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Fire Resistance of Steel C-Joist Floor Assemblies

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ABSTRACT

This paper discusses the factors that affect the fire resistance performance of lightweight steel-framed (LSF) unrestrained floor assemblies protected with Type X gypsum board ceiling finishes. Sixteen fire resistance experiments were conducted on full-scale load-bearing steel C-joist floor assemblies using the ULC standard fire exposure time- temperature curve that is similar to ASTM E119 standard. Parameters investigated in this study include the effects of insulation installation, insulation type, joist spacing, resilient channel installation, resilient channel spacing, type of sub-floor layer and number of sub-floor layers vs number of gypsum board layers. The impact of these parameters on the fire resistance of steel C-joist frame floor assemblies is discussed. The fire resistance of LSF floors appears to be essentially governed by the number of gypsum board layers, spacing of the joists or resilient channels where the gypsum boards are attached, sub-floor type and insulation type. Other parameters are of secondary importance.

Keywords: fire resistance, steel C-joist, insulation, resilient channel, concrete, rock fibre, glass fibre, cellulose fibre, gypsum board, plywood

INTRODUCTION

In recent years, there have been a number of efforts to improve the quality of residential building environments in North America to meet public demands for better acoustic isolation. More stringent acoustic requirements were recently adopted in Canadian building codes and have necessitated changes in traditional construction practices. In addition, new construction materials have been developed and many construction practices and product specifications may have changed over the past several years, which may alter the fire resistance of floor assemblies. Consequently, there was a need to reaffirm existing fire resistance data for common floor constructions. This includes the information contained in Part 9, "Housing and Small Buildings", Appendix A-9.10.3.1.B of the National Building Code of Canada (NBCC), 1995 Edition [1], which provides architects, building officials and fire protection engineers with simple detailed information on sound and fire resistance ratings for floor assemblies commonly used in the construction of housing in Canada.

In response to the changes noted above, the Institute for Research in Construction (IRC), National Research Council of Canada (NRC), in collaboration with industry and government partners, carried out two major research programs (Floors-I and Floors-II) to measure the fire resistance and acoustic performance of full-scale floor assemblies

with different framing including the wood joist, wood I- joist, steel C-joist and wood truss. Details on the assemblies' construction and results can be found in Ref [2] and [3]. This paper describes only the results of the fire resistance study of floor assemblies with steel C-joist framing using the ULC [4]/ASTM [5] standard fire exposure time-temperature curve. The results of the Floors-I study [2] on steel framing as well as on other framing (wood joist and wood-I joist) were used as a basis for the update to the Part 9 Appendix A table on floor assemblies of the NBCC. The results of the Floors-II study [3] are being utilized to provide a further update to the Part 9 Appendix A table on floor assemblies of the NBCC.

A study on the fire resistance of LSF was conducted by Alfawakhiri et al [6]. In that study, a limited number of full-scale floor tests (5) were conducted using the ULC fire exposure time- temperature curve for floor assemblies protected with Type X gypsum board, 12.7 mm thick, to validate thermal-structure numerical simulations.

The parameters studied in this paper include the insulation installation, insulation type, joist spacing, resilient channel installation, resilient channel spacing, and type of sub-floor layer, and number of sub-floor layers vs number of gypsum board layers. The impact of these parameters on the fire resistance of steel C-joist frame floor assemblies is discussed below.

DESCRIPTION OF TEST ASSEMBLIES

Sixteen floor assemblies, 4.8 m long by 3.9 m wide, were constructed in accordance with CAN/CSA-A82.31-M91 [7]. Floor framing consisted of galvanized cold formed steel joists spanning across the shorter dimension of the floor furnace (effective span 3.9 m). The stability of joists was ensured by channel tracks and web stiffeners at joist ends, blocking at 2-3 locations, flat strap bridging (bottom flange plane) at joist mid-span, and either the plywood or plywood deck/concrete sub-floor or steel deck/concrete sub-floor (upper flange plane). All connections were performed using screws – no welding was used. Steel frame fabrication details reflected the common practices used in North America. All steel joists had a C-shaped cross section, nominally, 203 mm deep by 41.3 mm wide, with 12.7 mm flange stiffening lips and a base metal thickness of 1.21 mm (MSG gauge 18). In 13 assemblies (see Table 1) resilient channels, spaced either 406 mm o.c. or 610 mm o.c., were used and attached perpendicular to joists to support the gypsum board ceiling finish. Additional resilient channels were also installed to support gypsum board ends (board short dimension). The resilient channels, 14 mm deep by 58 mm wide, were fabricated from 0.6 mm thick galvanized steel sheets. The channels had a 34 mm wide web, designed to support the gypsum board connection, and one 18 mm wide flattened flange lip connected to the bottom flanges of the steel joists by 19 mm long self-drilling screws. Three types of insulation were used: glass and rock fibre batts, 90 mm thick, and cellulose fibre insulation sprayed wet, from 91 mm to 112 mm thick, on the underside of the sub-floor and on the side of the joists and allowed to dry to achieve an 11% moisture content. The glass, rock and cellulose insulation satisfied CSA A101-M83 [8], CAN/ULC S702-M97 [9] and CGSB 51.60-M90 [10], respectively. The resilient channels and insulation were used in this study for acoustical purposes to reduce the sound transmission across the floor. The sub-floor types used in the assemblies were Canadian Softwood Plywood (CSP)

tongue and groove, 15.5 mm or 19 mm thick or CSP deck with, 51 mm thick, concrete topping or with steel deck with, 51 mm thick, concrete topping. The ceiling finish used in the assemblies was Type X gypsum board, 12.7 mm and 15.9 mm thick. The cross-sections of the floor specimens are illustrated in Figures 3 to 8. The gypsum board (nominal thickness 12.7 mm and 15.9 mm) used in specimens had the Firecode C Core Type X" designation and met the requirements of Type X gypsum board [11] and [12]. The gypsum boards used in this study were supplied from one manufacturer with an average surface density of 9.85 kg/m² for 12.7 mm thick board and 10.5 kg/m² for 15.9 mm thick board. The gypsum board sheets were attached perpendicular to either resilient channels or steel joists by screws 25 to 41 mm long, spaced at 300 mm o.c. depending on the number of gypsum board layers. Table 1 lists the variable parameters of the test assemblies. Complete construction details can be found in Ref [2] and [3].

INSTRUMENTATION

The temperature on the unexposed surface for all assemblies was measured at 9 locations in accordance with CAN/ULC-S101-M89 [4]. Thermocouples on the unexposed surface were installed under ceramic fibre pads (150 mm wide by 150 mm long by 12.7 mm thick) as per the test method. In addition to standard instrumentation, numerous thermocouples were placed within each floor assembly in order to obtain temperature histories at various locations during fire tests. Type K (20 gauge) chromel-alumel thermocouples, with a thickness of 0.91 mm, were used for measuring the temperatures of the sub-floor surface and gypsum board surface facing the floor cavity as well as the interface surface between the gypsum board for assemblies with two layers of gypsum board and between the gypsum board and insulation. Also, additional instrumentation to measure the deflection of the sub-floor was used at 9 locations: 3 along the centre line of the assembly and 3 on each side of the centre line at equal spacing. Details on the locations of the thermocouples and deflection gauges can be found in Refs [2] and [3]. Details on the deflection devices used in this study can be found in Ref [13]. The temperature and deflection measurements in this study are being used to verify mathematical models that were developed by NRC for predicting the fire resistance of steel-framed floor assemblies. All floor assemblies were tested with live load depending on the components of the assembly. Details on the loading system can be found in References 2 and 3. The total load for each assembly was calculated based on the maximum design load for each structural member (steel C-joist) multiplied by the number of joists. The dead load for each assembly was calculated based on the assembly dead load components. The superimposed test load was calculated as the difference between total and dead load for each assembly. The superimposed load used in this study for each assembly is given in Table 1.

TEST CONDITIONS AND PROCEDURE

The assembly's gypsum board ceiling finish was exposed to heat in a propane-fired horizontal furnace, shown in Figure 2, in accordance with CAN/ULC-S101-M89, "Standard Methods of Fire Endurance Tests of Building Construction and Materials" which is similar in temperature-time curve to ASTM E119 [5] "Standard Test Method for Fire Tests of Building Construction and Materials". The furnace temperature was

measured by nine (20 gauge) shielded thermocouples and the average of these thermocouples was used to control the furnace temperature in such a way that it followed, as closely as possible, the CAN/ULC-S101-M89 standard temperature-time curve.

The assembly was considered to have failed if one of the following failure criteria as per CAN/ULC-S101-M89 Standard, occurred:

1. A single point temperature reading measured by one of the nine thermocouples under insulation on the unexposed surface rose 180°C above the ambient temperature,
2. The average temperature measured by the 9 thermocouples under the insulated pads on the unexposed surface rose 140°C above the ambient temperature,
3. There was passage of flame or gases hot enough to ignite cotton waste, and
4. The assembly is no longer able to bear the applied load.

RESULTS AND DISCUSSION

The results of the 16 full-scale fire resistance floor tests are summarised in Table 1 in which the fire resistance and gypsum board layers fall-off time are provided for each assembly. The average temperatures at different surfaces in each assembly, furnace average temperature and three deflection measurements (maximum deflections) at the centre line of the assembly as well as the loading system pressure are plotted in Figures 9 to 40. Deflection data measured in the other six locations can be found in References 2 and 3.

Gypsum board is a product that provides significant fire resistance protection to building assemblies as it contains about 21% by weight chemically combined water.

From the temperature distributions of the assemblies studied, it can be seen that the gypsum board used to protect the floor framing has more or less provided the same trend in temperature, at least up to 15 minutes of fire exposure. Due to this similarity and to avoid repetition in explaining of such behaviour, the gypsum board trend is provided below. However, the behaviour of the gypsum board beyond this period is different depending on the type of assembly components and that will be explained separately for each parameter studied.

When the gypsum board ceiling finish is exposed to heat in the first 15 min, its temperature increases as time goes on. After 3 min, the gypsum board interface surface (between the base and face layers, GWB Face/Base at Cavity) temperature, in the case of assemblies with two layers of gypsum board or the gypsum board/insulation interface surface temperature (GWB Base at Cavity) or the gypsum board surface temperature facing the floor cavity rose rapidly to approximately 100 °C, where the water in the gypsum board had absorbed its sensible heat, and then it was followed by a gradual temperature rise to approximately 120 °C after 15 to 18 min. At that time, the gypsum board core is almost free from water and thus its temperature rose at a faster rate to approximately 600 °C - 700 °C depending on the assembly components. The

effects of different parameters on the fire resistance of floor assemblies are discussed below.

Effect of Insulation Installation and Type

The effects of insulation installation and type on the fire resistance in floor assemblies protected with either one or two layers of gypsum board were investigated as follows.

Effect of Insulation Installation in Floor Assemblies with Two Layers of Gypsum Board

To study the effect of insulation installation in a floor cavity on the fire resistance for assemblies with two layers of gypsum board, two cases were considered each with a different type of sub-floor material: one case with plywood and the other with steel deck/concrete.

In the first case with a plywood sub-floor, two floor assemblies, Assembly 1 (no insulation) and Assembly 2 (glass fibre insulation) were tested. The floor assemblies were constructed with steel C- joists and resilient channels spaced at 406 mm o.c., two layers of Type X gypsum board, 12.7 mm thick each, and a plywood sub-floor, 15.5 mm thick. The temperature and deflection measurements for these assemblies are shown in Figures 9 to 12.

In Assembly 1 with no insulation in the floor cavity (see Figure 9 and Table 1), the first piece of gypsum board face layer fell-off from the assembly at 66 min 26 s and this occurred when the gypsum board interface surface (Face/Base at floor cavity) temperature was approximately 730 °C. By 73 min 19 s, most of the gypsum board face layer had dropped from the assembly and the gypsum board base layer was exposed directly to furnace heat; as a result, its surface temperature (GWB Base at Cavity) rose rapidly (see Figure 9) due to heat transfer by conduction from the gypsum board face layer to the base layer. The first piece of gypsum board base layer dropped at 73 min 9 s and consequently, the steel joists as well as the underside surface of sub-floor were exposed partially to furnace heat. Figure 10 shows that there were a small deflection (2 mm) at the first 50 min of heat exposure, however, afterward the sub-floor deflected slowly until the gypsum board face and base layers had disappeared from the assembly and that was followed by a sudden drop in deflection at 74 min. At that time, due to excessive joist deflection, a flame appeared above the unexposed surface.

Assembly 2 was constructed the same as Assembly 1 but with glass fibre insulation batts, 89 mm thick, installed on resilient channels above the gypsum board base layer between joists. After 15 min of fire exposure (see Figures 9 and 11), the gypsum board interface (GWB Face/base at cavity) temperature was slightly higher in Assembly 2 than in Assembly 1. This is due to the presence of a thermal resistance caused by the installation of the glass fibre insulation in the floor cavity. The first piece of the gypsum board face layer in Assembly 2 dropped into the furnace at 59 min 23 s in which the gypsum board interface temperature was about 740 °C and by 64 min, most of the gypsum board face layer had dropped from the assembly. For the gypsum board base layer, the first piece had dropped at 63 min 26 s and by 68 min 40 s most of the gypsum board had also dropped. When the first piece of the gypsum board base layer dropped

from the assembly, the glass fibre insulation was exposed to furnace heat and in about 2 min the insulation melted and disappeared partly from the assembly. At that time, part of the steel C-joists and of the under surface of the plywood sub-floor were exposed to furnace heat. At 68 min, a sub-floor joint was open and a flame appeared above the unexposed sub-floor surface due to a rapid deflection of the steel joists (see Figure 12). The installation of insulation in the floor cavity presents an additional thermal resistance for the heat transfer across the assembly from the fire-exposed surface to the unexposed surface and this caused heat accumulation in the gypsum board core and made it fall faster than in the case where there was no insulation in the floor cavity.

Assembly 1 with no insulation provided 74 min fire resistance while Assembly 2, with the glass fibre insulation, provided 68 min fire resistance. Therefore, in a steel C-joist assembly with two layers of Type X gypsum board, the installation of the glass fibre insulation, 89 mm thick, on the resilient channels above the gypsum board has slightly reduced the fire resistance by 8%, however, both assemblies provided a 1 h fire resistance rating.

In the second case, two assemblies were tested: Assembly 8 (no insulation) and Assembly 9 (glass fibre insulation) with steel deck/concrete sub-floor to investigate the effect of the installation of glass fibre insulation in the floor cavity on the fire resistance performance of floor assemblies with steel C-joists and resilient channels spaced at 406 mm o.c., two layers of Type X gypsum board, 12.7 mm thick, steel deck and concrete sub-floor, 51 mm thick. The temperature and deflection measurements for these assemblies are shown in Figures 23 to 26.

In Assembly 8, the first piece of gypsum board face layer fell off at 60 min 39 s at which time the gypsum board interface temperature was approximately 720 °C. Most of the gypsum board face layer had dropped by 73 min. Figure 23 shows that the gypsum board base layer surface temperature facing the floor cavity is increasing gradually as a result of heat transfer by conduction from the gypsum board face layer to the base layer. The first piece of gypsum board base layer had dropped at 72 min 35 s and by 75 min, most of the gypsum board base layer had dropped. At that time, the steel joists and the steel deck were directly exposed to furnace heat. Figure 24 shows that there was a small floor deflection (10 mm) at about 70 min heat exposure due to the protection provided by the gypsum board, however afterward, the concrete sub-floor cracked and deflected more rapidly and the heat radiation from the crack ignited a cotton waste which represented the failure of the assembly at 75 min.

Assembly 9 is constructed the same as Assembly 8 but with glass fibre insulation batts, 89 mm thick, that were installed on resilient channels above the gypsum board base layer between the joists. In the first 15 min (see Figures 23 and 25), the gypsum board face layer interface surface temperature (GWB Face/Base at Cavity) was similar, however afterward; the interface temperature was slightly higher in Assembly 9 than in Assembly 8. This occurred due to the increase in the thermal resistance of the assembly caused by the installation of insulation in the floor cavity in Assembly 9. A similar trend was observed in the comparison of Assemblies 1 and 2. The first piece of gypsum board face layer dropped into the furnace at 54 min 28 s at which time the gypsum board interface surface temperature (GWB Face/Base at Cavity) was

approximately 750 °C (see Figure 25) and by 59 min 41 s, most of the gypsum board face layer had dropped from the assembly into the furnace. At 60 min 10 s, the first piece of the gypsum board base layer had dropped and by 67 min 23 s most of gypsum board base layer was also dropped. When the first piece of the gypsum board base layer dropped, the glass fibre insulation was exposed to furnace heat and about 2 min later it was partly melted. At about 60 min 10 s, some of the steel C-joists and part of the under surface of the steel deck and concrete sub-floor facing floor cavity were exposed to furnace heat and at approximately 65 min, the concrete sub-floor was cracked. Figure 26 shows that, there was a small floor deflection (10 mm) at about 55 min followed by a gradual deflection at 62 min and then the joists were rapidly deflected and made the assembly fail at 68 min 25 s. The heat radiation from the crack was able to ignite the cotton waste sample, which represented the failure of the assembly.

The presence of glass fibre insulation in the floor cavity added an additional thermal resistance as explained earlier and caused the gypsum board to fall off faster in Assembly 9 than in Assembly 8. The later assembly with no insulation provided 75 min fire resistance while the former assembly with glass fibre insulation provided 68 min 25 s fire resistance. Therefore, in a steel C-joist assembly with two layers of Type X gypsum board, the installation of 89 mm thick glass fibre insulation on the resilient channels above the gypsum board and steel deck and concrete topping has reduced (by 9%) the fire resistance, however, both assemblies with and without insulation provided a 1 h fire resistance rating.

From the results of the two cases discussed above using two different sub-floor materials, the installation of the glass fibre insulation in the assembly reduced the fire resistance compared to a similar assembly but with no insulation in the floor cavity.

Effect of Insulation Type in Floor Assemblies with Two Layers of Gypsum Board

Assemblies 9 (glass fibre insulation) and 14 (rock fibre insulation) were tested to investigate the effect of insulation type on the fire resistance of a floor assembly with two layers of Type X gypsum board, steel deck/concrete sub-floor and steel C-joists and resilient channels spaced at 406 mm o.c. Assembly 9 was constructed the same as Assembly 14 but with a different type of insulation. The gypsum board fall-off time in Assembly 9 was discussed earlier, however, in Assembly 14 with rock fibre, the first piece of the gypsum board face layer fell into the furnace at 51 min 6 s and by 57 min 17 s most of the face layer had dropped from the assembly. The first piece of the gypsum board base layer fell off was at 57 min 46 s and by 64 min 53 s most of the base layer had dropped from the assembly. When the gypsum board base layer partly dropped, the rock fibre insulation sagged at the batts short ends and then the furnace hot gases entered the floor cavity. Consequently, the temperature of the underside surface of the steel deck rose rapidly at approximately 60 min and the floor started to deflect but at a slower rate (Figure 26) than in the case of the assembly with glass fibre insulation (Figure 25). Unlike the glass fibre insulation, the rock fibre insulation does not melt when exposed to furnace heat. Assembly 9 provided 68 min 25 s fire resistance and Assembly 14 provided 70 min fire resistance. Thus, in the assemblies with two layers of gypsum board, the difference in fire resistance between the glass and rock fibre insulation is not significant as both the glass fibre melted and rock fibre insulation

batts sagged when they were both exposed to furnace heat. The difference in fire resistance could be significant if the rock fibre insulation batt short ends remain in place after the gypsum board base layer dropped from the assembly but this was not addressed in this study.

Effect of Insulation Installation in Floor Assemblies with One Layer of Gypsum Board

The Assembly 6 (no insulation), and Assembly 7 (with rock fibre insulation) were tested to investigate the effect of the installation of rock fibre insulation on the fire resistance performance of steel C-joist floor assemblies with one layer of Type X gypsum board 15.9 mm thick and two layers of plywood sub-floor, 15.5 mm thick each. The test observations for the gypsum board fall-off time are provided in Table 1. The temperature and deflection measurements for these assemblies are shown in Figures 19 to 22.

In Assembly 6, the first piece of gypsum board face had dropped from the assembly at 36 min 30 s in which the gypsum board surface temperature facing the cavity was 630 °C (see Figure 19). Most of the gypsum board had dropped from the assembly by 38 min 13 s. Figure 19 shows that at 18 min, the gypsum board surface temperature facing the floor cavity was increasing gradually as a result of heat transfer by conduction across the board until the board first piece fall-off. At 36 min 30 s, the steel joists and underside of the plywood sub-floor surface-facing cavity were partly exposed to furnace heat. Figure 20 show that, there was approximately 5 mm of deflection at about 22 min, however afterward, the sub-floor deflected slowly until 32 min, due to the penetration of heat via the board joints. This was followed by a more rapid deflection of the sub-floor due to the loss of the gypsum board protection. At 38 min 49 s min, a flame penetrated the sub-floor at the joints due to a rapid deflection of the steel joists and this constituted to the failure of the assembly.

Assembly 7 was constructed the same way as Assembly 6 but with two layers of rock fibre insulation batts, 89 mm thick each, installed on the resilient channels above the gypsum board base layer between joists. In the first 15 min of fire exposure (see Figures 19 and 21), the gypsum board face layer interface temperatures (GWB Face/Base at Cavity) in Assemblies 6 and 7 were similar. However afterward, in Assembly 7 with rock fibre insulation, the interface temperature was slightly higher in Assembly 7 than in Assembly 6 (no insulation). This is also due to the presence of the thermal resistance caused by the installation of insulation. In this assembly, the first piece of the gypsum board fell off at 26 min 41 s in which the interface gypsum board temperature, GWB Face at Cavity was approximately 710 °C and by 38 min 43 s, most of the gypsum board had dropped from the assembly. When the first piece of the gypsum board dropped, the rock fibre insulation continued to protect both the steel joists and the underside of the plywood sub-floor further from the direct furnace heat for the remaining time of the test unlike Assembly 14 with two layers of gypsum board where the board short end sagged and did not protect the joists and sub-floor from the furnace heat due to a longer exposure to heat than in Assembly 7 with one layer of gypsum board. At 53 min 38 s, a sub-floor joint opened and a flame appeared above the unexposed sub-floor surface. Figure 24 shows that up to 23 min, the floor deflection was about 5 mm as it was protected from furnace heat by the gypsum board

and afterward the floor deflection was gradual as a result of gradual penetration of hot gasses to the floor cavity. Assembly 6 with no insulation in the floor cavity provided 38 min 49 s while Assembly 7 with rock fibre insulation provided 53 min 38 s. Therefore, in a steel C-joist assembly with one layer of Type X gypsum board, the installation of 178 mm thick rock fibre insulation has increased the fire resistance by 38% compared to an assembly with no insulation in the floor cavity.

Effect of Insulation Type in Floor Assemblies with One Layer of Gypsum Board

Assemblies 7 and 11 were tested to investigate the effect of insulation type on the fire resistance of a floor assembly with one layer of Type X gypsum board, two layers of plywood sub-floor and steel joists and resilient channels spaced at 406 mm o.c. Assembly 11 was constructed the same as Assembly 7 but, the type and thickness of insulation were different.

Assembly 11 was constructed with cellulose fibre insulation sprayed wet (cellulose fibre with added water) on to the steel C-joists sides and on to the underside of the plywood sub-floor. The average thicknesses of the cellulose fibre insulation were 91 mm and 112 mm on the underside of sub-floor and on the sides of steel C-joists, respectively. Assembly 7 was constructed with rock fibre insulation, 178 mm thick, placed on the resilient channels above the gypsum board between joists. The temperature and deflection distributions are given in Figures 21, 22, 29 and 30. The fall-off times of the gypsum board in Assembly 7 were mentioned above, however, for Assembly 11, the first piece of the gypsum board dropped at 34 min 17 s and by 45 min, most of the board had dropped from the assembly. During the fire exposure (see Figures 21 and 29), the temperature distributions of the gypsum board facing the floor cavity (GWB Face at Cavity) are more or less similar. As the first piece of the gypsum board dropped from Assembly 7, the rock fibre insulation continued to protect both the steel joists and the underside of the plywood sub-floor further from the direct furnace heat for the remaining time of the test. At 53 min 38 s, a flame penetrated the unexposed sub-floor surface at the joints as a result of gradual deflection of the sub-floor and the steel framing as shown in Figure 22 due to the gradual loss of joist strength caused by heat penetration to the floor cavity. The deflection at the centre location of the joist was much higher than at the other two locations as the insulation batts was sagging more at the centre. The assembly with rock fibre insulation provided 53 min 38 s of fire resistance while Assembly 11 with cellulose fibre insulation of less thickness provided 63 min 47 s. Thus, the assembly with cellulose fibre insulation of a smaller insulation thickness provided 19% more fire resistance compared to a similar assembly but with rock fibre insulation of a larger thickness. This could be attributed to the longer period that the insulation stayed in place for the cellulose fibre than in the case of rock fibre insulation. In the assembly with one layer of Type X gypsum board, resilient channels as well as steel C-joists spaced at 406 mm o.c. and two layers of plywood sub-floor, the effect of insulation type (cellulose fibre vs rock fibre) on the fire resistance is significant compared to a non-insulated assembly.

Effect of Joists Spacing

Two cases of assembly were studied to investigate the effect of joists spacing (406 mm o.c. vs 610 mm o.c.) on the fire resistance; one case for assemblies with the gypsum board attached to the resilient channels spaced at 406 mm o.c. that were attached to the steel C-joists spaced at either 406 mm o.c. or at 610 mm o.c. The other case for assemblies with the gypsum board attached directly without resilient channels to the steel C-joists spaced at either 406 mm o.c. or 610 mm o.c.

Assemblies with the Gypsum Board Attached to Resilient Channels

Assemblies 2 and 3 were tested to investigate the effects of the joist spacing (406 mm o.c. and 610 mm o.c., respectively) on the fire resistance of steel C-joists assemblies with two layers of Type X gypsum board attached to resilient channels spaced at 406 mm o.c. The temperature and deflection distributions for these assemblies are shown in Figures 11 to 14. Assembly 2 had joists spaced at 406 mm o.c. while Assembly 3 had joists spaced at 610 mm o.c. The gypsum board fall-off times for both the face and base layer in Assembly 2 is provided above, however, in Assembly 3 the first piece of the face layer gypsum board dropped from the assembly at 59 min 23 s and most of the gypsum board face layer fell off by 62 min 6 s. The first piece of the gypsum board base layer dropped at 65 min 4 s and most of the base layer dropped at 67 min 23 s. The deflection distributions for both assemblies are more or less similar. Assembly 2 with the gypsum board attached to resilient channels spaced at 406 mm o.c. and steel C-joist spaced at 406 mm o.c. provided 68 min fire resistance while Assembly 3 with the gypsum board attach also to the resilient channels spaced the same as Assembly 2, 406 mm o.c., but with the steel C-joist spaced at 610 mm o.c. provided 69 min. These results showed that the effect of joist spacing on the fire resistance performance is insignificant as the gypsum board was not attached to the joists but rather was attached to resilient channels of the same spacing in both assemblies.

Assemblies with Gypsum Board Attached to Steel C-Joists

Assemblies 12 and 16 were tested to investigate the effects of the joist spacing (406 mm o.c. and 610 mm o.c., respectively) on the fire resistance of the steel C-joists assembly with two layers of Type X gypsum board attached directly to the steel C-joists. The temperature and deflection distributions are shown in Figures 31, 32, 39 and 40. In Assembly 12 with joists spaced at 406 mm o.c., the first piece of the gypsum board face layer fell off was at 51 min 16 s and most of the face layer dropped by 61 min 29 s. The first piece of the gypsum board base layer fell off was at 62 min and by 65 min 2 s most of the base layer had fallen off from the assembly. In Assembly 16 with joists spaced at 610 mm p.c., the first piece of the gypsum board face layer dropped at 46 min 15 s and most of the gypsum board had fallen off by 55 min 31 s. The first piece of the gypsum board base layer fell off was at 54 min 7 s and most of the base layer dropped by 54 min 50 s. Assembly 12 with joist spaced at 406 mm o.c. provided a 66 min 55 s fire resistance while assembly 16 with joists spaced at 610 mm o.c. had only a 54 min 59 s fire resistance. The fall-off time for gypsum board layers was less in Assembly 16 (joists spaced at 610 mm o.c.) than in Assembly 12 (joists spaced at 406 mm o.c.) as the gypsum board was attached to steel joists with a lesser number of screws in the assembly with wider joists spacing. The effect of steel C-joist spacing (406 mm o.c. vs

610 mm o.c.) in assemblies with two layers of gypsum board attached to joists is significant.

In the two cases studied above, the effect of joists spacing on fire resistance is significant only when the gypsum board is attached directly to the joists of different spacing. If the gypsum board is attached to resilient channels of the same spacing, the joists spacing becomes irrelevant.

Effect of Resilient Channels Installation

Assembly 1 (with resilient channels) and Assembly 12 (without resilient channels) were tested to study the effect of resilient channels installation on the fire resistance of assemblies with two layers of Type X gypsum board, no insulation in the floor cavity and one layer of plywood sub-floor. The gypsum board fall-off time for these assemblies is given in Table 1. The temperature distribution at different surfaces and sub-floor deflection for both assemblies are shown in Figures 9, 10, 33 and 34. The temperature distributions in Figures 9 and 31 show that the temperature of the interface between the gypsum board layers (GWB Face/Base at Cavity) for both assemblies are more or less similar for the first 45 min of fire exposure. However, there is a shorter increase in the interface temperature in Assembly 12 than in Assembly 1 due to an early gradual opening of the gypsum board joints in Assembly 12 at 51 min. This was followed by a rapid temperature increase at 58 min where most of the gypsum board face layer dropped from the assembly. This rapid increase in gypsum board interface temperature occurred at approximately 750 °C. In Assembly 1, the interface temperature increased rapidly at approximately 66 min where most of the gypsum board face layer dropped into the furnace. The gypsum board base layer surface temperature facing the floor cavity in both assemblies was similar up to approximately 60 min; however, the temperature of this surface in Assembly 12 was slightly higher than in Assembly 1. The reason for this is that, the gypsum board short edge in Assembly 12 (with no resilient channels) was attached to the steel C-joists with screws 10 mm from the board edges while in Assembly 1 the board short edge was attached to two additional resilient channels to allow the board edges to be attached with screws at a distance of 38 mm from the board edges. When the gypsum boards are exposed to furnace heat, they shrink, particularly at the board edges (about 12 mm). For those boards with screws at 38 mm from the board edges, the gypsum board remains attached longer to the framing than those with screws at 10 mm from the board edges². Figures 10 and 34 show that, the deflection in Assembly 12 was 5 mm more than in Assembly 1 after 60 min due to an early gypsum board fall-off in Assembly 12. Assembly 1 with resilient channels provided 74 min fire resistance while Assembly 12 with no resilient channels provided 66 min 55 s. As a result of attaching the gypsum board short edge to resilient channels with screws at 38 mm from the board edges the fire resistance had increased by 11% compared to a similar assembly with no resilient channels.

Effect of Resilient Channels Spacing

Two cases of assemblies were studied to investigate the effect of resilient channels spacing on the fire resistance: one case for assemblies with a plywood sub-floor and the other case for assemblies with a steel deck/concrete sub-floor.

Assemblies with Plywood Sub-floor

Two tests were conducted to study the effect of resilient channels spacing on the fire resistance of assemblies with two layers with Type X gypsum board, glass fibre insulation in the floor cavity and plywood sub-floor assemblies: Assembly 3 with resilient channels spaced at 406 mm o.c. and Assembly 13 with resilient channels spaced at 610 mm o.c. The gypsum board fall-off time for these assemblies is given in Table 1. The temperature distribution at different surfaces and sub-floor deflection for both assemblies are shown in Figures 15, 16, 33 and 34. In these assemblies, the two gypsum board face and base layers were attached to resilient channels. In Assembly 3, the gypsum board face and base layers fall-off times are mentioned above. As the resilient channels in Assembly 13 were spaced at 610 mm o.c., fewer screws were used to support the gypsum board and the first piece of the gypsum board face layer fell off at 42 min 17 s and most of the face layer board fell off at 49 min 50 s. Figures 13 and 32 show that the temperature of the interface between the gypsum board face and base layers (GWB Face/Base at Cavity) for both assemblies are more or less similar up to approximately 40 min, however, in Assembly 13 there was a rapid increase in the temperature due to the earlier fall-off of the gypsum board face layer than in Assembly 3. The temperature distributions on the interface between the glass fibre insulation and the gypsum board base layer on the cavity side show that, the temperature is more or less the same up to approximately 35 min. This is then followed by a higher temperature in Assembly 13, due to the shrinkage and opening of the gypsum board joints earlier than in Assembly 3. After the gypsum board face and base layers had fallen-off in both assemblies, the surface temperature of the underside of the sub-floor increased rapidly due to the melting of the glass fibre insulation when exposed to furnace heat. Figures 14 and 34 show the deflection measured at the sub-floor centre line for Assemblies 3 and 13, respectively. There was a very small deflection for both assemblies in the first 52 min, however, it was followed by a rapid deflection in Assembly 13 due to an early loss of both the gypsum board layers and melting of the glass fibre insulation. In Assembly 3, the deflection after 50 min increased gradually due to the shrinkage and opening of the gypsum board base layer joints which was followed by a sudden deflection at 69 min where the assembly was unable to carry the applied load. Assemblies 3 and 13 provided 69 min and 52.5 min of fire resistance, respectively. The assembly with resilient channels spaced at 406 mm o.c. provided 31% more fire resistance compared to a similar assembly but with resilient channels spaced at 610 mm o.c.

Assemblies with Steel Deck/Concrete Sub-floor

Assemblies 9 and 10 were tested to study the effect of resilient channel spacings (406 mm o.c. vs 610 mm o.c.) on the fire resistance in floor assemblies with two layers of Type X gypsum board, glass fibre insulation in floor cavity and steel deck/concrete sub-floor. The gypsum board fall-off time for these assemblies is given in Table 1. The temperature distributions at different surfaces and sub-floor deflection for both assemblies are shown in Figures 25 to 28. In these assemblies, the gypsum board interface layers temperature (GWB Face/Base at Cavity) followed a similar trend as those in Assemblies 3 and 13. The deflection was also more or less similar in both

assemblies for the first 55 min and then followed by a more rapid deflection as a result of the fall-off of the gypsum board layers and melting of the glass fibre insulation. Assemblies 9 and 10 provided 68 min 25 s and 61 min fire resistance, respectively. The assembly with resilient channels spaced at 406 mm o.c. provided 11% more fire resistance compared to a similar assembly with resilient channels spaced at 610 mm o.c.

From the two cases studied above, the effect of resilient channels spacing on the fire resistance is significant, and more pronounced in the case of the floor assembly with plywood sub-floor.

Effect of Adding Concrete Topping

Two cases of assembly were studied to investigate the effect of adding concrete topping above the sub-floor on the fire resistance: one case using assemblies with concrete topping above the steel deck and the other case using assemblies with no concrete topping.

Assemblies with Gypsum Board Attached to Steel C-Joists

Two tests were conducted using Assemblies 15 and 16 to study the effect of adding concrete topping above the sub-floor (steel deck sub-floor with concrete in Assembly 15 vs plywood sub-floor with no concrete topping in Assembly 16) on the fire resistance of assemblies with two layers with Type X gypsum board attached directly to the steel C-joists spaced at 610 mm o.c. and no insulation in the floor cavity. The gypsum board fall-off time for these assemblies is given in Table 1. The temperature distributions at different surfaces and sub-floor deflection for both assemblies are shown in Figures 37 to 40. In Assembly 15, the first piece of the gypsum board face layer had dropped from the assembly at 37 min 38 s and by 56 min 17 s most of the face layer dropped into the furnace. The first piece of the gypsum board base layer dropped at 60 min 37 s where the joists and the underside of the steel deck were exposed partly to the furnace heat; by 66 min most of the base layer had dropped and the steel joist was fully exposed to the furnace heat. In Assembly 16, the first piece of the gypsum board face layer had fallen off from the assembly at 46 min 15 s and most of the face layer had dropped by 55 min 31 s. The first piece of the gypsum board base layer had dropped from the assembly at 54 min 7 s and by 54 min 50 s, most of the base layer had dropped into the furnace. The gypsum board interface surface temperature between the gypsum board face and base layers (see Figures 37 and 39, GWB Face/Base at Cavity) followed a similar trend in the first 37.5 min, however, the temperature was slightly higher in Assembly 15 than in Assembly 16 due to the early fall-off of a large piece of gypsum board from the face layer in Assembly 15. The temperature of the gypsum board base layer facing the floor cavity was slightly higher in Assembly 16 than in Assembly 15 and then was followed by an apparent increase in temperature at 46 min where the furnace hot gases penetrated the gypsum board joints. The temperature of the plywood sub-floor facing floor cavity also shows an increase at 46 min as the gypsum board base layer dropped into the furnace. There was a small deflection (approximately 6 mm) prior to the drop of the gypsum board layers in both assemblies; however, the rate of deflection was larger in Assembly 16 than in assembly 15, as the latter was made of non-combustible sub-floor. Assembly 15 provided 66 min fire resistance while

Assembly 16 provided 54 min 59 s. The assembly with concrete topping above steel deck sub-floor provided 20% more fire resistance compared to an assembly with plywood sub-floor and no concrete topping.

Assemblies with Gypsum Board Attached to Resilient Channels Spaced at 406 mm o.c.

Two tests were conducted using Assemblies 5 (plywood deck/concrete) and 9 (steel deck/concrete) to study the effect of a sub-floor deck type on the fire resistance in assemblies with two layers of Type X gypsum board, resilient channels and steel C-joists spaced at 406 mm o.c. and glass fibre insulation in floor cavity. The gypsum board fall-off time for these assemblies is given in Table 1. The temperature distribution at different surfaces and sub-floor deflection for both assemblies are shown in Figures 17, 18, 25 and 26. The interface surface temperature (GWB Face/Base at Cavity) in Assemblies 5 and 9 followed a similar trend in the first 50 min of fire exposure, however afterward, the temperature was higher in Assembly 5 than in Assembly 9 due to the early fall-off of a large piece of gypsum board from the face layer in assembly 5. Most of the gypsum board face layer fell off from both assemblies at approximately at 55 min 24 s in Assembly 5 and at 59 min 41 s in Assembly 9. The temperature of the gypsum board base layer facing the floor cavity was similar in both assemblies until 49 min of fire exposure followed by a slightly higher temperature in Assembly 5 than in Assembly 9. This was caused by the early fall-off of the first piece of gypsum board face layer in Assembly 5. The temperature of the plywood deck sub-floor facing floor cavity also shows a faster increase at 55 min and burning of the deck as a result of a drop of the first piece of the gypsum board base layer. The plywood deck deteriorated rapidly and the joists were not able to carry the load as shown by the deflection of the sub-floor in Figure 20. There is a small deflection (approximately 10 mm) prior to the fall-off of the gypsum board base layer in both assemblies and the rate of deflection was similar but at a different time as the non-combustible sub-floor steel deck provided an additional resistance to the applied load. Assembly 5 provided 60 min of fire resistance while Assembly 9 provided 68 min 25 s. The assembly with steel deck/concrete sub-floor provided 14% more fire resistance than the assembly with a plywood deck/concrete sub-floor.

From the two cases studied above, the results show that the effect of the type of sub-floor deck on the fire resistance is significant.

Effect of Number of Gypsum Board Layers vs Number of Sub-floor layers

Two assemblies, 1 and 6, were tested to determine the effect of the number of gypsum board layers vs the number of sub-floor layers on the fire resistance. Assembly 1 was constructed with two layers of Type X gypsum board (12.7 mm thick each) attached to resilient channels spaced at 406 mm o.c. and one layer of plywood sub-floor (15.5 mm thick). Assembly 6 was constructed with one layer of Type X gypsum board (15.9 mm thick) attached to resilient channels spaced at 406 mm o.c. and two layers of plywood sub-floor (16 mm thick each). In both assemblies the steel C-joists were spaced at 406 mm o.c. The gypsum board fall-off time is given in Table 1, however, the temperature and deflection distributions for these assemblies are shown in Figures 9, 10, 19 and 20.

In Assembly 1 with two layers of gypsum board, the first piece of the gypsum board face layer had dropped at 66 min 26 s and most of the gypsum board face layer dropped by 73 min 19 s. An entire gypsum board base layer had dropped by 73 min 9 s and at that time the joists and the underside of the plywood sub-floor were exposed to furnace heat. In Assembly 6 with one layer of gypsum board, the first piece of the gypsum board had dropped at 36 min 30 s and most of the gypsum board dropped by 38 min 13 s. When the first piece of the gypsum board fell off, the joists sides and the underside of the plywood sub-floor were exposed to furnace heat. Assembly 1 with two layers of gypsum board and one layer of sub-floor provided 74 min fire resistance while Assembly 6 with one layer of gypsum board and two layers of sub-floor provided 38 min 49 s. These results showed that the assembly with two layers of gypsum board with joints staggered and one layer of sub-floor provided 90% more fire resistance than the assembly with one layer of gypsum board and two layers of sub-floor.

SUMMARY OF KEY FINDINGS

In this paper, the results of sixteen full-scale fire resistance tests conducted to investigate various parameters on the fire resistance of lightweight frame floor assemblies were presented. Based on the results of the tests, the following key findings can be drawn:

1. In floor assemblies with two layers of gypsum board, the installation of either glass or rock fibre insulation in a floor cavity reduced slightly the fire resistance by 8% and 6% respectively, compared to an assembly with no insulation. However, the difference in fire resistance for floor assemblies with a different insulation type (rock fibre vs glass fibre) was insignificant (the assembly with glass fibre insulation provided 2% less fire resistance compared to an assembly with rock fibre insulation).
2. In floor assemblies with one layer of gypsum board, the installation of rock fibre insulation increased the fire resistance by 38% compared to an assembly with no insulation. However, the assembly with cellulose fibre provided 19% more fire resistance than the assembly with rock fibre insulation.
3. The effect of the joists spacing (406 mm vs 610 mm o.c.) on the fire resistance of floor assemblies where the gypsum boards are attached to resilient channels of the same spacing is insignificant (the assembly with joists spaced at 610 mm o.c. provided 1% less fire resistance than in an assembly with joist at 406 mm o.c.). However, the effect of the joists spacing is significant when the gypsum boards are directly attached to the joists (the assembly with joist spaced at 610 mm o.c. provided 18% less fire resistance than in an assembly with joist at 406 mm o.c.).
4. The effect of resilient channels installation on the fire resistance is significant (the assembly with resilient channels installation provided about 11% more fire resistance than in an assembly with no resilient channels) and the effect of the channels spacing on the fire resistance is also significant (the assembly with resilient channels spaced at 406 mm o.c. provided 31% more fire resistance than in an assembly with resilient channels spaced at 610 mm o.c.).
5. The effect of adding concrete topping above the sub-floor type on the fire resistance is significant. The floor assembly with adding concrete topping above the steel deck sub-floor provided 20% more fire resistance compared to an assembly with plywood sub-floor and no concrete topping.

6. The assembly with a steel deck/concrete sub-floor provided 14% more fire resistance than an assembly with a plywood deck/concrete sub-floor.
7. The floor assembly with two layers of gypsum board and one layer of sub-floor provided 90% more fire resistance than an assembly with only one layer of gypsum board and two layers of sub-floor.

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No.	Steel C-Joist		Ceiling Finish Type X		Sub-Floor			Cavity Insulation			Resilient Channels	Load	Fire	Gypsum Board Fell-off Min,s			
	Depth	Spacing	Thick	Layers	Type	Thick	Layers	Type	Thick	Location	Spacing	(N/m ²)	Resistance	Face Layer		Base Layer	
	(mm)	(mm)	(mm)			(mm)			(mm)		(mm)		(min:second)	1 st	Last	1 st	Last
1	203	406	12.7	2	Ply	15.5	1	***	***	***	406	2945	74:00	66,26	73,19	73,09	*
2	203	406	12.7	2	Ply	15.5	1	G1	89	B	406	2945	68:00	59,23	64,06	63,26	*
3	203	610	12.7	2	Ply	19	1	G1	89	B	406	1796	69:00	59,48	62,06	65,04	67,23
4	203	406	12.7	1	Ply	15.5	1	R1	89	B	406	2945	46:00	35,50	43,17	***	***
5	203	406	12.7	2	Ply	15.5	1	G1	89	B	406	1915	60:00	49,26	55,24	53,22	58,05
6	203	406	15.9	1	Ply	15.5	2	***	***	***	406	3366	38:49	36,30	38,13	***	***
7	203	406	15.9	1	Ply	15.5	2	R1	178	B	406	3318	53:38	26,41	38,43	***	***
8	203	406	12.7	2	St/Con	* 51.0	- - -	***	***	***	406	2351	75:00	60,39	73,00	72,35	*
9	203	406	12.7	2	St/Con	* 51.0	- - -	G1	89	B	406	2341	68:25	54,28	59,41	60,10	66,11
10	203	406	12.7	2	St/Con	* 51.0	- - -	G1	89	B	610	2341	61:00	52,32	54,34	53,30	59,15
11	203	406	15.9	1	Ply	15.5	2	C1	91 ^a /112 ^b	T	406	3285	63:47	34,17	45,00	***	***
12	203	406	12.7	2	Ply	15.5	1	***	***	***	***	3342	66:55	51,16	61,29	62,00	65,02
13	203	610	12.7	2	Ply	19	1	G1	89	B	610	2097	52:30	42,17	49,50	50,14	51,41
14	203	406	12.7	2	St/Con	*51.0	- - -	R1	89	B	406	2341	70:00	51,06	57,17	57,46	64,53
15	203	610	12.7	2	St/Con	*51.0	- - -	***	***	***	***	1130	66:00	37,38	56,18	60,37	*
16	203	610	12.7	2	Ply	19	1	***	***	***	***	2123	54:59	46,15	55,31	54,07	54,50

Legend:

R1 - Rock Fibre Insulation Batts

C1 - Cellulose Fibre Insulation, Wet Sprayed

G1 – Glass Fibre Insulation

St/Con – Steel Deck/Concrete

a - Thick of cellulose fibre on Underside of plywood sub-floor

* - Pieces of the Gypsum Board still attached to the assembly

*** - Null Value

B – on Resilient Channels above the Gypsum Board Base Layer

T – Underside of the sub-floor and side of joists

Ply - Plywood

b - Thick of cellulose fibre on Steel C-joist Side

The assembly with fire resistance less than 45 min is not considered as a fire rated assembly, however, an assembly with fire resistance in the range of 45 min to less than 60 min is considered as an assembly with 45 min Fire Resistance Rating. An assembly with fire resistance in the range of 60 min to less than 90 min is considered as an assembly with one hour Fire Resistance Rating.

Table 1 Parameters and results

Figure 1 NRC Full-Scale Floor Furnace

Figure 2 NRC Floor Furnace Loading System

Figure 3 Assembly with no insulation in floor cavity

Figure 4 Assembly with either glass or rock fibre insulation

Figure 5 Assembly with cellulose fibre insulation

Figure 6 Assembly with plywood sub-floor and concrete topping

Figure 7 Assembly with steel deck and concrete topping

Figure 8 Assembly with two layers of sub-floor

Figure 9 Temperature Distribution (Assembly 1)

Figure 10 Deflection Distribution (Assembly 1)

Figure 11 Temperature Distribution (Assembly 2)

Figure 12 Deflection Distribution (Assembly 2)

Figure 13 Temperature Distribution (Assembly 3)

Figure 14 Deflection Distribution (Assembly 3)

Figure 15 Temperature Distribution (Assembly 4)

Figure 16 Deflection Distribution (Assembly 4)

Figure 17 Temperature Distribution (Assembly 5)

Figure 18 Deflection Distribution (Assembly 5)

Figure 19 Temperature Distribution (Assembly 6)

Figure 20 Deflection Distribution (Assembly 6)

Figure 21 Temperature Distribution (Assembly 7)

Figure 22 Deflection Distribution (Assembly 7)

Figure 23 Temperature Distribution (Assembly 8)

Figure 24 Deflection Distribution (Assembly 8)

Figure 25 Temperature Distribution (Assembly 9)

Figure 26 Deflection Distribution (Assembly 9)

Figure 27 Temperature Distribution (Assembly 10)

Figure 28 Deflection Distribution (Assembly 10)

Figure 29 Temperature Distribution (Assembly 11)

Figure 30 Deflection Distribution (Assembly 11)

Figure 31 Temperature Distribution (Assembly 12)

Figure 32 Deflection Distribution (Assembly 12)

Figure 33 Temperature Distribution (Assembly 13)

Figure 34 Deflection Distribution (Assembly 13)

Figure 35 Temperature Distribution (Assembly 14)

Figure 36 Deflection Distribution (Assembly 14)

Figure 37 Temperature Distribution (Assembly 15)

Figure 38 Deflection Distribution (Assembly 15)

Figure 39 Temperature Distribution (Assembly 16)

Figure 40 Deflection Distribution (Assembly 16)