing asymmetrical gypsum board (1 × 2) wall assemblies with wood stud and resi-

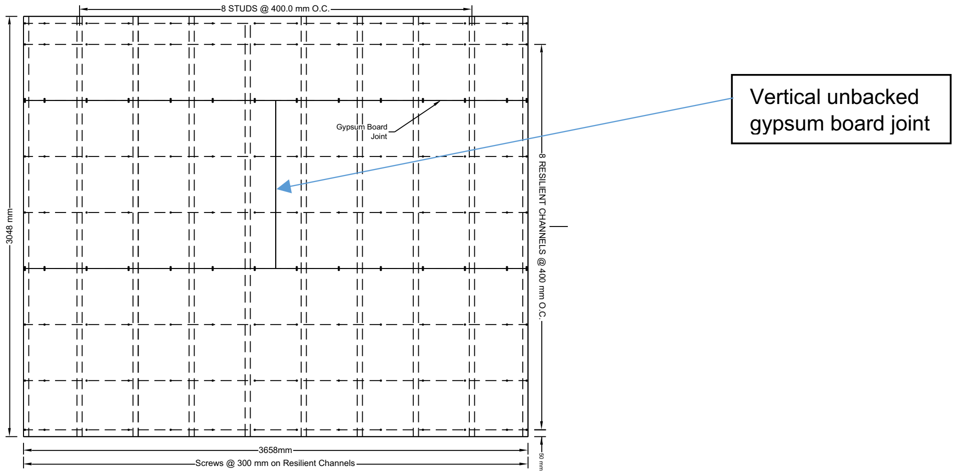

Figure 1. Gypsum boards layout on the fire exposed single layer side of asymmetrical (1 × 2) assembly with one vertical gypsum board joint not connected to stud framing [2].

lient channels spaced at 406 mm o.c. and resilient channels installed on the fire exposed side (gypsum board single layer side)

Two asymmetrical (1 × 2) wall assemblies: Assembly 10-PW with GFI and Assembly 11-PW with RFI, were studied to investigate the effect of insulation type on the fire resistance where the resilient channels installed on the single gypsum board layer fire exposed side. Details on the construction design is given in Table 1 and Ref. [2]. The Assembly 10-PW provided 51 min fire resistance while Assembly 11-PW provide 52 min fire resistance. The reason for not having a higher fire resistance for the assembly with RFI compared to an assembly with GFI was due to the presence of unprotected gypsum board joint on the fire exposed side that created by the installation of resilient channels as shown in Figure 1. Additional results analysis can be found in Ref. [2].

- Effect of insulation type on the fire resistance in loadbearing asymmetrical (1 × 2) wall assemblies with wood stud and resilient channels spaced at 406 mm o.c., and resilient channels installed on the unexposed gypsum board double layer side

Two asymmetrical (1 × 2) wall assemblies: Assembly 12-PW with CFI dry blown and Assembly 13-PW with RFI, were studied to investigate the effect of insulation type on the fire resistance where the resilient channels were installed on the unexposed double gypsum board layer side. Details on the construction design is given in Table 1 and Ref. [2]. The Assembly 12-PW provided 56 min fire resistance while Assembly 13-PW provide 58 min fire resistance. Additional results analysis is given in Ref. [2]. In loadbearing asymmetrical (1 × 2) wall assembly with wood studs and resilient channels installed on the double gypsum bard layer unexposed side, the effect of insulation type of either CFI dry-blown insulation or RFI on the fire resistance is insignificant.

- Effect of insulation width between steel studs on the fire resistance of non-load bearing asymmetrical (1×2) wall assembly

Two non-loadbearing asymmetrical (1 × 2) wall assemblies: Assemblies 3-PW (RFI 615 mm width, tight fit between studs) and 5-PW (RFI 548 mm width, loose fit between studs) constructed without resilient channels installation were studied to investigate the effect of RFI insulation width between steel studs on the fire resistance. Details on the construction design is given in Table 1 and Ref. [2]. In non-loadbearing wall assembly with steel studs spaced at 610 mm o.c., test results showed that the assembly with 548 mm width (loose fit) provided 60 min fire resistance while the assembly with 615 mm width (standard fit) provided 100 min fire resistance. Additional results discussion is provided in Reference [2]. These results show that, to maximize the benefits of RFI installation on the fire resistance, it is important to have the insulation installed tightly between the steel studs.

- Effect of resilient channel installation on the fire resistance in symmetrical (2×2) wood stud walls

Two loadbearing symmetrical (2 × 2) wall assemblies: Assemblies 6-PW with resilient channels installation on the fire exposed side and 14-PW (without resilient channels installation) were studied to investigate the effect of resilient channels installation on the fire resistance. Assembly 6-PW and 14-PW were constructed with steel studs and without insulation in wall cavity. Details on the construction design are given in Table 1 and Ref. [2]. Assembly 6-PW provided 77 min fire resistance while Assembly 14-PW provided 83 min fire resistance. These results showed that the fire resistance in assembly with resilient channel installation was reduced by about 7% compared to an assembly without resilient channel installation. Additional results discussion is provided in Ref. [2]. If the assembly is not design for acoustics sound reduction, for better fire resistance performance avoid the use of resilient channels.

- Effect of resilient channels location in asymmetrical assembly (1 × 2) on the fire resistance of loadbearing wood stud walls

Two loadbearing asymmetrical (1 × 2) wood stud wall assemblies: Assembly 11-PW with resilient channels installed on the single layer of gypsum board fire exposed side and Assembly 13-PW with resilient channels installed on the unexposed gypsum board double layers side were studied to investigate the effect of resilient channels location on the fire resistance. Details on the construction design is given in Table 1 and Ref. [2]. The Assembly 11-PW provided 52 min fire resistance while Assembly 13-PW provided 58 min fire resistance. Having the resilient channels installed on the single layer side decreased the fire resistance of the assembly by about 10% compared to an assembly with resilient channel installed on the double layers side. This reduction in the fire resistance could be caused by having unbacked vertical gypsum board joint, shown in Figure 1 above, as e×plained in Ref. [2]. Therefore, the location of resilient channels plays an important role in the fire resistance performance of asymmetrical (1 × 2) wall assembly.

- Effect of gypsum board thickness on fire resistance of asymmetrical wall assemblies with resilient channels installed on fire exposed side

Two loadbearing asymmetrical (1 × 2) wood stud wall assemblies: Assembly 10-PW with gypsum board 12.7 mm thick and Assembly 15-PW with gypsum board, 15.9 mm thick, were studied to investigate the effect of gypsum board thickness on the fire resistance. Details on the construction design are given in Table 1 and Ref. [2]. The Assembly 10-PW provided 51 min fire resistance while Assembly 15-PW provide 52 min. The reasons for not having a tangible increase in fire resistance when the gypsum board thickness increased from 12.7 mm to 15.9 mm is caused by the installation of resilient channels on the single layer side with unprotected vertical gypsum board joint shown in Figure 1 above and e×plained in Ref. [2].

- Effect of number of gypsum board layers on fire resistance of an asymmetrical (1&2) vs a symmetrical (2&2) wood stud assemblies with resilient channels installed on the fire exposed side

Two assemblies: asymmetrical (1 × 2) Assembly 13-PW with one layer of gypsum board on the fire exposed side and symmetrical (2 × 2) Assembly 16-PW with two layers of gypsum board on the fire exposed side were studied to investigate the effect of gypsum board number of layers on the fire resistance. Details on the construction design are given in Table 1 and Ref. [2]. The Assembly 13-PW with one layer of gypsum board on the fire exposed side provided 58 min fire resistance while Assembly 16-PW with two layers on the fire exposed side provided 79 min fire resistance. In loadbearing wood studs wall asymmetrical (1 × 2) gypsum board arrangement and RFI in wall cavity and resilient channels installed on the unexposed side and symmetrical (2 × 2) assemblies gypsum board arrangement and GFI in wall cavity and resilient channels installed, on the fire exposed side, the effect of having a second layer of Type × gypsum on the fire exposed side increased the fire resistance by at least 36%. Therefore, the addition of a second layer of gypsum board increase significantly the fire resistance. Additional results analysis is provided in Ref. [2].

- Effect of steel stud row on fire resistance (single row vs double row) in loadbearing symmetrical steel stud wall assemblies without insulation or resilient channels

Two symmetrical (2 × 2) gypsum board arrangement wall assemblies constructed with steel studs: Assemblies 14-PW (single-row) and 19-PW (double-row) were studied to investigate the effect of the number of stud rows on the fire resistance in loadbearing symmetrical (2 × 2) wall assembly. Details on the construction design are given in Table 1 and Ref. [3]. Assebly14-PW provided 83 min fire resistance while Assembly 19-PW provided 100 min fire resistance even though the double rows were not loaded separately. The results showed that the wall with two rows of steel studs provide 20% more fire resistance compared to wall with one row of steel studs. Additional results analysis is provided in Ref. [3].

- Effect of steel stud spacing in loadbearing assemblies with two layers of gypsum board on both the fire exposed and unexposed sides

Two symmetrical (2 × 2) gypsum board arrangement wall assemblies: Assembly 9-PW (steel studs spaced at 406 mm o.c.) and Assembly 20-PW (steel studs spaced at 610 mm o.c.) were studied to investigate the effect of steel stud spacing on the fire resistance in loadbearing assemblies constructed with two layers of Type × gypsum board on each side, resilient channel installed on the fire exposed side and spaced at 406 mm o.c. and RFI in wall cavity. Details on the construction design are given in Table 1 and Ref. [3]. Assembly 9-PW with studs spaced at 406 mm o.c. provided 59 min fire resistance while Assembly 20-PW with studs spaced at 610 mm o.c. provided 74 min fire resistance. In loadbearing symmetrical (2 × 2) gypsum board arrangement wall assembly with steel studs, the Assembly with studs spaced at 610 mm o.c. provided 25% more fire resistance compared to a similar wall assembly but with steel studs spaced sat 406 mm o.c. [3]. Additional results analysis can be found in Ref. [3].

- Effect of stud type (wood vs steel) on the fire resistance in non-loadbearing symmetrical wall assemblies (2 × 2) with two layers of regular gypsum board on both the fire exposed and unexposed sides

Two symmetrical (2 × 2) gypsum board arrangement wall assemblies: Assemblies 21-PW (steel studs) and 22-PW (wood studs) were studied to investigate the effect of studs type (wood vs steel) in non-loadbearing symmetrical (2 × 2) gypsum board arrangement wall assembly without installation of resilient channels or insulation in wall cavity. Details on the construction design are given in Table 1 and Refs. [2, 3]. The Assembly 21-PW with steel stud provided 63 min fire resistance while Assembly 4-PW with wood studs provided 65 min fire resistance. Additional results discussion is provided in Refs. [2, 3]. In a non-loadbearing wall assembly with asymmetrical (2 × 2) gypsum board arrangements constructed with either steel or wood studs spaced at 610 mm o.c. and two layers of regular gypsum board on both the fire exposed and unexposed sides, and without resilient channels or insulation in wall cavity, the fire resistance results showed that the effect of stud type of steel or wood is insignificant.

4.1.2. Interior Fire Separation Walls Seven loadbearing interior fire separation wood stud wall assemblies (1-FS to 7-FS) were studied to investigate the effect of different design parameters on the fire resistance for a single- and double-row of wood stud walls. Details on the construction design for these assemblies are given in Table 2 and Ref. [4]. A brief summary results for the design parameters investigated followed by a comparison of performance in assemblies with a single- and double-row of wood stud walls are provided below.
4.1.2.1. Wall Assemblies with a Single-Row of Wood Studs Three symmetrical (2×2) fire separation wall tests, Assemblies 1-FS, 2-FS and 4-FS with a single-row of wood studs, were conducted to investigate the effect of insulation type and mid-height blocking on the fire resistance. A brief summary results is provided below and additional results analysis can be found in Refs. [4, 15].

- Effect of insulation type (glass fibre vs rock fibre) on the fire resistance of wood stud wall assemblies with two layers of Type × gypsum board on both the fire-exposed and unexposed sides and resilient channels on fire-exposed side

Assembly 1-FS with GFI and Assembly 2-FS with RFI were studied to investigate the effect of insulation type on the fire resistance. The Assembly 1-FS provided 103 min 45 s and Assembly 2-FS provided 109 min 50 s fire resistance. Comparison of temperature measurement is given in References [4], however, comparison of deflection measurement is presented in Figure 2. The results showed that the deflection in both assemblies started approximately at 60 min followed by a similar increase in deflection for up to 90 min and then followed by a more rapid increase in deflection in Assembly 1-FS as results of the gypsum board fell-off earlier which exposed the wall cavity to furnace heat and caused more rapid deterioration and melting of the GFI and more burning of wood studs compared to Assembly 2-FS with RFI. Additional results analysis can be found in Refs. [4, 15].

The Installation of RFI improved slightly the fire resistance of a wall assembly by 6 min (6%) compared to an assembly with GFI, therefore, the effect of insulation type GFI vs RFI on fire resistance is insignificant.

- Effect of mid-height blocking installation on the fire resistance of wall assemblies with two layers of Type × gypsum board on both the fire-exposed and unexposed sides, rock fibre insulation in wall cavity and resilient channels on fire-exposed side

Assembly 2-FS (without mid-height blocking) and Assembly 4-FS (with mid-height blocking) were studied to investigate the effect of mid-height blocking installation on the fire resistance. The Assembly 2-FS provided 109 min 50 s fire resistance while Assembly 4-FS provided 119 min 28 s fire resistance. Comparison of temperature measurement distributions is giving in Ref. [15], however, the comparison of the wall deflection measurement for Assemblies 2-FS and 4-Fs is presented in Figure 3. The results show that in both assemblies, the deflection started approximately at 60 min and followed by an increase in deflection, however, in

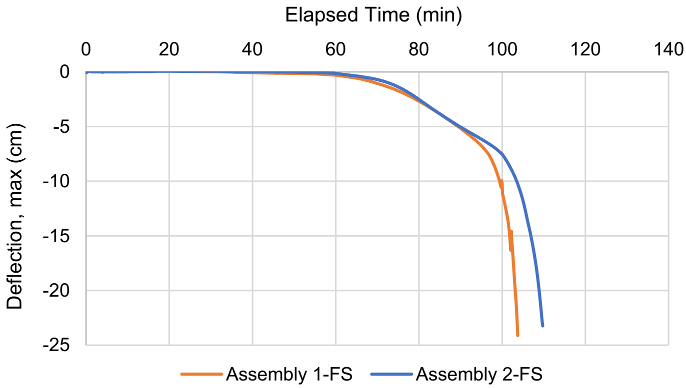

Figure 2. Deflection distributions for Assembly with a single-row of wood studs and different type of insulation, Assemblies 1-FS (GFI) and 2-FS (RFI) [15].

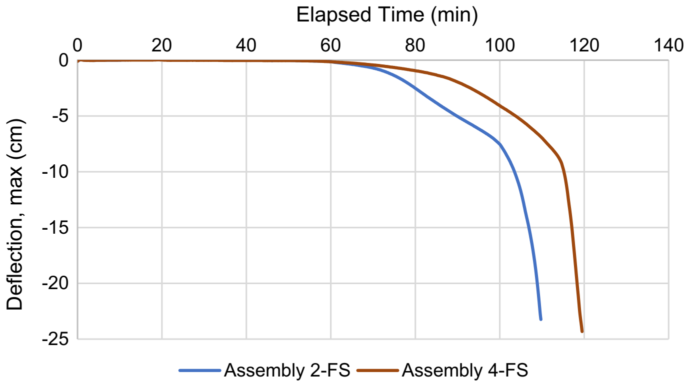

Figure 3. Deflection distributions for Assembly with a single-row of wood studs and without mid-height blocking, 2-FS (without mid-height blocking) and Assembly 4-FS (with mid-height blocking) [15].

assembly without mid-height blocking the deflection was higher than in assembly with mid-height blocking due to a possible e×tra rigidity that was provided by the mid-height blocking installation. Additional results analysis is provided in Refs. [4, 15]. The wall assembly with mid-height blocking provided 10 min more fire resistance compared to the wall assembly without mid-height blocking. This 10 min difference was enough to have the wall assembly with mid-height blocking to be considered as 2-h FRR while the assembly without mid-height blocking can only be considered to be 1.5-h FRR. Therefore, the effect of med-height blocking installation on the fire resistance is significant.

4.1.2.2. Wall Assemblies with a Double-Row of Wood Studs Four symmetrical (2 × 2) wall assembly: Assemblies 3-FS, 5-FS, 6-FS and 7-FS, with a double-row of wood studs were studied to investigate the effect of studs and resilient channels spacing, insulation type and med-height blocking. The results finding below is limited to assemblies with the same load applied on both stud rows during the entire test duration. A future research may consider similar studies but with each row of wood stud loaded separately and a comparison of test results can be realized. The results of the three comparative design parameters investigated are presented as follows:

- Effect of wood stud and resilient channel spacing (406 mm o.c. vs 610 mm o.c.) on the fire resistance of assemblies with two layers of Type × gypsum board on both the fire-exposed and unexposed sides, mid-height blocking, rock fibre insulation and resilient channels installed on fire-exposed side

Assembly 3-FS (wood studs and resilient channels spaced at 610 mm o.c.) and Assembly 5-FS (wood studs and resilient channels spaced at 406 mm o.c.) were studied to investigate the effect of studs and resilient channels spacing on the fire resistance. The Assembly 3-FS provided 113 min 54 s while Assembly 5-FS provided 117 min 28 s fire resistance. Comparison of temperature measurement is given in Reference [15], however, the comparison of the wall deflection measurement distributions for Assemblies 3-FS and 5-FS is presented in Figure 4. The results show that in both assemblies, deflection started approximately at 60 min followed by an increase in deflection in assembly 5-FS compared to Assembly 3-FS, however, after the gypsum board fell-off approximately at 105 min, the deflection in assembly with stud and resilient channel spacing of 610 mm o.c. was only

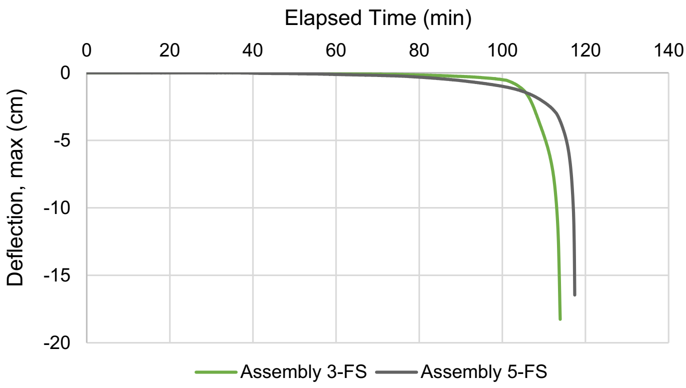

Figure 4. Deflection distributions for Assemblies with a double-row of wood studs and different stud and resilient channels spacing, 3-FS (wood studs and resilient channels spaced at 610 mm o.c.) and 5-FS (wood studs and resilient channels spaced at 406 mm o.c.) [15].

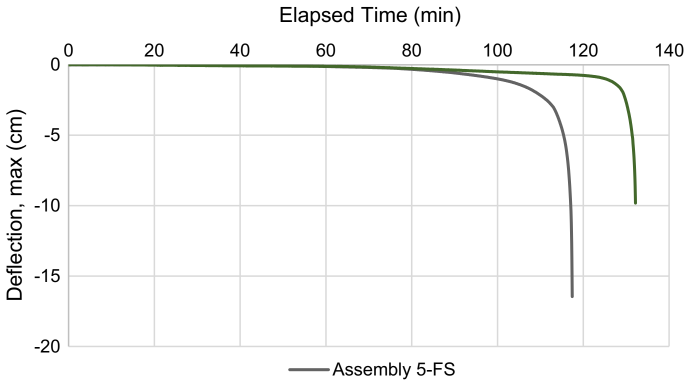

Figure 5. Deflection distributions for Assemblies with a double-row of wood studs and different type of insulation, 5-FS (RFI) and 6-FS (sprayed CFI with water-based mixture) [15].

higher by 1% than assembly with spacing of 406 mm o.c., therefore, the effect of wood studs and resilient channels spacing on the fire resistance is insignificant.

- Effect of insulation types/application (rock fibre vs sprayed cellulose fibre with water-based mixture) on the fire resistance of wall assemblies with two layers of Type × gypsum board on both the fire-exposed and unexposed sides, insulation in wall cavities, mid-height blocking and both the wood studs and resilient channels installed on fire-exposed side spaced at 406 mm o.c.

Assembly 5-FS with RFI and Assembly 6-FS with sprayed CFI with water-based mixture were studied to investigate the effect of insulation type RFI vs CFI on the fire resistance. Assembly 5-FS with RFI provided 117 min 28 s fire resistance while Assembly 6-FS with CFI provided 132 min 12 s fire resistance. Comparison of temperature measurement distributions is given in Ref. [4], however, the comparison of the wall deflection distributions for Assemblies 5-FS and 6-FS is presented in Figure 5. The results show that in both assemblies, deflection started approximately at 60 min followed by an increase in deflection and then a rapid deflection until the failure occurred. Additional results analysis is provided in References [4]. The wall assembly with sprayed CFI filled the cavities between the studs and vertical gap space between studs' rows provided 15 min more fire resistance compared to wall assembly with RFI batts installed only in cavities between studs, therefore, the effect of insulation type and its application on the fire resistance is significant.

- *Effect of mid-height blocking on the fire resistance of wall assemblies with two layers of Type × gypsum board on both the fire-exposed and unexposed sides, sprayed cellulose* fibre insulation with water-based mixture, and resilient channels on fire-exposed side

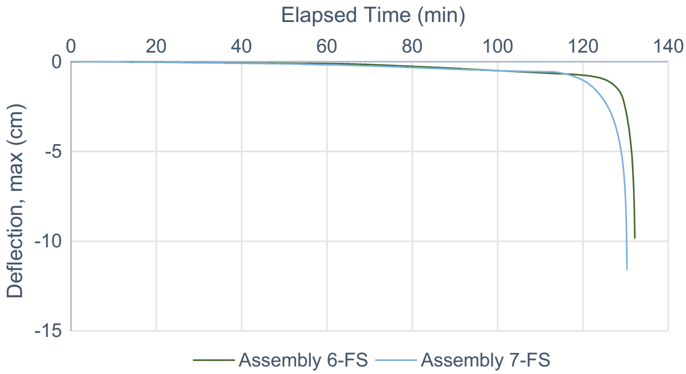

Figure 6. Deflection distributions for Assemblies with a double-row of wood studs, sprayed cellulose fibre insulation with water-based mixture and with and without mid-height blocking, 6-FS with mid-height blocking and 7-FS without mid-height blocking [15].

Assembly No. 6-FS (with mid-height blocking) and Assembly 7-FS (without mid-height blocking) were tested to investigate the effect of mid-height blocking installation on the fire resistance. The Assembly 6-FS provided 132 min 12 s while Assembly 7-FS provided 130 min 50 s fire resistance. Comparison of temperature measurement distributions is given in Ref. [15], however, comparison of the wall deflection distributions for Assemblies 6-FS and 7-FS is presented in Figure 6. The results show that in both assemblies, the deflection started approximately at 60 min followed by a slight increase in deflection in both assemblies up to 116 min and then followed by a rapid deflection until the failure occurred. Additional results discussion is provided in Ref. [15]. In wall assembly with double-row of wood studs on a separate plates, under the same load during the entire test duration, the wall assembly with mid-height blocking provided only about 1 min more fire resistance compared to wall assembly without mid-height blocking, therefore, unlike the case in single row of wood studs, the effect of mid-height installation in the wall assembly on fire resistance is insignificant.

- Effect of wood stud rows (single vs double) on the fire resistance of wall assemblies with two layers of Type × gypsum board on both the fire-exposed and unexposed sides, rock fibre insulation, mid-height blocking and resilient channels on the fire-exposed side

Assembly 3-FS (double-row of wood studs on a separate plates and under the same load during the entire test duration) and Assembly 4-FS (single-row of wood studs) were tested to investigate the effect of the number of wood stud rows on the fire resistance. The Assembly 3-FS provided 113 min 54 s while Assembly 4-FS provided fire resistance of 119 min 28 s fire resistance. The wall assembly with a single-row of wood studs provided 6 min more fire resistance than the assembly with a double-row of studs on a separate plates. This comparison could be miss leading if the wall Assembly 3-FS with double-row of wood studs were to be tested with load applied separately and this could be investigated by further research.

4.1.3. Exterior Walls Six loadbearing exterior wood stud wall assemblies (Assemblies 1-EW to 6-EW) were studied to investigate the effect of different design parameters on fire resistance. A brief fire resistance results and parameters investigated on the effect of insulation type using standard and non-standard screw spacing for attaching the gypsum board to wood studs followed by a comparison of fire resistance using those spacing are provided below, however, detail fire resistance analysis are also provide in Ref. [16]. The thermocouples locations and deflection gauges locations, gypsum board layout, screws spacing for attaching the gypsum board to wood studs and temperature and deflection measurements during the fire tests for the assemblies are given in Ref. [4].

- Effect of insulation type in exterior walls with gypsum board attached to wood studs using standard screws spacing of 406 mm o.c. and Oriented Strand Board (OSB) sheathing

Assembly 1-EW with GFI, 3-EW with RFI and Assembly 5-EW with CFI with water-adhesive-based mixture were studied to investigate the effect of insulation type on the fire resistance of wall assemblies with OSB sheathing. The Assembly 1-EW provided 45 min 40 s and Assembly 3-EW provided 55 min 11 s while Assembly 5-EW with CFI provided 46 min 35 s fire resistance. Comparison of temperature measurement distributions is given in Ref. [16], however, comparison of the wall deflection measurement for Assemblies 1-EW, 3-EW and 5-EW is presented in Figure 7. Comparisons of deflection results showed a slight increase in deflection for up to 40 min and then followed by a rapid deflection increase, as results of gypsum board fell-off, until the failure occurred. Additional results analysis is provided in Refs. [4, 16].

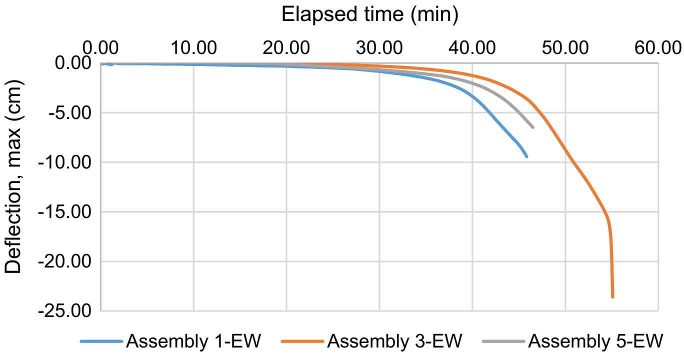

Figure 7. Deflection distributions for exterior wall Assemblies with OSB sheathing and different type of insulations, 1 -EW (GFI), 3-EW (RFI) and 5-EW (CFI) [16].

In exterior wall assembly with one layer of Type × gypsum board attached to wood studs with standard screw spacing at 406 mm o.c. and OSB sheathing, the Assembly with RFI provided approximately 10 min more fire resistance 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 insulation type in exterior walls with gypsum board attached to wood studs using non-standard screws spacing of 203 mm o.c. and Type × gypsum glass mat sheathing

Assembly 4-EW with CFI dry-blown and Assembly 6-EW with GFI were studied to investigate the effect of insulation type on the fire resistance of exterior walls with gypsum board glass mat sheathing. The Assembly 4-EW provide 59 min 10 s while Assembly 6-EW provided 56 min 10 s fire resistance. Comparison of temperature measurement distributions is given in Ref. [16], however, comparison of the wall deflection measurement distributions for Assemblies 1-EW, 3-EW and 5-EW is presented in Figure 8. Comparisons of deflection results showed that the walls had a slight deflection up to 30 min as gypsum board joints opened and followed by more increase in deflection up to 40 min as board joints became more 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. Additional results analysis is provide in Ref. [16].

In exterior wall assembly protected with one layer of Type × gypsum board and one layer of Type × gypsum glass mat sheathing with both boards attached to wood studs with non-standard reduced screw spacing of 203 mm o.c., the Assembly with CFI provided 3 min more fire resistance than the assembly with GFI, therefore, unlike performance with standard screw spacing, the effect of

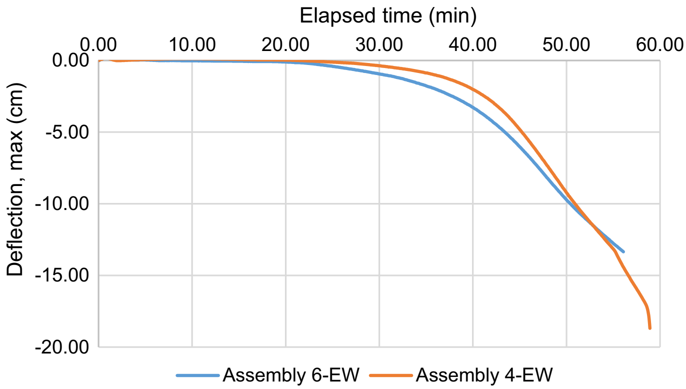

Figure 8. Deflection distributions for exterior wall Assemblies with gypsum sheathing and different type of insulations, 4 -EW (CFI) and 6-EW (GFI) [16].

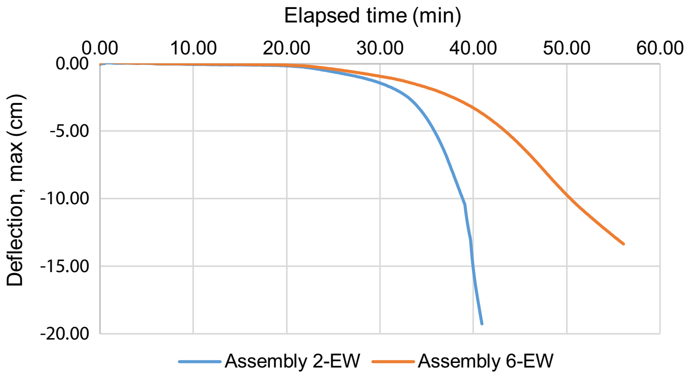

Figure 9. Deflection distributions for exterior wall Assemblies with gypsum sheathing and different screw spacing, 2 -EW with 406 mm o.c. and 6-EW with 203 mm o.c.) [16].

insulation types GFI vs CFI on fire resistance the assembly can be considered insignificant.

- Effect of screw spacing (standard 406 mm o.c. vs non-standard 203 mm o.c.) in exterior walls

Assembly 2-EW with standard screw spacing at 406 mm o.c. and Assembly 6-EW with non-standard screw spacing at 203 mm o.c. were studied to investigate the effect of screw spacing, on the fire resistance of exterior walls. The Assembly 2-EW provided 41 min while Aassembly 6-EW provided 56 min 10 s fire resistance. Comparison of temperature measurement distributions is given in Ref. [16], however, comparison of the wall deflection measurement distributions for Assemblies 2-EW, 6-EW is presented in Figure 9. Comparisons of deflection results showed that the walls had a slight deflection first at 10 min as results of gypsum board joints start to open up and furnace heat penetrated the wall cavity followed by further 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 3 shows that, the time difference between the gypsum board fall-off on the fire exposed side and assembly failure for Assemblies 2-EW and 6-EW is less than 1.17 min. Also, the gypsum board fell-off time difference between Assemblies 2-EW and 6-EW is 14 min. These results clearly indicate two key findings: first, the gypsum board on the fire-exposed side is controlling the fire resistance of the assembly and second, the longer the gypsum board on fire-exposed side stays-in-place, with reduced screw spacing at 203 mm o.c., the more fire resistance of 15 min than in assembly with screw spaced at 406 mm o.c. Additional results discussion is provided in Refs. [4, 16].

In exterior wall assembly protected with one layer of Type × gypsum board and one layer of Type × gypsum glass mat sheathing, the assembly with reduced non-standard screw spacing of 203 mm o.c. provided approximately 15 min more fire resistance than the assembly with standard screw spacing at 406 mm o.c. Therefore the effect of screw spacing (203 mm o.c. vs 406 mm o.c.) on fire resistance is significant.

4.2. Design Guidelines

Based on the limited knowledge gained from the results of above mentioned projects, the followings are suggested guidelines for practioners' use on the fire resistance design of interior party walls, interior fire separation walls and exterior walls. Should sound isolation with STC rating for the assemblies below is required, the rating need to be determined either by testing or other available published data in association with the description giving for FRR assembly's design details. For easier reading navigation, the design guidelines below are presented for three sections: interior party walls, interior fire separation walls and exterior walls.

4.2.1. Interior Party Walls The followings are suggested design guidelines for interior party wall assemblies:

In non-loadbearing asymmetrical (1 × 2) wall assembly constructed with one layer on the fire exposed side and two layers on unexposed side Type × gypsum board, no resilient channels, steel studs 38 mm by 90 mm and spaced at 610 mm o.c., insulation include: none, GFI, RFI and CFI and Type × gypsum board, 12.7 mm thick, the installation of RFI in wall cavity increased significantly the fire resistance by 54% compared to a non-insulated insulated or assembly with either GFI or CFI. Therefore, the use of RFI to achieve 1.5-h FRR and the use of no insulation or GFI or CFI to achieve 1-h FRR are suggested (Assemblies 3-PW, 1-PW, 2-PW and 4-PW).

In non-loadbearing asymmetrical (2 × 2) wall assembly constructed with two layers of regular gypsum board, steel or wood studs spaced at 610 mm o.c., without resilient channels insulation in wall cavity, the fire resistance results showed that the effect of stud type of steel or wood is insignificant. Therefore, the use of these assemblies with steel or wood studs and regular gypsum board to achieve 1-h FRR is suggested (Assemblies 20-PW and 21-PW).

In loadbearing symmetrical (2 × 2) wall assembly with steel studs and resilient channels spaced at 406 mm o.c., insulation in wall cavity include: none, GFI, RFI and CFI and two layers of Type × on unexposed side, 12.7 mm thick, on both the fire exposed and unexposed sides—the installation of either GFI or CFI or RFI in wall cavity reduces the fire resistance compared to non-insulated assembly by 27%, 8% and 23%, respectively. If sound isolation and 1-h FRR ratings are required then, the use of either CFI or RFI in wall cavity is suggested. If sound isolation is not required and 1-h FRR is required, then, the use of non-insulated assembly is suggested. If sound isolation and 45-min FRR are required then, the use of GFI is suggested (Assemblies 6-PW, 7-PW and 8-PW, 9-PW).

In loadbearing symmetrical (2 × 2) wall assembly with steel studs spaced at 406 mm o.c., with or without resilient channels spaced at 406 mm o.c., two layers of Type × gypsum board, 12.7 mm thick each, on each side of the wall and no insulation in wall cavity—the assembly without resilient channels installation provide 7% more fire resistance compared to a similar assembly but with resilient channels installation. This assembly is an example that shows resilient channel installation between the gypsum board and studs may improve the sound isolation [6], however, it reduced slightly the fire resistance. If the sound isolation is not required and 1-h FRR is required, then the assembly without resilient channels installation is suggested (Assemblies 6-PW and 14-PW).

In loadbearing symmetrical (2 × 2) wall assembly with steel studs spaced on 406 mm or 610 mm o.c., RFI in cavity and resilient channel spaced at 406 mm o.c.—the Assembly with steel studs spaced at 610 mm o.c. provided 25% more fire resistance compared to a similar wall assembly but with steel studs spaced sat 406 mm o.c. The use of studs with 610 mm o.c. provide a better sound isolation compared to assembly with spacing of 406 mm o.c. [6]. If sound isolation and 1-h FRR ratings are required, then the assembly with steel studs spaced at 610 mm o.c. is suggested (Assemblies 9-PW and 19-PW).

In loadbearing asymmetrical (1 × 2) wall assembly with wood studs spaced at 406 mm o.c. and cavity filled with RFI, having the resilient channels installed on the fire exposed side (single gypsum board layer) decreased the fire resistance of the assembly by about 10% compared to an assembly with resilient channel installed on the gypsum board double layer side (Assemblies 11-PW and 13-PW). The location of resilient channels plays an important role in the fire resistance of wall assembly and if resilient channels were to be installed for acoustical purposes to reduce the sound transmission through the wall, placing the resilient channels on either side of the wall had no effect on STC rating [6]. However, the gain in fire resistance when the channels were installed on the double layer side was better than if the channels were installed on the fire exposed side even though the assembly was unable to achieve 1-h FRR. To accomplish the 1-h FRR, further research is suggested by reducing the gypsum board screw spacing on the fire exposed side.

4.2.2. Interior Fire Separation Walls The followings are suggested design guidelines for interior fire separation wall assemblies:

In loadbearing symmetrical (2 × 2) wall assemblies with two layers of Type × gypsum board, 15.9 mm thick, the Installation of RFI improved the fire resistance by 6 min (6%) compared to GFI installation. Therefore, the use of either GFI or RFI in wall cavity to achieve 1.5 FRR is suggested (Assemblies 1-FS and 2-FS).

In loadbearing symmetrical (2 × 2) wall assemblies protected with two layers of Type × gypsum board, 15.9 mm thick, and RFI in wall cavity, the wall assembly with mid-height blocking provided 10 min more fire resistance compared to the wall assembly without mid-height blocking. Therefore, The use of med-height blocking on the fire resistance to achieve 2-h FRR, (Assembly 4-FS) or to use the assembly without mid-height blocking to achieve 1.5-h FRR are suggested (assembly 2-FS).

In loadbearing symmetrical (2 × 2) wall assembly with a double-row of wood stud wall assembly, RFI in wall cavity and mid-height blocking, the assembly with wood studs and resilient channels spaced at 406 mm o.c. added slightly 3.5 min more fire resistance compared to assembly with wood studs and resilient channels spaced at 610 mm o.c, where the fire resistance is 2.5 min to 6 min, respectively, less than the 2-h FRR. Therefore, users may have a suggested choice to use these assemblies for 1.5-h FRR (Assemblies 3-FS and 5-FS).

In loadbearing symmetrical (2 × 2) wall assembly with a double-row of wood studs, the wall assembly with sprayed CFI provided approximetly15 min more fire resistance compared to wall assembly with rock fibre insulation. Therefore, users may have a suggested choice to use CFI to achieve 2-h FRR or to use RFI to achieve 1.5-h FRR (Assemblies 5-FS and 6-FS).

In loadbearing symmetrical (2 × 2) wall assembly with a double-row of wood and CFI in wall cavity, the wall assembly with mid-height blocking provided only 1 min more fire resistance compared to wall assembly without mid-height blocking, therefore, users have a suggested choice to use mid-height blocking or not to achieve 2-h FRR (Assemblies 6-FS and 7-FS).

The loadbearing symmetrical (2 × 2) wall assembly protected with wood studs, two layers of Type × gypsum board, rock fibre insulation in wall cavity and mid-height blocking, the assembly with a single-row provided 6 min more fire resistance than the assembly with a double-row of studs. Therefore, users may have a suggested choice to use the assembly with a single-row to achieve 2-h FRR or to use a double-row of wood studs and achieve 1.5-h FRR (Assemblies 3-FS and 4-FS).

4.2.3. Exterior Walls The followings are suggested design guidelines for exterior wall assemblies:

In exterior wall assembly protected with one layer of Type × gypsum board, 15.9 mm thick on the fire-exposed side and one layer of OSB, 11 mm thick, sheathing. The Assembly with RFI provided approximately 10 min more fire resistance than the assemblies with either CFI or GFI (Assemblies 1-EW, 3-EW and 5-EW), therefore, users may have a suggested choice to use any type of insulation to achieve 45-min FRR or alternatively, reduces the screw spacing for attaching the gypsum board on the fire exposed side from 406 mm o.c. to 203 mm o.c. to achieve 1-h FRR based on the fire resistance gain of 15 min in Assembly 6-EW over Assembly 2-EW.

In exterior wall assembly protected with one layer of Type × 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 with screw spacing at 203 mm o.c., the Assembly with CFI provided 3 min, slightly more fire resistance than the assembly with GFI, therefore, users may have a suggested choice to use CFI to achieve 1-h FRR or use GFI to achieve 45-min FRR (Assemblies 4-EW and 6-EW).

In exterior wall assembly protected with one layer of Type × gypsum board, 15.9 mm thick, on the fire exposed side and one layer of Type × 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, users may have a suggested choice to use screw spacing of 406 mm o.c. to achieve 30-min FRR or to use 203 mm o.c. to achieve 45-min FRR (Assemblies 1-EW and 6-EW).

4.3. Gaps for Future Research

The fire resistance brief summary results above was instrumental in identifying the gaps for future research to improving the fire resistance performance of interior and exterior wall assemblies. The research gaps below are presented for three construction application wall systems namely: interior party walls, interior fire separation walls and exterior walls for easier reading navigation.

4.3.1. Interior Party Walls The gaps below are suggested for future research to improve the fire resistance performance of interior party wall assemblies as follows:

Asymmetrical (1 × 2) walls The application of the wet spray cellulose fibre on the double layer side is suggested to determine the tangible fire resistance increase in comparison to the available data with the application of insulation spray applied on single gypsum board layer on the fire exposed side.

Asymmetrical (1 × 2) walls The installation of the resilient channels on the double gypsum board side is suggested to determine the effect of insulation type and gypsum board thickness and measure the tangible fire resistance benefit in comparison to the available data with installation of resilient channels on the fire exposed single layer gypsum board is suggested.

Asymmetrical (1 × 2) walls The application of screws for attaching the gypsum board to the resilient channels or to stud framing at a reduce spacing from the standard 406 mm o.c. to non-standard 203 mm o.c. and in some cases the spacing need to be even further reduced to 150 mm o.c. or 100 mm o.c. at the gypsum board joints are suggested to measure the tangible fire resistance benefit in comparison to available data with the application of standard screw spaced at 406 mm o.c.

Symmetrical (2 × 2) walls The application of a separate load on each of separate rows in double-row stud assemblies is suggested to measure the tangible fire resistance benefit in comparison to available data with load applied on both rows simultaneously during the entire fire test.

4.3.2. Interior Fire Separation Walls The gaps below are suggested for future research to improve the fire resistance performance of interior fire separation wall assemblies as follows:

Single-row wood stud walls The application of screws for attaching the gypsum board to wall framing at a reduce spacing from the standard 406 mm o.c. to non-standard 203 mm o.c. and in some cases the spacing need to be even reduced further to 150 mm o.c. or 100 mm o.c. at the gypsum board joints are suggested to measure the tangible fire resistance benefit in comparison to the available data with application of screw spaced at 406 mm o.c.

Double-row wood stud walls The application of a separate superimposed load on each of separate stud rows in double-row stud assemblies is suggested to measure the tangible fire resistance benefit in comparison with the available data when the load is applied on both rows simultaneously during the entire fire test.

4.3.3. Exterior Walls The gaps below are suggested for future research to improve the fire resistance performance of exterior wall assemblies as follows:

Walls with OSB Sheathing The installation of screws for attaching the Type × gypsum board to wood framing at reduced spacing from the standard 406 mm o.c. to non-standard 203 mm o.c. in board field and to 150 mm o.c. at the board joints are suggested to maximise tangible fire resistance benefit for exterior walls with OSB sheathing,

Walls with gypsum board glass mat sheathing The installation of screws for attaching the Type × gypsum board, 15.9 mm thick, and Type × gypsum board glass mat sheathing, 15.9 mm thick, to wood framing at reduced spacing from the standard 406 mm o.c. to non-standard 203 mm o.c. in board field and to 150 mm o.c. at the board joints are suggested to maximise the tangible fire resistance benefit in exterior walls with gypsum mat sheathing.

5. Conclusions

Concluding remarks on the summary results, gaps future research and design guidelines are presented for three construction wall applications: interior party walls, interior fire separation walls and exterior walls as follows:

5.1. Interior Party Walls

1. The effect of insulation type on the fire resistance in asymmetrical non-loadbearing wall assembly (1 × 2), is significant, however, the effect of insulation type in symmetrical (2 × 2) wall assembly is insignificant as the fire resistance protection is mainly provide by the two layers of gypsum board where joints are staggered. In loadbearing wall assembly (1 × 2) with resilient channels installed on the single gypsum board layer exposed to furnace heat, the effect of insulation type and gypsum board thickness on the fire resistance is insignificant due to the unprotected gypsum board joint installation. In (1 × 2) assembly, the effect of resilient channels installation location (single- vs double-layer side) on fire resistance may be significant as it provided10% more fire resistance when installed on the double layer side compared to single layer side, however, in (2 × 2) wall assembly the effect of resilient channels installation and location is insignificant as the fire resistance protection was mainly provide, as mentioned above, by the two layers of gypsum board. In (1 × 2)

assembly, the installation of a second layer of gypsum board to the single layer side increased the fire resistance by 36%.
2. Future research to improve the fire resistance for (1 × 2) wall assembly is suggested such as the use of a reduced screw spacing for attaching the gypsum board to studs from 406 mm o.c. to 203 mm o.c. Additional future research gap examples are also provided.
3. Design guidelines for asymmetrical (1 × 2) and symmetrical (2 × 2) steel or wood stud wall assemblies are provided. For examples, in non-loadbearing steel stud asymmetrical (1 × 2) wall assembly, if 1.5-h fire resistance rating is required, filling the wall cavity with rock fibre insulation is suggested and another example for loadbearing asymmetrical (1 × 2) wood stud wall, if 45-min FRR is required, the resilient channels can be installed on either side of the wall however, if 1-h FRR is require it's suggested to install the resilient channels on the double layer side with reduce the screw spacing from 406 mm o.c. to 203 mm o.c. on the gypsum board edges. Additional guidelines examples are also provided for design practioners use.

5.2. Interior Fire Separation Walls

1. In single-row of wood studs symmetrical wall assemblies (2 × 2), the effect of insulation type and mid-height blocking installation on the fire resistance is insignificant as the fire resistance protection was mainly provided by the installation of two layers of gypsum board. In double-row of wood stud wall assemblies (2 × 2), the effect of insulation type on the fire resistance is significant, however, the effect of mid-height blocking and resilient channels spacing (403 mm o.c. vs 610 mm o.c.) on fire resistance is insignificant.
2. Future research to improve the fire resistance for symmetrical (2 × 2) wall assemblies is suggested by reducing the screw spacing for attaching the gypsum board to wood studs from 406 mm o.c. to 203 mm o.c.
3. Design guidelines for single-row of wood studs symmetrical wall assemblies (2×2) are provided. For example if 2-h FRR is required, the use of med-height blocking is suggested, however, if only 1.5 h FRR is required the use of mid-height blocking is not suggested. Another example, for double-row of wood stud wall, if 2-h FRR is required, the use of CFI to fill the wall cavities and the vertical space between the two stud rows is suggested. Additional guidelines examples for loadbearing symmetrical (2 × 2) wall assemblies with single- or double-row of wood stud are provided for design practioners use.

5.3. Exterior Walls

1. In exterior wall assembly with OSB sheathing where standard screw spacing 406 mm o.c. for attaching the gypsum board to wood studs on the fire exposed side is used, the effect of insulation type on the fire resistance is significant, however, in the exterior wall assembly with glass mat gypsum board sheathing, where non-standard 203 mm o.c. is used, the effect of insulation type on fire resistance is insignificant. In exterior wall assembly with gypsum board glass mat sheathing, the effect of reducing the screw spacing from 406 mm o.c. to 203 mm o.c. for attaching both the gypsum board and to wood studs, on the fire resistance is significant. The difference between the gypsum board fall-off time, on the fire exposed side, and assembly's time to failure is within three minutes which suggesting that the gypsum board on the fire exposed side is controlling the fire resistance of the assembly. Comparison of FRR of this study versus available literature showed that the exterior walls with OSB and gypsum board glass mat sheathing when tested on maximum load provide 45-min FRR compare to the ULC listing of 1-h FRR when the assembly tested on restricted load 82% of the maximum design load.
2. Future research to improve the fire resistance for exterior wall assembly with OSB sheathing is suggested by reducing the screw spacing for attaching the gypsum board on the fire exposed side to wood studs from 406 mm o.c. to 203 mm o.c. in board field and from 406 mm o.c. to 150 mm o.c. at the board edges
3. Design guidelines for loadbearing exterior wall assemblies with either OSB or glass mat are provided. For example in assembly with gypsum board sheathing, the reduction of screw spacing from 406 mm o.c. to 203 mm o.c. can expand the FRR from no useful use of 30 min to a useful code compliance use of 45-min FRR. Additional design guidelines examples are also provided for design practioners use.

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