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Performance of Gypsum Board Exposed to Fire

By

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of

Master of Applied Science

In Civil Engineering

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ABSTRACT

Gypsum board provides significant protection to timber and steel frame floor assemblies exposed to fire. Typically, the behaviour of those boards is assessed based on the standard fire exposure which is conservative for long fire exposures. However, the severity of a non-standard fire might exceed the standard exposure, especially in the early stages.

Full-scale tests in which floor assemblies were subjected to standard and non-standard time-temperature exposures conducted as part of this study revealed that the performance of gypsum board is highly dependent on the severity of the fire. In addition, intermediate-scale tests exposed to standard and non-standard fire on floor assemblies conducted as a part of this research showed that intermediate-scale tests can be used in the evolution stages to reduce costs.

The time of gypsum board fall-off has been investigated by analysing fall-off times observed in 80 full-scale standard fire resistance tests conducted on floor assemblies. This investigation resulted in correlations that can be used to predict the fall-off time of the first piece of the gypsum board from the assembly.

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1. INTRODUCTION

1.1 Background

The earliest traces of gypsum plaster, calcium sulphate hemi-hydrate ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$), was 9,000 years ago in Anatolia and Syria. 5,000 years ago, Egyptians burnt gypsum in open-air fires, then crushed it into powder, and finally mixed this powder with water to make slurry to joint the blocks of Pyramids. Greeks also used gypsum as windows for their temples when it was of a transparent quality ("selenite gypsum"). In the 1700's, "Plaster of Paris", calcium sulphate hemi-hydrate was named after the capital of plaster, Paris, since all the walls of wooden houses were covered with plaster as a protection against fire.

In 1894, Augustine Sackett invented what we know today as gypsum board and since then the industry has shown remarkable growth due to improvements in manufacturing. Today, American and Canadian market demands necessitate the manufacture of over 30 billion square feet (2.79 billion square meters) of gypsum board on an annual basis (Gypsum Board Association's website).

1.2 Manufacture of gypsum board

Gypsum board is the generic name for panel-type products that consist of a non-combustible core made of gypsum and additives with paper covering both faces of the panel. The non-combustible core material is a crystalline mineral that can be excavated from the sedimentary rocks in many parts of the world. After mining gypsum, it is

crushed, grounded to a fine powder and heated to 175°C to drive off most of the chemically bound water which is defined as the calcination process. The calcined gypsum, also called calcium sulphate hemi-hydrate, is the material that is used for the manufacture of gypsum board.

The manufacture process of gypsum board starts by mixing the calcined gypsum with water and additives to form slurry which is fed between continuous layers of paper on a board machine. The paper becomes chemically and mechanically bonded to the core gypsum. After that, the board is cut to length and placed in dryers in order to remove any free moisture. In Canada, the manufacturing process of gypsum board is performed according to the standard CAN/CSA-A82.27-M91 [1].

1.3 Chemistry

Gypsum is chemically known as calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), a crystalline mineral that contains 21% by weight chemically bound water which contributes to its excellent fire resistance behaviour [2]. Also, gypsum contains 3% of free water. As mentioned earlier, the calcination process is performed by heating the gypsum powder in order to remove most of the chemically bound water. This process produces calcium sulphate hemi-hydrate ($\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$) commonly recognized as “Plaster of Paris”. The calcination (dehydration) process is summarised by the following equation:

Mixing the calcined gypsum with water follows a reverse hydration reaction as follows:

Furthermore, when gypsum board is exposed to fire and reaches a temperature between 100°C and 120°C the dehydration reaction starts again and follows equation 1-1 yielding to the powder form of gypsum again.

1.4 Study objectives

The aim of this research is to assess the performance of gypsum board protecting floor assemblies that are exposed to fire. This information is necessary for the development and validation of computer models to predict the fire resistance of those assemblies. In order to achieve that, the following objectives were addressed:

- Comparison of gypsum board behaviour in intermediate- and full-scale fire resistance tests;
- Study of gypsum board performance when exposed to standard and non standard time-temperature curves;
- Investigation the fall-off time of gypsum board for different floor assemblies;
- Determination of the factors that affect the fall-off time of gypsum board panels;

- Development of criteria for the time to fall-off of gypsum board panels.

To accomplish the established objectives, the following tasks were performed:

- Two intermediate-scale fire resistance tests wood joist assemblies subjected to standard and non-standard time-temperature curves;
- Two full-scale fire resistance tests were conducted on wood-joist assemblies following standard and non-standard time-temperature curves;
- Observation of the time to fall-off of gypsum board panels for various floor assemblies which had tested previously at the National Research Council of Canada.

2. LITERATURE REVIEW

2.1 Fire and thermal properties

Gypsum board is widely used as a lining material to provide lightweight-framed construction the necessary fire resistance. Gypsum boards can provide up to 90% of the protection; therefore, understanding their fire properties is important. Furthermore, since the fall-off time of gypsum board during tests varies from one assembly to another due to the variation of the assembly's components, such as the type of joist and cavity insulation, it is helpful to be familiar with the thermal properties of these materials in order to better understand their effect on the fall-off of gypsum board.

Buchanan [2] discussed the fire resistance of gypsum board. He mentioned that as a result of the moisture-related reactions all gypsum board products exhibit similar behaviour in fires. He stated that "When a board is heated from one side, temperature on the exposed face will increase continuously until about 100 °C is reached, at which time there will be a delay while the water of crystallization is driven off". He mentioned that as heating continues, the temperature through the board increases slowly until the complete dehydration of the board. After that, the gypsum turns to a powder form with almost no strength. The book also includes a discussion for wood when exposed to fires. In the discussion, Buchanan reported that the temperature of the charred layer is close to the fire temperature. Below this layer and above 200°C known as the pyrolysis zone because wood is undergoing thermal decomposition into gaseous pyrolysis products accompanied by loss of weight and discolouration.

Buchanan and Gerlich [3] reported that the quality and composition of gypsum board can have a major effect on the fire performance of light-frame systems. They noted that in order to have good fire performance, gypsum board should remain in place for the duration of the fire and have sufficiently low shrinkage to prevent cracking or pulling away at board joints. This accomplished by providing glass fibres to control shrinkage and prevent board fall-off, and additives to reduce shrinkage. They also noted that increasing the gypsum's density increases its heat capacity and thus improving its fire performance.

Benichou et al [4] presented thermal properties of wood, gypsum board, and insulation at elevated temperatures based on experimental data generated at the National Research Council of Canada. The thermal properties reported included thermal conductivity, specific heat, mass loss, and thermal expansion/contraction as a function of temperature. They reported that the gypsum board contributes a major part of the fire resistance wood-frame assemblies, as it retards the failure of the assembly until at least the drying process of the gypsum is complete. They concluded that mass loss of gypsum board occurs mostly in the temperature range between 100 and 160 °C. The maximum mass loss of 24.5% was observed at 1000 °C. They also showed that thermal contraction of gypsum board increases slowly up to about 800 °C, after which the contraction occurs at a faster rate. They reported that the temperature at which the peak specific heat of gypsum board occurs depends on the rate of heating. In addition, they showed that the thermal conductivity of glass fibre insulation is generally higher than that of rock fibre insulation especially after 500 °C, and that the mass loss of glass fibre insulation is

significant before reaching a temperature of 300 °C while the mass loss of rock fibre insulation is spread over the temperature range of interest (70-1000 °C).

Sultan [5] presented the result of tests to obtain thermophysical properties of gypsum board when exposed to fire. These tests were part of the development of a model for predicting heat transfer through non-insulated unloaded steel-stud gypsum board wall assemblies exposed to fire. The thermophysical properties included the specific heat, thermal conductivity, and density. Figure 2-1 and Figure 2-2 show a reproduced plot from Sultan [5] for the specific heat and the thermal conductivity of gypsum board at elevated temperatures. The significant increase in the specific heat between 80 and 120 °C presented in Figure 2-1 shows the enormous amount of energy required for calcination of gypsum board.

Figure 2-1 Specific heat of gypsum board reproduced from Sultan [5]

Figure 2-2 Thermal conductivity of gypsum board reproduced from Sultan [5]

Thomas et al [6] presented the range of variations of the density of Type X gypsum board. Type X gypsum board (term used in North America) is the gypsum core mixed with additives (glass fibre) to improve its fire resistance. The study included the average density for three samples of 12.5 mm thick gypsum board, and the average density for four samples of 15.9 mm thick gypsum board. They reported that the variation was fairly large, for the 12.5 mm samples the density varied from 759-811 kg/m³ while for 15.9 mm samples; the variation range was 687-750 kg/m³. This variation of the density would result in a high degree of uncertainty that will impact on the performance of gypsum board in fires. The study was conducted on gypsum board available in Canada and might not reflect the density of all gypsum board products.

2.2 Fire Resistance Test

To control the spread of fire and prevent early collapse of buildings exposed to fire, building codes require structural elements exhibit a prescribed fire resistance. This resistance is determined by standard tests and is called the fire resistance rating of the elements. CAN/ULC-S101-04 [7] is the standard fire resistance test used in Canada. It requires that the fire resistance test be conducted on full-scale complete building assemblies/systems and not on building assembly components. The performance of gypsum board when exposed to fire may depend on factors other than its properties. To reduce costs, intermediate-scale tests of fire resistance can also be conducted for assembly development purpose. For this reason, it is important to understand the correlation between intermediate-scale tests and full-scale tests.

Sultan et al [8] and Sultan et al [9] presented results of full-scale fire resistance tests for different floor assemblies that were conducted at the National Research Council of Canada. In the study, they discussed the effect of different variables on the fire resistance performance of the assemblies. Some of the variables included:

- Type, depth, and spacing of joists;
- Floor cavity insulation type;
- Sub-floor topping;
- Number of sub-floor layers;
- Number of gypsum board layers;
- Resilient channels installation and spacing.

Sultan et al [9] provided the fall-off time of gypsum board layer for the compared assemblies, however, data presented in this thesis for the fall-off time of gypsum board were obtained using videotapes observations of the same tests that were used in Sultan et al [8] and Sultan et al [9].

Sultan et al [10] presented a comparison of the average heat exposure in full-scale and intermediate-scale fire resistance test furnaces using castable refractory slabs in order to show the effect of furnace size on heat exposure in fire resistance test furnaces. Both furnaces were heated according to the CAN/ULC-S101-89 [11]. The results showed that the heat exposure in the intermediate-scale fire resistance furnace (1.2 m wide by 1.8 m long and 0.5 m deep) is slightly (15 %) higher than in the full-scale furnace (4 m wide by 5 m long by 3 m deep). The comparison of the heat exposure in both floor furnaces is shown in Figure 2-3. The average slab temperature for both tests at a depth of 40 mm from the exposed surface is shown in Figure 2-4.

Figure 2-3 Comparison of heat exposure in intermediate-scale vs full-scale floor furnace

(Sultan et al [10])

Figure 2-4 Comparison of temperature at 40 mm (intermediate-scale vs full-scale)

(Sultan et al [10])

Nyman [12] discussed the standard room fire vs the real building fires. He reported that the standard ISO 834 [13] fire test is not representative of realistic fires. The standard fire is conservative for long duration fires as ISO 834 [13] time-temperature relationship has no decay phase whereas in a real fire compartment temperature decreases during the decay phase. He added that shorter fires, such as fires involving upholstered furniture and thermoplastics, are more severe in the early stages than the standard fire. The severity of fires at the early stages is critical as it is the time when the rescue activities are required to be undertaken. Also, he mentioned that the compartment temperatures of real fires, involving upholstered furniture, can reach 1300°C soon after ignition, although temperatures of 1000-1100°C are more common, while the standard ISO 834 fire is still at 834°C after 30 minutes.

2.3 Computer Fire Modeling

Over the last decade, there has been marked increase in the development of fire models. With the advent of performance based codes, computer modeling is expected to become an alternative method to full-scale testing since the later is expensive and time consuming. However, while many studies have contributed to the development of computer models that predict the fire resistance and heat transfer within wall assemblies, few have focused on the development of models that deal with floor assemblies. Furthermore, validation of computer models has been mostly done by conducting standard tests which might not represent the severity of real building fires.

Benichou [14] described the theoretical framework of a structural response model, which predicts the time to failure and deflection of structurally-loaded wood-joist floor assemblies. The paper also illustrates an example of a simulation that compares experimental results with analytical predictions.

Sultan et al [15] discussed the development of a model for predicting the thermal response of steel C-joist floor assemblies exposed to fire. The model was validated with the data from five full-scale experiments test data. They reported that the model predicts a slightly higher temperature distribution across steel C-joists protected with gypsum board floor assemblies, with and without insulation in the floor cavity. Model predictions are conservative for most fire safety structural model designs.

Mehaffey et al [16] presented a simple two-dimensional model to predict heat transfer through wood-stud walls protected by gypsum board exposed to fire. In the model, input data for the thermophysical properties of gypsum board were obtained from standard bench-scale tests while input data for wood were selected from the literature. The model was validated using four small-scale and two full-scale fire resistance tests on gypsum-board/wood stud walls.

2.4 Previous work on gypsum board

Jones [17] conducted a study on the performance of gypsum board wall assemblies when exposed to real building fires. In the study, he evaluated the thermal behaviour of gypsum board wall assemblies subjected to standard and non-standard time-

temperature curves. The study also included a comparison of real compartment fires with standard and non-standard fire tests. Five pilot-scale furnace tests and three full-scale compartment tests were carried out to provide observations of the performance of gypsum board systems exposed to such environments. Jones concluded that the fire resisting performance of gypsum board assemblies is highly dependent on the severity of fire exposure.

Nug [18] conducted bench-scale cone calorimeter tests exposing gypsum boards to different heat fluxes for varying exposure time to quantify the depth of calcination. The objective of the study was to establish a correlation among the depth of calcination of gypsum boards, fire exposure and exposure duration which can be used as an indication for fire severity. A new measuring tool for the depth of calcination called “*Constant force drop*” was developed in the study.

3. FIRE RESISTANCE TESTING METHOD

3.1 General

In most countries, building codes prescribe fire resistance ratings for building elements, which can be obtained by conducting full-scale tests on complete building assemblies/systems. The performance of gypsum board in such tests depends not only on its properties but also on factors related to the construction methods. This impact has not been completely studied; hence there is a need to further investigate the behaviour of gypsum board in standard fire resistance tests. In Canada, the fire resistance rating of building assembly is determined by testing assemblies according to the standard procedure CAN/ULC-S101-04 [7]. As this standard test does not reflect real building fires, it is also necessary to understand the behaviour of gypsum board when exposed to non-standard time-temperature curve.

Two full-scale fire resistance tests of wood-joint floor assemblies were conducted to compare the performance of gypsum board when exposed to a standard exposure, CAN/ULC-S101-04 [7] and a non-standard exposure. Tests observations and temperature distributions from these tests are provided and discussed.

Two non-loaded intermediate-scale floor tests were also conducted to compare the distributions of temperature for the intermediate-scale test with the data of the full-scale test. To facilitate the comparison with the tests exposed to a standard fire, the intermediate-scale tests followed the same fabrication and heat exposure as the full-scale

tests.

This section of the thesis describes the intermediate-scale and full-scale test apparatuses, the fabrication of the assemblies, the instrumentation used to obtain the temperature distributions and the applied loads for the full-scale tests. It also shows the standard and non standard time-temperature curves.

3.2 Intermediate-Scale Test Furnace

The intermediate-scale furnace, shown in Figure 3-1, was constructed using materials similar to that of the full-scale furnace. It has a steel frame and is lined with insulated fire brick. The furnace is capable of testing loaded and unloaded wall and floor assemblies with maximum size of 1.35 m x 1.95 m. The load is applied using hydraulic jacks with five hydraulic pistons connected to a loading beam that can apply a maximum of 117.8 kN for the wall testing mode, and four hydraulic jacks that are uniformly distributed with maximum 218.2 kN for the floor testing mode. The furnace is heated using four propane burners with peak heat release rate of 73 kW per burner. The exposure of the assembly can be according to the CAN/ULC-S101-04 [7] standard time-temperature curve or can be a non-standard exposure. The furnace temperature is measured in compliance with CAN/ULC-S101-04 [7] using the average of four thermocouples located 0.3 m from the exposed surface of the sample. The assembly, when tested, is sealed against the furnace boundaries using ceramic fibre blanks in order to reduce heat loss.

Figure 3-1 Intermediate-scale furnace at NRCC

3.3 Intermediate-Scale Floor Assemblies

3.3.1 Fabrication

Two similar assemblies with dimensions of 1.35 m x 1.95 m as shown in Figure 3-2 were used. The assemblies were fabricated using solid wood joists, nominal 2x10 (38 mm wide by 235 mm deep); according to CSA 0141-1970 [19]. Two layers of 15.9 mm thick Canadian Softwood Plywood (CSP) panels were used as sub-floor on the unexposed side of each assembly. Both sub-floor layers were attached to the wood joists by common nails 64 mm long around the perimeter and 51 mm long in the field. The nails were

spaced 300 mm o.c. Both assemblies were constructed without cavity insulation and resilient channels. Two layers of 12.7 mm thick Type X gypsum board conforming to the requirements of CAN/CSA-A82.27-M91 [1] standards were used on the exposed side of each assembly. The base layer and the face layer of gypsum board were both attached to the joists with type S drywall steel screws 32 mm long for the base layer and 41 mm for the face layer. The screw spacing was 150 mm around the edges of the assembly and 300 mm in the field for both face layer and base layer.

To establish the effect of moisture content on temperature rise, both ends of joist C which is shown in Figure 3-2 (in both intermediate-scale assemblies) were sealed with silicon.

(Dimensions are in millimetres)

Figure 3-2 Intermediate-scale floor assembly plan

3.3.2 Instrumentation

Type K (20 gauge) chromel-alumel thermocouples that have 0.91 mm thickness were used to measure the temperature at different locations along the joists. Type K (24 gauge) chromel-alumel thermocouples that have 0.5 mm thickness were used to measure the temperature between sub-floor layers and between gypsum board layers. A number of small holes at different heights were drilled through the wood joists in order to install thermocouples at a 10 mm depth from the surface of the joists and at the centre of the joists. Thermocouples that were installed between gypsum board layers were taped in the desired position.

3.3.3 Result Recording

The temperatures of the furnace and floor assemblies were recorded every one minute intervals using “Agilent 34970A” data acquisition system and “Agilent VEE” data acquisition software.

3.4 Full-Scale Test Furnace

The full-scale test furnace is constructed according to the requirements of CAN/ULC-S101-04 [7]. It is a large steel box lined with fire bricks. The furnace can test floor assemblies with maximum dimension of 4.87 m x 3.96 m. It is heated using fifteen propane gas burners on each side with a maximum of heat release rate of 4700 kW. Furnace temperatures are measured according to CAN/ULC-S101-04 [7] using nine thermocouples distributed in the furnace in order to show the temperature near all parts of

the assembly. The furnace is capable of testing loaded and unloaded assemblies. Ceramic fibre blanks were used to reduce the heat leakage between the furnace frame and the assemblies. Stationary video cameras are placed at two small windows in the West and the East sides of the furnace to record the events inside the furnace. An additional video camera recorded the exterior view of the test assembly on fire-exposed side. Digital cameras are also used before and during the tests to produce photos of the floor from construction to testing. A typical full-scale floor furnace is shown in Figure 3-3.

Figure 3-3 Full-scale floor furnace at NRCC

3.5 Full-Scale Floor Assemblies

3.5.1 Fabrication

Two assemblies with dimensions of 4840 mm long by 3950 mm wide as shown in Figure 3-4 were fabricated with solid wood joists, nominal 2x10 (38 mm wide by 235 mm deep), according to CSA 0141-1970 [19]. The joists were spaced 406 mm o.c. A row of wood cross-bracing, 19 mm thick by 64 mm wide plywood, was placed at the centre of the assembly between the joists. Two layers of 15.9 mm thick Canadian Softwood Plywood (CSP) panels were used as sub-floor on the unexposed side of each assembly. The sub-floor panels were attached to the wood joist by common nails 64 mm long around the perimeter and 51 mm long in the field. The nails were spaced 300 mm o.c. Both assemblies were constructed with no cavity insulation and no resilient channels. Two layers of 12.7 mm thick each Type X gypsum board were used on the exposed side of each assembly conforming to the requirements of CAN/CSA-A82.27-M91 [1]. The joints between boards in the face and base layers were staggered. The layout of the face layer and base layer of gypsum boards is shown in Figure 3-5 and Figure 3-6 respectively. Both the base layer and face layer of gypsum boards were attached to the joists with type S drywall steel screws 32 mm long for the base layer and 41 mm for the face layer. The screws spacing was 150 mm around the edges of the assembly and 300 mm in the field for both the face layer and base layer.

(Dimensions are in millimetres)

Figure 3-4 Full-scale floor assembly plan

(Dimensions are in millimetres)

Figure 3-5 Gypsum board face layer layout

Figure 3-6 Gypsum board base layer layout

3.5.2 Instrumentation

Thermocouples were installed in order to determine the temperature distributions throughout the floor assembly at different locations. Type K (20 gauge) chromel-alumel thermocouples with a thickness of 0.91 mm were used to measure the temperature at the joists, and type K (24 gauge) chromel-alumel thermocouples with a thickness of 0.5 mm were used to measure the temperature between sub-floor layers and between gypsum board layers.

3.5.3 Result Recording

The temperatures of the furnace and floor assemblies were recorded at one minute intervals using “Agilent data acquisition/switch unit 34970A (20 channels)”

The gage pressure of the loading was also recorded at one minute intervals.

3.5.4 Loading System

The load was applied uniformly using a steel frame, as shown in Figure 3-7, which has thirty hydraulic jacks with a load capacity of 13.3 kN per jack. Each jack transfers the load to the specimen using three circular steel pads that have diameter of 178 mm and thickness of 12.7 mm. Both full-scale assemblies were loaded with 4870 N/m² (101.7 lb/ft²) based on the deflection criteria (100% maximum strength load).

Figure 3-7 Full-scale test loading system at NRCC

3.6 Furnace Time-Temperature Curves

Figure 3-8 and Figure 3-9 show the standard and non-standard time-temperature curves used as input to the furnace in both intermediate- and full-scale tests. The furnace temperature of both the intermediate- and full-scale tests exposed to standard fire followed the standards CAN/ULC-S101-04 [7] time-temperature curve. The curve as shown in Figure 3-8 and Figure 3-9 gradually increased until it reached 963 °C by the end of the test. The non-standard time-temperature curve that was used for the intermediate-scale test increased rapidly until it reached 1050 °C after one minute and remained steady as shown in Figure 3-8. While the non-standard time-temperature curve used for the full-scale test also reached 1050 °C, as shown in Figure 3-9, it took 12 minutes for this due to the large size of the full-scale furnace. In order to represent a real compartment fire with a limited amount of fuel in the non-standard exposure, the furnace was shut off after 37

minutes and 20 minutes in the intermediate- and full-scale tests respectively. The tests were not stopped after shutting off the furnace; rather, floor temperatures were continuously recorded until 69 minutes for the intermediate-scale test and until 54 minutes for the full-scale test.

The time-temperature curve used in the non-standard exposure represented, compared to the standard exposure, a faster fire growth but shorter burning duration. The rate of growth was based on the maximum furnace temperature (1050 °C) that could be obtained in the shortest time.

Figure 3-8 Intermediate-scale tests exposure

Figure 3-9 Full-scale tests exposure

4. TEST RESULTS

4.1 General

This section of the report presents the results of the tests and compares the temperature distributions of the intermediate- and full-scale tests. Significant events that were observed which may impact the performance of gypsum board are discussed. Test results and comparisons are presented in the following sequence:

- Temperature distribution for the intermediate-scale test exposed to a standard fire;
- Temperature distribution for the intermediate-scale test exposed to a non-standard fire;
- Comparison between the results of the two intermediate-scale tests;
- Temperature distribution for the full-scale test exposed to a standard fire;
- Temperature distribution for the full-scale test exposed to a non-standard fire;
- Comparison between the results of the two full-scale tests;
- Comparison between the temperature distributions for the intermediate- and full-scale tests exposed to a standard fire;

4.2 Intermediate-scale Test Exposed to a Standard Fire

Thermocouples installed at two sections, A-A and B-B, as shown in Figure 4-1 in order to determine the temperature distributions of the intermediate-scale floor. The temperature distributions at both sections are shown in Figure 4-2 to Figure 4-9. The average temperature of the furnace (Fave) and the temperature distribution at Trees #1

and # 7 are shown in Figure 4-2 and Figure 4-3 respectively. Temperature at Tree # 1 represents the measurements of thermocouples installed as shown in section A-A of Figure 4-1 which includes: the temperature between the face layer and the base layer of gypsum board at joist B (G.B. Layers); the temperature measured at the interface between the base layer of gypsum board and joist B (G.B and joist); the temperature at the centre of joist B at distances 10, 35, 60, 110, 160, and 210 mm from the bottom of the joist; the temperature measured at the interface between joist B and the sub-floor (joist and S.F.); and the temperature between sub-floor layers at joist B (S.F. Layers).

The temperature at Tree # 7 represents the measurements of thermocouples installed as shown in section B-B of Figure 4-1. The ends of joist C were sealed in order to determine the effect of moisture content on the temperature of the joist. The thermocouples installed at Tree # 7 were located: between the face layer and the base layer of gypsum board at joist C (G.B. Layers); at the interface between the base layer of gypsum board and joist C (G.B and joist); at the centre of joist C at distances 10, 35, 60, 110, 160, and 210 mm from the bottom of the joist; at the interface between joist C and first layer of sub-floor (joist and S.F.); and between sub-floor layers at joist C (S.F. Layers).

Figure 4-1 Intermediate-scale assembly plan and sections with thermocouple locations

(Dimensions are in millimetres)

As shown in Figure 4-2, the temperature between the gypsum board layers at joist B (Tree # 1) began to increase approximately 3 minutes after the test started reaching about 80 °C in about 5 minutes. This was followed by a slower temperature increase as a result of driving off the free and chemically bound water from the gypsum board core. The calcination of the face layer of gypsum board, as shown by the flattened curve, continued up to 15 minutes. An enormous amount of energy absorbed in this calcination as showed earlier in Figure 2-1. When the free and molecular water were driven off, the temperature between the gypsum board layers increased rapidly and reached 775 °C by the end of the test. The temperature between the base layer and joist B started to increase 6 minutes after the test started and reached around 80 °C in 19 minutes. Calcination of the base layer started about 20 minutes and continued to 43 minutes. The temperature between the base layer of gypsum board and joist B also increased rapidly after the completion of the calcination of the base layer and reached 400 °C by the end of the test. The temperature of the centre of joist B at the different distances from the bottom of the joist increased slowly until 50 minutes. At that time, the temperature at 10 mm started to increase rapidly until it reached the thermal decomposition temperature of 200 °C [2] at 64 minutes. At the end of the test, the temperature at 10 mm was 300 °C while the maximum temperature recorded at 35 mm and above along the centre of joist B was 175 °C. This shows that by the end of the test points above 35 mm along the centre of joist B did not reach the thermal decomposition temperature of wood. The maximum temperature measured between sub-floor layers by the end of the test was 101 °C.

Figure 4-2 Temperature distributions at Tree # 1

The temperature distributions at Tree # 7 which is shown in Figure 4-3 followed the same trend as the temperature at Tree # 1. However, the temperature between the gypsum board layers at joist C was higher between 15 and 40 minutes than that at joist B. As shown by the flatten curve of the temperature between gypsum board layers and the temperature between the joist and the base layer, calcination of the face layer was completed at 15 minutes while calcination of the base layer started at 16 minutes and continued up to 40 minutes. The temperature of the centre of joist C at the different distances from the bottom of the joist was higher than that at the centre of joist B due to the sealing of the ends of joist C. The temperature at 10 mm increased slowly up to 42 minutes followed by a rapid increase until it reached the thermal decomposition temperature of 200 °C at 57 minutes and a maximum temperature of 300 °C by the end of

the test. The temperatures at 35 mm and above of the centre of joist C increased slowly until the end of the test. The thermal decomposition temperature (200 °C) at 35, 60, 110 mm were recorded at 75, 78, 78 minutes respectively while the rest of the centre of joist C remain under 200 °C until the end of the test. The maximum temperature recorded at 35 mm and above of the centre of joist C was 239 °C by the end along the test. The maximum temperature measured between sub-floor layers by the end of the test was 100 °C.

Figure 4-3 Temperature distributions at Tree # 7

The temperature distributions at Tree # 5 and Tree # 4 are shown in Figure 4-4 and Figure 4-5. Tree # 5 and Tree # 4, as shown in Figure 4-1, are located at 10 mm from the surface of joist B (section B-B) and joist C (section A-A) which include thermocouples installed at distances of 10, 35, 60, 110, 160, and 210 mm from the bottom of the joists.

Figure 4-4 shows that the temperature at Tree # 5 did not change for the first 6 minutes followed by a slow increase until 50 minutes. At that time, the temperature at 10 mm increased rapidly until it reached the thermal decomposition temperature of 200 °C at 67 minutes and a maximum temperature of 272.5 °C by the end of the test. The temperatures at 35 mm and above were equal and lower than the temperature of the joist at 10 mm until 68 minutes. Slight differentiations following that can be noticed in Figure 4-4 between 68 minutes and the end of the test. The maximum temperature recorded at 35 mm and above was 160 °C, which shows that the joist at those distances did not undergo thermal decomposition.

Figure 4-4 Temperature distributions at Tree # 5

Figure 4-5 shows the temperature of joist C at Tree # 4. The temperature began to increase slowly reaching 115 °C by 45 minutes of the test followed that by rapid increase until it reached the thermal decomposition temperature of wood (200 °C) at 54 minutes and a maximum temperature of 414 °C by the end of the test. In contrast with joist B, slight differentiations can be noticed in the temperatures at 35 mm and above of joist C. The thermal decomposition temperature at 35 mm depth occurs at 77 minutes while the maximum temperature measured at 35 mm depth was 220 °C. At depth 60 mm the maximum temperature was 187 °C which shows that this part of the joist did not reach the thermal decomposition temperature by the end of the test.

Figure 4-5 Temperature distributions at Tree # 4

Figure 4-6 shows a comparison between the temperatures of joist B and C at 10 mm from the bottom of the joists at Tree # 1, Tree # 4, Tree # 5 and Tree # 7. The figure shows that sealing joist C resulted in higher temperature of the joist after 50 minutes of the test.

Figure 4-6 Temperature distributions at 10 mm from the bottom of the joists

The average temperature of the furnace (Fave) and the temperature distribution at Tree # 3 are shown in Figure 4-7. As shown in Figure 4-1, Tree # 3 was installed at the furnace geometric centre and included thermocouples installed: between the face layer and the base layer of gypsum board (G.B. Layers); at the floor cavity at gypsum board surface (Cavity at G.B.); at the floor cavity at distance of 110 mm from the base layer of the gypsum board (Cavity at 110 mm); at the floor cavity at sub-floor (Cavity at S.F.); and between sub-floor layers centre (S.F. Layers).

Figure 4-7 shows that the temperature between the gypsum board layer at Tree # 3 began to increase at approximately 3 minutes after the test started reaching around 80 °C in about 5 minutes. This was followed by a slower temperature increase as a result of driving off the free and chemically bound water from the gypsum board core. The calcination of the face layer of gypsum board, as shown by the flattened curve, continued

up to 13 minutes. As shown by the temperature of the floor cavity at the gypsum board surface, calcination of the base layer was completed by 39 minutes. After this time the temperature increased rapidly. The maximum measured floor cavity temperature by the end of the test was 400 °C at the gypsum board surface while at 110 mm and at the sub-floor were around 334 °C and 313 °C respectively. The maximum temperature recorded by the end of the test between the sub-floor layers at the furnace geometric centre was 124 °C which was slightly higher than the sub-floor temperature at the joists as a result of the heat transferred through the floor cavity.

Figure 4-7 Temperature distributions at Tree # 3

Figure 4-8 and Figure 4-9 show the temperature distributions at Tree # 2 and Tree # 6 which represent the temperature distributions at the surface of joist B and joist C

respectively as shown in Figure 4-1 that include the temperature at distances of 35, 110, and 210 mm from the bottom of joist B and C.

Figure 4-8 shows that the temperatures of the surface of joist B at the three mentioned locations were equal until 40 minutes. A slight rise of the temperature at 35 mm can be observed after 40 minutes in Figure 4-8. The temperature at the surface of joist B started to increase 5 minutes after the test started followed by a slow increase until it reached around 100 °C by 44 minutes of the test. A rapid increase of temperature occurred after 44 minutes as a result of the rise in temperature in the floor cavity due to the completion of the calcination of the base layer of gypsum board. At 35 mm, the thermal decomposition temperature of 200 °C began at 57 minutes and at 60 minutes at depths 110 and 210 mm. The maximum temperature recorded at 35 mm was 308 °C while at 110 and 210 mm was 288 °C. The temperature at the surface of joist B was higher than that at the centre and at 10 mm of the surface of joist B especially after 44 minutes of the test where the calcination of the base layer of gypsum board has occurred.

Figure 4-8 Temperature distributions at Tree # 2

Figure 4-9 shows that the temperatures of the surface of joist C at distances of 35, 110, and 210 mm from the bottom of the joist were equal until 33 minutes. The temperatures at the surface of joist C started to increase 5 minutes after the test started, followed by a slow increase until it reached around 100 °C by 40 minutes of the test, which is earlier than that for joist B due to sealing the ends of joist C. A rapid increase of temperature occurred after that as a result of the completion of the calcination of the base layer of gypsum board at the floor cavity. In general, the temperatures at the surface of joist C were higher than the temperatures at the surface of joist B. The surface of joist B at 35, 110, and 210 mm reached the thermal decomposition of 200 °C at 53, 55, and 57 minutes while the maximum temperatures recorded by the end of the test at the same locations were 330, 304, and 295 °C respectively. The temperature at the surface of joist C was higher than both the temperatures at the centre and at 10 mm of the surface of the

joist especially after 40 minutes when the calcination of the base layer of gypsum board was completed.

Figure 4-9 Temperature distributions at Tree # 6

4.3 Intermediate-scale Test Exposed to Non-standard Fire

The temperature distributions for the intermediate-scale test exposed to non-standard fire are shown in Figure 4-10 to Figure 4-17. In comparison to the intermediate-scale test exposed to standard fire, thermocouple trees installed at the non-standard test were similar to the numbers and locations shown in Figure 4-1. Trees # 1 and # 7 represent the distribution of thermocouples installed at the centre of joist B and C respectively which include thermocouples as shown in Figure 4-1.

The average temperature of the furnace (Fave) and the floor temperature from time of ignition at Tree #1 and # 7 are shown in Figure 4-10 and Figure 4-11 respectively. Figure 4-10 shows that the temperature between the gypsum board layers at joist B began to increase 2 minutes after the test started reaching around 80 °C in about 4 minutes. This was followed by a slower temperature increase as a result of driving off the free and chemically bound water from the gypsum board core. The calcination of the face layer of gypsum board, as shown by the flattened curve, continued up to 12 minutes. When the free and chemically bound water were driven off, the temperature between the gypsum board layers at joist B increased rapidly and reached the average furnace temperature (1030 °C) in 32 minutes. The temperature then followed the furnace temperature until the furnace was shut off at 37 minutes. The resulting sudden rise in temperature was due to the fast growth rate of exposure which increased the temperature from below 100 °C to over 1000 °C between 12 and 32 minutes. As shown in the figure, the severity of the fire exposure started to diminish after 37 minutes when the temperature rapidly decayed until it reached 302 °C at the time of the test termination. The temperature between the base layer and the joist started to increase 3 minutes after the test began and reached around 80 °C in 15 minutes. Calcination of the base layer, as shown by flattened curve of the temperature between the joist and the gypsum board, started about 16 minutes and continued to 32 minutes. Followed calcination, a rapid increase of temperature occurred until it reached 590 °C at 51 minutes. The temperature at the centre of joist B increased slowly until 40 minutes. At that time, the temperature at 10 mm from the bottom of the joist started to increase rapidly until it reached the thermal decomposition temperature of 200 °C at 49 minutes and a maximum temperature of around 368 °C by the end of the

test. The maximum temperature recorded at the centre of joist B at 35 mm and above was 200 °C by the end of the test which shows that 35 mm and above of the centre of joist B did not go through thermal decomposition during the test. The maximum temperature measured between the sub-floor layers was 101 °C by the end of the test. It was noticed in Figure 4-10 that the temperature between the gypsum board and the joist was higher than the average temperature of the furnace and the temperature between gypsum board layers after 50 minutes. Since the temperature of the joist at 10 mm was more than 200 °C at that time, therefore, charring of the joist might result in flames and affected the temperature between the joist and the temperature.

Figure 4-10 Temperature distributions at Tree #1

At the centre of joist C (Tree # 7), the temperature distributions which is shown in Figure 4-11 followed the same trend as the temperature at Tree # 1. However, the temperature between the gypsum board layers at joist C was higher than the temperature at joist B between 15 and 30 minutes. As shown in the figure, the calcination of the face layer was completed at 12 minutes while the calcination of the base layer started at 20 minutes and continued up to 35 minutes. At 10 mm at the centre of the joist, the temperature increased slowly up to 42 minutes followed that by rapid increase until it reached the thermal decomposition temperature around 48 minutes and maximum temperature of 423 °C by the end of the test. The temperatures at 35 mm and above were increased slowly until the end of the test. The thermal decomposition temperature was recorded at 61 minutes at 35 mm and at 63 minutes at 60 mm. The maximum temperature recorded at 35 mm and above of the centre of joist C was 273 °C. The maximum measured temperature between joist C and the sub-floor was 192 °C while the maximum temperature between sub-floor layers at joist C was 100 °C by the end of the test.

Figure 4-11 Temperature distributions at Tree # 7

Temperature distributions at Tree # 5 and Tree # 4 are shown in Figure 4-12 and Figure 4-13. Tree # 5 and Tree # 4, as shown in Figure 4-1, are located 10 mm from the surface of joist B (section B-B) and joist C (section A-A) which include thermocouples installed at distances of 10, 35, 60, 110, 160, 210 mm from the bottom of the joists. Figure 4-12 shows that the temperature at joist B started to increase after the first 4 minutes. After 42 minutes, the temperature 10 mm from the bottom of the joist was significantly higher than the temperature at the rest of the joist. At that time the temperature rapidly increased until it reached the thermal decomposition temperature around 49 minutes and a maximum temperature of 307 °C by the end of the test. The maximum temperature recorded at 35 mm and above was 200 °C by the end of the test.

Figure 4-12 Temperature distributions at Tree # 5

Figure 4-13 shows that the temperature at joist C at 10 mm depth from the surface of the joist, Tree # 4, followed the same trend of the temperature at Tree # 5. As shown in the figure, the temperature 10 mm from the bottom of the joist reached the thermal decomposition temperature of 200 °C at around 48 minutes and a maximum temperature of 327.5 °C at 57 minutes. The maximum measured temperature at 35 mm and above was 202 °C by the end of the test.

Figure 4-13 Temperature distributions at Tree # 4

Figure 4-14 shows a comparison between the temperatures of joist B and C at 10 mm from the bottom of the joists at Tree # 1, Tree # 4, Tree # 5 and Tree # 7. The figure shows that sealing joist C resulted in higher temperature of the joist after 45 minutes of the test.

Figure 4-14 Temperature distributions at 10 mm from the bottom of the joists

The average temperature of the furnace (Fave) and the temperatures distribution at Tree # 3 are shown in Figure 4-15. Temperature at Tree # 3 represents the temperature distributions at the furnace geometric centre measured by thermocouples installed as shown in Figure 4-1. Tree # 3 includes thermocouples installed: between the face layer and the base layer of gypsum board at the furnace geometric centre (G.B. Layers); the temperature measured at the bottom of the floor cavity at the top of the base layer of gypsum board (Cavity at G.B.); the temperature of the floor cavity at 110 mm from the bottom of the joist (Cavity at 110 mm); the temperature at the top of the floor cavity under the sub-floor (Cavity at S.F.); and the temperature between sub-floor layers at the furnace geometry centre (S.F. Layers).

The temperature between gypsum board layers at the furnace geometric centre, as shown in Figure 4-15, followed the same trend of the temperatures at the centre of the

joists. It began to increase at approximately 3 minutes reaching around 80 °C in about 4 minutes. The calcination of the face layer of gypsum board, as shown by the flattened curve, continued up to 11 minutes. The temperature increased rapidly reaching the average furnace temperature by 33 minutes and followed the average furnace temperature until the furnace was shut off at 37 minutes. The maximum temperature measured between the gypsum board layers at the furnace geometric centre was 1068 °C at 37 minutes. Calcination of the base layer was completed by 31 minutes which resulted in a rapid increase of temperature of the floor cavity at the surface of the gypsum board as shown in Figure 4-15. The maximum measured floor cavity temperature at the gypsum board surface was 428 °C at 51 minutes while the maximum recorded temperatures of the floor cavity at 110 mm from the surface of the gypsum board and at the surface of the sub-floor were around 400 °C and 373 °C at 46 and 51 minutes. The maximum temperature between the sub-floor layers was 141 °C by the end of the test which was higher than the temperature between sub-floor layers of both joists B and C as a result of heat transferred through the floor cavity.

Figure 4-15 Temperature distributions at Tree # 3

Figure 4-16 and Figure 4-17 show the floor temperature at each thermocouple on Tree # 2 and Tree # 6 that are installed at the surface of joist B (section A-A) and joist C (section B-B) respectively as shown in Figure 4-1. The temperature at the surface of the joists followed a similar trend of the temperature at the floor cavity. It was also noticed that the temperatures at the surface of the joists were higher than the temperature at the centre and at 10 mm depth from the surface of joists.

The temperatures at the surface of joist B, as shown in Figure 4-16, reached the thermal decomposition temperature of 200 °C at 37 minutes. The temperature at 35 mm from the bottom of the joist was slightly higher than the rest of the joist. The maximum temperature at 35 mm was 384 °C at 51 minutes.

Figure 4-16 Temperature distributions for Tree # 2

The temperatures of the surface of joist C followed a similar trend as the temperature at joist B. The thermal decomposition temperature of 200°C was recorded at 37 minutes. The maximum temperatures recorded at the 35, 110, and 210 mm depths were 368, 354, and 339°C respectively.

Figure 4-17 Temperature distributions for Tree # 6

4.4 Intermediate-scale Test: Standard vs Non-Standard Exposure

Figure 4-18 shows a comparison of the average furnace temperatures for both intermediate-scale tests using a standard and non-standard fire. The average temperature of the furnace during the standard test followed a slow growth rate, which reached 844°C by 30 minutes, and lasted for a longer duration (80 minutes) while the average furnace temperature during the non-standard test began with a fast growth, which reached 855°C in 6 minutes and continued to increase until it reached around 1000°C. The furnace of the non-standard test was shut-off at 37 minutes which resulted in decay for the average temperature of the furnace. This difference of the furnace temperatures between standard

and non-standard tests affected the temperatures of the floor and consequently the calcination of the gypsum board layers and the thermal decomposition of the wood joists.

Figure 4-18 Average furnace temperatures for intermediate-scale tests

The temperatures between the gypsum board layers were the same for both intermediate-scale tests for the first 13 minutes, although, the average furnace temperature at that time was 737 °C for the standard test and 1007 °C for the non-standard test. The similarity in temperatures for the first 13 minutes resulted in an insignificant variation for the time of calcination of the face layer of the two tests. As a result of the fast growth of the non-standard exposure, a sudden increase in temperature between the gypsum board layers followed the calcination of the face layer causing a faster rate of driving off the free and chemically bound water from the gypsum board core of the base layer. This resulted in an acceleration of the time of calcination of the base layer for the non-standard test. Table 4-1 presents the time of calcination of the face

layer and the base layer of gypsum board for both intermediate-scale tests at different locations of the floor.

Table 4-1: Calcination time of the gypsum board layers for both intermediate-scale tests

Location	Standard Exposure		Non-standard Exposure	
	Face Layer (min)	Base Layer (min)	Face Layer (min)	Base Layer (min)
Joist B	5-15	19-43	4-12	16-32
Joist C	5-15	16-40	4-13	20-35
Furnace geometric centre	5-13	20-39	4-12	16-31

Three different locations of the joists, at centre of the joist; at 10 mm depth from the surface of the joist; and at surface of the joist, were studied to investigate the effect of standard and non-standard exposures on the thermal decomposition of the wood joists. The temperatures of the joists were equal for both tests until 34 minutes at the surface of the joists and until 40 minutes of both at the centre of the joist and at 10 mm depth from the surface of the joist. However, the early completion of the calcination of the base layer for the non-standard test as recorded in Table 4-1 resulted in a rising of the temperature of the joists and consequently caused early thermal decomposition. Table 4-2 summarizes the time when the thermal decomposition occurred at different locations of the joists for both tests. The results in the table show that sealing the edges of the joist accelerated its thermal decomposition significantly in the standard test, however, the effect was minor on the thermal decomposition of the non-standard test.

Table 4-2: Thermal decomposition time of different locations of the joists

Location	Distances (mm)	Standard Test		Non-standard Test	
		Non-Sealed Joist (min.)	Sealed joist (min.)	Non-sealed Joist (min.)	Sealed Joist (min.)
Centre of the joist	10	64	57	49	49
	35	***	75	***	62
	60	***	78	***	64
10 mm depth from the surface of the joist	10	67	54	49	48
	35	***	77	69	69
Surface of the joist	35	57	53	37	36
	110	60	55	37	37
	210	60	57	37	37

*** This location did not reach the thermal decomposition temperature by the end of the test

The temperature between the sub-floor layers did not vary significantly for both tests. The maximum temperature recorded between the sub-floor layers at the joists for both tests was 100°C while the maximum temperature measured at the furnace geometric centre was 124°C for the standard test and 141°C for the non-standard test. The average temperature of the five thermocouples on the unexposed side also did not much vary for the two tests. At the termination of the test, the maximum recorded temperatures on the unexposed side were 73°C and 78°C for the standard and non-standard test respectively.

4.5 Full-scale Test Exposed to Standard Fire

The temperature distributions of the floor for the full-scale test exposed to standard fire were measured using thermocouples installed at sections shown in Figure 4-19. Six sections on joist # 8 were chosen to investigate the temperature distributions of the centre joist of the floor. Sections A-A is located at the centre of the floor, A1-A1 is

located 800 mm from the centre and section A2-A2 is located 800 mm from the centre on the other side. All the three sections had the same thermocouple location, as shown in Figure 4-20, as section A-A. Two sections B1-B1 and B2-B2 were located at the intersection of joist # 8 and the joint of the face layer and intersection of joist # 8 and the joint of the base layer of gypsum board with thermocouple located as shown in Figure 4-20 for section B-B. Section C-C was positioned at 25 mm from the side of joist # 8 to examine the temperature at the edge of the floor. Four more sections, C1-C1; C2-C2; D1-D1; and D2-D2 were installed two on each joist, #4 and # 12, to study the impact of the distribution of the furnace temperature on the temperatures of the floor. The location of thermocouples and number of trees installed at C-C, and D-D are shown in Figure 4-20.

The following sections in this thesis describe the temperature distributions at the different sections shown in Figure 4-20. The assembly resisted the fire exposure until 54 minutes.

Figure 4-19 Full-scale test assembly plan and location of sections

Figure 4-20 Full-scale test sections with thermocouples locations

4.5.1 Temperature distributions at the centre of the joists

The average temperature of the furnace (F_{avg}) and the temperature distributions at Trees #1 of section A-A are shown in Figure 4-21. Temperatures at Tree # 1 represent the measurements of thermocouples installed, as shown in Figure 4-20, at different locations which include: between the gypsum board layers at the joist (G.B. Layers); at the interface between the base layer of gypsum board and the joist (G.B and joist); at the centre of joist # 8 at distances of 10, 35, 60, 117.5 mm from the bottom of the joist; at the interface between the joist and first layer of sub-floor (joist and S.F.). No temperature measurements are shown in the figure for the thermocouple installed between the gypsum board layers (G.B. Layers) due to thermocouple malfunction.

As shown in Figure 4-21, the temperature between the gypsum board and the joist at Tree # 1 of section A-A began to increase approximately 3 minutes after the test started reaching around 80 °C in about 12 minutes at which time the calcination of the base layer started. This was followed by a slower temperature increase as a result of driving off the free and chemically bound water from the gypsum board core. The calcinations of gypsum board absorbed an enormous amount of energy as showed earlier in Figure 2-1. The calcination of the base layer of gypsum board, as shown by the flattened curve, continued up to 26 minutes. When the free and chemically water were driven off, the temperature between the gypsum board and the joist increased rapidly and reached around 400 °C at 50 minutes. The figure also shows that the temperature at 10 mm of the centre of the joist was higher than the rest of the joist and reached of 200 °C at around 45 minutes. The maximum temperature recorded at 10 mm before the fall-off of

the first piece of the base layer of gypsum board was 343 °C at 50 minutes. The temperature at 35 mm and above along the centre of the joist and between the joist and the sub-floor increased slowly until 50 minutes when they reached a maximum temperature of 92 °C. The sudden increase of all temperatures shown in the figure after 50 minutes was followed the fall-off of the first piece of the base layer as recorded in the test observation and presented in Appendix A.

Figure 4-21 Temperature distributions at Tree # 1 of section A-A

The temperature distribution at Tree # 1 of section A1-A1 and the average furnace temperature (Favg) is shown in Figure 4-22. The figure shows that the temperature between the gypsum board layers at joist # 8 began to increase approximately 1 minute after the test started reaching around 80 °C in about 4 minutes. This was followed by a

slower temperature increase as a result of driving off the free and chemically bound water from the gypsum board core. The calcination of the face layer of gypsum board, as shown by the flattened curve, continued up to 12 minutes. When the free and chemically bound water were driven off, the temperature between gypsum board layers increased rapidly and reached around 601 °C by 47 minutes of the test. The test observations (Appendix A) show that the face layer of gypsum board started to fall at 45 minutes and 37 seconds. The temperatures after 47 minutes represented the fall-off at this section.

The temperature between the gypsum board and the joist started to increase after 2 minutes reached around 80 °C in 7 minutes. At this section, the temperature between the gypsum board and the joist did not show the flat curve which presents the duration of the calcination of the base layer. A temperature of around 120 °C which occurred at 12 minutes can be considered as the end of the calcination. Comparing to the completion of the calcination of the base layer at the other sections this time is quite early. The maximum temperature recorded between the gypsum board and the joist was 422 °C at 50 minutes. The figure also shows the temperature at the centre of joist # 8. Similar to the temperature distributions at the centre of joist # 8 of section A-A, the temperature at 10 mm of the centre of the joist was higher than the rest of the joist. The maximum recorded temperature was 170 °C at 50 minutes which shows that the centre of joist # 8 did not reach the thermal decomposition temperature of 200 °C by 50 minutes. The temperature at 35 mm and above of the centre of the joist and between the joist and the sub-floor increased slowly until 50 minutes when they reached a maximum temperature of 106 °C.

Figure 4-22 Temperature distributions at Tree # 1 of section A1-A1

Thermocouples installed at Tree # 1 of section A2-A2 were like those installed at section A-A which are shown in Figure 4-20. The temperature distributions of Tree # 1 at section A2-A2 and the furnace average temperature are shown in Figure 4-23. As shown in the figure, the temperature between the gypsum board layers at joist # 8 began to increase at approximately 1 minutes of the test reaching around 80 °C in about 4 minutes when the calcination of the face layer started. The calcination of the face layer of the gypsum board, as shown by the flattened curve, continued up to 13 minutes. As the calcination of the face layer was completed, the temperature between gypsum board layers increased rapidly and reached around 680 °C at 47 minutes. The temperature between the gypsum board and the joist started to increase after 2 minutes and reached around 80 °C in 14 minutes. At that time, the temperature increased slowly as a result of

driving off the free and chemically bound water from the gypsum board core. The calcination of the base layer of gypsum board, as shown by the flattened curve, continued up to 35 minutes. After the end of the calcination of the base layer, the temperature increased rapidly and reached around 280 °C at 50 minutes. The figure also shows the temperature at the centre of joist # 8. At 10 mm of the centre of the joist the temperature was slightly higher than the rest of the joist. The maximum recorded temperature was 130 °C at 50 minutes which shows that the centre of joist # 8 at section A2-A2 did not reach the thermal decomposition temperature of 200 °C at that time. The temperatures at 35 mm and above of the centre of the joist and between the joist and the sub-floor increased slowly until 50 minutes when they reached a maximum temperature of 87 °C at 50 minutes.

Figure 4-23 Temperature distributions at Tree # 1 of section A2-A2

The average temperature of the furnace (F_{avg}) and the temperature distributions at Trees #5 at section C-C are shown in Figure 4-24. Temperatures at Tree # 5 represent the measurements of thermocouples installed as shown in Figure 4-20 at: the interface between the base layer of gypsum board and the joist (G.B and joist); and the centre of joist # 8 at distance of 10, 35, 60 mm from the bottom of the joist. Section C-C, as shown in Figure 4-19, was located 25 mm from the sides of the joist. In contrast with the temperature distributions of the other sections, the temperature distributions in Figure 4-24 show that the thermocouples at this section recorded the temperature measurements until the end of the test (54 minutes).

The temperature between the gypsum board and the joist started to increase after 3 minutes until it reached 80 °C at 13 minutes when the calcination of the base layer of gypsum board started. This was followed by a slower temperature increase as a result of calcination. The calcination of the base layer continued up to 40 minutes when the trend of the temperature curve as shown in the figure started to increase rapidly. The maximum temperature recorded by the end of the test was 325 °C. Figure 4-24 also shows the temperature distribution at the centre of the joist at distances 10, 35, and 60 mm from the bottom of the joist. The figure shows that the temperature at 10 mm was slightly higher than the rest of the joist. The maximum temperature recorded by the end of the test was 201 °C at 10 mm and 153 °C at 35 mm and above which shows that the centre of the joist at this section started to reach the thermal decomposition temperature of 200 °C by the end of the test.

Figure 4-24 Temperature distributions at Tree # 5 of section C-C

Two sections, B1-B1 and B2-B2, located at the gypsum board joints were chosen to measure the temperatures between the gypsum board layers and between the joist and the gypsum board. Section B1-B1 was located at the intersection of the joint of the base layer of gypsum board and joist # 8 (centre joist) while section B2-B2 was located at the intersection of the joint of the face layer of gypsum board and joist # 8. Thermocouples, as shown in Figure 4-20, were installed for both sections between the gypsum board layers and between the joist and the gypsum board.

Figure 4-25 shows that the temperature between the gypsum board layers at both sections started to increase after 1 minute of the test until they reached 80 °C around 4 minutes. At that time the calcination of the face layer started and a slower temperature increase resulted from driving off the free and chemically bound water from the gypsum

board core. The calcination of the face layer continued, as shown by the flattened curve, up to 12 minutes. As the calcination of the face layer was completed, the temperature between the gypsum board increased rapidly and reached 610 °C at section B1-B1 and 697 °C at section B2-B2 at 47 minutes. The figure also shows that the temperature between the joist and the gypsum board started to increase after 3 minutes until it reached 80 °C at 12 minutes when the calcination of the base layer started. This was followed by a slower increase of temperature until the completion of the calcination of the base layer at 23 minutes in section B1-B1 and 31 minutes in section B2-B2. The maximum measured temperature between the joist and the base layer was 472 °C at section B1-B1 and 423 °C at section B2-B2 at 50 minutes.

Figure 4-25 Temperature distributions at Sections B1-B1 and B2-B2

The furnace average temperature (F_{avg}) and the temperature distributions of Tree # 5 at section C1-C1 are shown in Figure 4-26. Thermocouples installed at Tree # 5 of

section C1-C1 were similar those installed at section C-C which are shown in Figure 4-20, however, section C1-C1 was located on joist # 4 as shown in Figure 4-19. The temperature between the gypsum board and the joist started to increase after 3 minutes until it reached 80 °C at 13 minutes when the calcination of the base layer of gypsum board started. This was followed by a slower temperature increase. The calcination of the base layer continued up to 35 minutes when temperature as shown in the figure started to increase rapidly. The maximum recorded temperature between the joist and the base layer of gypsum board was 323 °C at 52 minutes. The temperature distributions at the centre of the joist at distances from the bottom of the joist are shown in Figure 4-26. The figure shows that the temperature at 10 mm was slightly higher than the rest of the joist. The maximum temperature recorded before the thermocouples fell-off in the furnace was 165 °C at 10 mm and 92 °C at 35 mm and above at 52 minutes. This shows that the centre of joist # 4 at this section did not reach the thermal decomposition temperature of 200 °C at 52 minutes.

Figure 4-26 Temperature distributions at Tree # 5 of section C1-C1

Thermocouples installed at Tree # 5 of section C2-C2 were similar to those installed at section C-C as shown in Figure 4-20. The furnace average temperature (F_{avg}) and the temperature distributions of Tree # 5 at section C2-C2 are shown in Figure 4-27. The temperature between the joist and the gypsum board started to increase after 3 minutes of the test and reached 80°C by 16 minutes. The calcination of the base layer, as shown by the flattened curve, was completed by 41 minutes. At that time the temperature between the joist and the gypsum board increased faster and reached 249°C by 52 minutes. As shown in the figure, the temperature at 10 mm of the centre of the joist was slightly higher than the temperature at 35 mm and above. The maximum temperature recorded was 115°C at 10 mm and 95°C at 35 mm at 52 minutes. This shows that joist # 4 did not reach the thermal decomposition temperature at 52 minutes.

Figure 4-27 Temperature distributions at Tree # 5 of section C2-C2

Figure 4-28 shows the temperature distributions at Tree # 8 of section D1-D1 which was installed at the centre of joist # 12. The location of the section on the plan of the floor is shown in Figure 4-19. Thermocouple locations installed at Tree # 8 are also shown in Figure 4-20 and they are: between the interface of joist # 12 and the base layer of gypsum board and at the centre of the joist at distances of 10, 35, and 60 mm from the bottom of the joist. As shown in Figure 4-28, the temperature between the gypsum board and the joist started to increase after 3 minutes of the test followed by a slow increase until it reached 80 °C by 12 minutes. The calcination of the base layer, as shown by the flattened curve, continued up to 43 minutes. At that time, the temperature started to increase rapidly and reached 245 °C at 51 minutes. The temperature at the centre of the joist as shown in Figure 4-28 was higher at 10 mm. The maximum temperature measured at the centre of joist # 12 at this section was 163 °C at 10 mm and 95 °C at 35 mm and above at 51 minutes. The finding shows that the centre of joist did not reach the thermal decomposition temperature of 200 °C by the end of the test.

Figure 4-28 Temperature distributions at Tree # 8 of section D1-D2

The furnace average temperature (Favg) and the temperature distributions of Tree # 8 at section D2-D2 are shown in Figure 4-29. Thermocouple locations at Tree # 8 of section D2-D2 were similar to those installed at section D1-D1 as shown in Figure 4-20. Figure 4-29 shows that the temperature between the gypsum board and the joist started to increase after 3 minutes of the test followed by a slow increase until it reached 80 °C by 14 minutes. The calcination of the base layer, as shown by the flattened curve, continued up to 40 minutes. At that time, the temperature started to increase rapidly and reached 309 °C at 50 minutes. The temperature at the centre of the joist, as shown in the figure, was higher at 10 mm. The maximum temperature measured at the centre of joist # 12 at this section was 146 °C at 10 mm and 94 °C at 35 mm and above at 51 minutes which shows that the joist at that time did not reach the thermal decomposition temperature of 200 °C.

Figure 4-29 Temperature distributions at Tree # 8 of section D2-D2

4.5.2 Temperature distributions at 10 mm from the surface of joist # 9

Figure 4-30 to Figure 4-32 show the temperature at Tree # 4 of sections A-A, A1-A1, and A2-A2 as located in Figure 4-19. Tree # 4 includes thermocouples installed as shown in Figure 4-20 10 mm from the surface of joist # 9 at distances of 10, 35, 60, and 117.5 mm from the bottom of the joist. The figures show that the temperatures started to increase after 4 minutes and followed by a slight increase of temperature. It was noticed also that temperature at 10 mm was slightly higher than the rest of the joist. Figure 4-30 shows that the temperature at 10 mm reached the thermal decomposition temperature of 200 °C at 47 minutes and a maximum temperature of 252 °C at 50 minutes. The temperatures at 35 mm and above were the same until they reached 92 °C at 50 minutes.

Figure 4-30 Temperature distributions at Tree # 4 of section A-A

Figure 4-31 shows that the maximum temperature measured at 10 mm was 148 °C at 50 minutes. The figure also shows that the temperatures at 35 mm and above were the same until they reached 101 °C at 50 minutes. This data shows that at 10 mm from the surface of joist #9 at section A1-A1 the joist did not reach the thermal decomposition temperature of 200 °C at 50 minutes.

Figure 4-31 Temperature distributions at Tree # 4 of section A1-A1

Figure 4-32 shows that the maximum temperature measured at 10 mm was 118 °C at 50 minutes. A slight variation in temperature was noticed at 35 mm and above of the joist, however, the maximum measured temperature was 98 °C at 50 minutes which shows that the joist did not reach the thermal decomposition of 200 °C.

Figure 4-32 Temperature distributions at Tree # 4 of section A2-A2

4.5.3 Temperature distributions at surface of the joists

The temperature distributions at the surface of joists # 4, # 8 and # 12 are shown in Figure 4-33 to Figure 4-35. As shown in the figures, the temperature at the surfaces of the three joists started to increase after 5 minutes of the test followed that by a slow increase until 50 minutes. Figure 4-33 shows the temperature distributions at the surface of joist # 8 which includes measurements of thermocouples at Tree # 2 of section A-A, section A1-A1, and section A2-A2. The figure also included the temperature of joist # 8 at Tree # 6 of section C-C. The location of the sections is provided in Figure 4-19 and the distribution of the thermocouples is shown in Figure 4-20. Tree # 2 includes thermocouples installed at the surface of the joist at distances of 10, 35, and 60 mm from the bottom of the joist. Tree # 6 includes thermocouples installed at the surface of the

joist at distances of 10 and 35 mm from the bottom of the joist. The temperature at the surface of the joist was the same for all thermocouples until 40 minutes of the test, followed by a slight rise at 10 mm. The maximum recorded temperature at the surface of the joist at 10 mm was 193 °C at section A-A, 191 °C at both sections A1-A1 and A2-A2, and 135 °C at section C-C. The maximum temperatures were recorded at 50 minutes which shows that the surface of joist # 8 at those sections did not reach the thermal decomposition temperature of 200 °C at 50 minutes. The finding also shows that the surface temperatures along joist # 8 were fairly equal at the middle and lower at the edge of the joist.

Figure 4-33 Temperature distributions at Tree #2 of sections A-A, A1-A1, and A2-A2 and at Tree # 6 of section C-C

Figure 4-34 shows the temperature distributions at the surface of joist # 4. The figure shows the temperature of Tree # 6 at sections C1-C1 and C2-C2 as located in Figure 4-19. As shown in Figure 4-34, the temperature at the surface of the joist of both sections was the same for all thermocouples until 40 minutes. This was followed by a slight rise of the temperature at 10 mm from the bottom of the joist. The maximum recorded temperature was 168 °C at 50 minutes which shows that the temperature of the surface of joist # 4 at the two sections did not reach the thermal decomposition temperature of 200 °C at 50 minutes.

Figure 4-34 Temperature distributions at Tree # 6 of sections C1-C1 and C2-C2

Figure 4-35 shows the temperature distributions at the surface of joist # 12. The figure shows the temperature of Tree # 7 at sections D1-D1 and D2-D2 as located in Figure 4-19. As shown in Figure 4-35, the temperature at the surface of the joist of both

sections was the same until 40 minutes followed that by a slight rise at section D1-D1. The maximum recorded temperature at 50 minutes was 175 °C at section D1-D1 and 154 °C at section D2-D2 indicating that the temperature of the surface of joist # 12 at both sections did not reach the thermal decomposition temperature of 200 °C by the end of the test.

Figure 4-35 Temperature distributions at Tree # 7 of sections D1-D1 and D2-D2

4.5.4 Temperature distributions at the floor cavity

Figure 4-36 to Figure 4-38 show the temperature distributions at Tree # 3 of section A-A, A1-A1, and A2-A2 as shown in Figure 4-19 and Figure 4-20. This tree is installed at half the distance between joist # 8 and # 9 and included thermocouples: between the gypsum board layers (G.B. Layers), at the bottom of the floor cavity on top of the surface of the base layer of gypsum board (Cavity at G.B.), at mid height of the

floor cavity (Cavity at 117.5 mm), at the top of the floor cavity under the sub-floor (Cavity at S.F.), and between sub-floor layers (S.F Layers). The temperature distribution at Tree # 3 of section A-A and the furnace average temperature are shown in Figure 4-36. The measurements of the thermocouple between the gypsum board layers are not shown in the figure due to thermocouple malfunction. The figure shows that the temperature at the bottom of the floor cavity started to increase after 4 minutes of the test and it reached 80 °C at 19 minutes. This was followed by a slower temperature increase as a result of the calcination of the base layer of gypsum board, as shown by the flattened curve, which was continued up to 38 minutes. When the free and chemically water were driven off, the temperature at the bottom of the floor cavity increased rapidly and reached around 281 °C at 50 minutes. The temperature at 117.5 mm and under the sub-floor was equal and slightly lower than the temperature at the bottom of the floor cavity up to 40 minutes. The maximum temperature recorded was 210 °C at 117.5 mm and 138 °C under the sub-floor at 50 minutes. The temperature between the sub-floor layers increased slowly and recorded a maximum temperature of 101 °C by the end of the test.

Figure 4-36 Temperature distributions at Tree # 3 of sections A-A

Figure 4-37 shows the furnace average temperature and the temperature distributions at Tree # 3 of section A1-A1. The figure shows that the temperature between the gypsum board layers started to increase at 1 minute and reached 80 °C at 4 minutes. At that time, the temperature increased slowly as a result of the calcination of the face layer which continued until 12 minutes. The completion of calcination was followed by a rapid increase of the temperature between the gypsum board layers reaching 619 °C at 47 minutes. The figure also shows that the temperature at the bottom of the floor cavity started to increase after 4 minutes until it reached 80 °C at 23 minutes when the calcination of the base layer started. At 35 minutes, the calcination was completed and the temperature at the bottom of the floor cavity increased rapidly and reached around 277 °C at 50 minutes. The temperature at 117.5 mm and under the sub-

floor was equal to the temperature at the bottom of the floor cavity up to 33 minutes. The maximum temperature recorded was 203 °C at 117.5 mm and 174 °C under the sub-floor at 50 minutes. The temperature between the sub-floor layers increased slowly and recorded a maximum temperature of 135 °C by the end of the test.

Figure 4-37 Temperature distributions at Tree # 3 of sections A1-A1

Figure 4-38 shows the temperature distributions at Tree # 3 of section A2-A2. The figure shows that the temperature of this section is similar to the temperature at Tree # 3 of section A1-A1 with slightly higher temperatures.

Figure 4-38 Temperature distributions at Tree # 3 of sections A2-A2

4.5.5 Summary for findings of the full-scale test exposed to standard fire

The temperatures between the gypsum board layers are shown in Figure 4-39. As shown in the figure, the temperatures of all sections are the same up to 13 minutes. The temperatures at the floor cavity were higher than the temperature at the joists. At the sections where the joints of the face and the base layers of gypsum board were located, sections B1-B1 and B2-B2, the impact of the joints was insignificant until 27 minutes when a rise of temperature occurred at both sections. As noticed in the figure, the temperature at the joint of the face layer (section B2-B2) was higher than the temperature at the joint of the base layer (section B1-B1). It was recorded in the test observations (Appendix A) that the fall-off of the first piece of the face layer occurred at 45 minutes and 37 seconds. The sudden increase in the temperature between the gypsum board layers at section A2-A2 represents this fall-off. However, a delay of 2 minutes can be noticed at

the other sections since the face layer of gypsum board fell-off piece by piece.

Figure 4-39 Temperature distributions between the gypsum board layers

The temperatures between the gypsum board and the joists are shown in Figure 4-40. As shown in the figure, the temperature at section A2-A2 was higher than the temperature at the other sections after few minutes from the ignition due to the higher furnace temperature at the south side. The temperatures at the other sections were fairly equal until 25 minutes. The temperature between the gypsum board and the joist at the base layer joint (section B1-B1) was higher than the temperature at the face layer joint (section B2-B2). The fall-off of the first piece of the base layer, as recorded in the test observations (Appendix A), occurred at 50 minutes and 3 seconds. The sudden increase in the temperature at most of the sections represents this fall-off. However, a delay of 2 minutes can be noticed at sections C1-C1 and C2-C2 since the gypsum board layer fell-off piece by piece.

Figure 4-40 Temperature distributions between the gypsum board and the joist

The test results discussed above showed that the temperature distributions of the floor were fairly equal (maximum variation of 50 °C) at the joists including the centre of the joist, at 10 mm from the surface of the joist and at the surface of the joists. The only temperatures that behave differently were at section A-A. At this section, the temperature at 10 mm from the bottom of the joist at both the centre of joist # 8 and at 10 mm from the surface of the joist 9 was slightly higher than the measured temperatures at the other joists. The temperature records also show that at the fall-off time of the first piece of the base layer of gypsum board (50 minutes and 3 seconds) only 10 mm from the bottom of the centre of joist # 8 at section A-A was charred. However, by the end of the test at 54 minutes all the joists were charred as shown in the test observations in Appendix A.

4.6 Full-scale Test Exposed to Non-standard Fire

The temperature distributions for the full-scale test exposed to non-standard fire are presented in this section. In comparison to the full-scale test exposed to standard fire, thermocouple trees were similar to the number and location shown in Figure 4-19 and Figure 4-20.

4.6.1 Temperature distributions at the centre of the joists

The temperature distributions at Tree #1 of section A-A and the average temperature of the furnace (F_{avg}) are shown in Figure 4-41. Temperatures at Tree # 1 represent the measurements of thermocouples installed, as shown in Figure 4-20, at different locations which include: between the gypsum board layers at the joist (G.B. Layers); at the interface between the base layer of gypsum board and the joist (G.B and joist); at the centre of joist # 8 at distances of 10, 35, 60, and 117.5 mm from the bottom of the joist; at the interface between the joist and first layer of sub-floor (Joist and S.F.).

As shown in Figure 4-41, the temperature between the gypsum board layers started to increase after 1 minute until it reached 80 °C in 3 minutes when the calcination of the face layer started. This was followed by a slower temperature increase as a result of calcination of the face layer, as shown by the flattened curve, which continued up to 9 minutes. When the calcination of the face layer was completed the temperature started to increase rapidly and reached 248 °C in 13 minutes followed by a sudden increase of temperature from 248 °C to 1112 °C one minute later. At that time, the test observations

indicated that the fall-off of the first piece of the face layer which caused this sudden increase in temperature. After that fall-off, the temperature remained quite close to the furnace average temperature until 20 minutes when the furnace was shut-off. The figure also shows that the temperature between the gypsum board and the joist at Tree # 1 of section A-A began to increase at approximately 2 minute after the test started reaching around 80 °C in about 10 minutes when the calcination of the base layer was started. The calcination of the base layer of gypsum board, as shown by the flattened curve, continued up to 18 minutes. Following the calcination of the base layer the temperature between the joist and the gypsum board increased rapidly and reached 356 °C at 26 minutes. A decay of the temperature can be seen in the figure after this time until it reached the joist temperature by the end of the test. As shown in the figure, the temperature between the gypsum board and the joist was higher than the temperature between the gypsum board layers after 27 minutes of the test. The reason was due to the early fall-off of the face layer that resulted in cooling of the temperature between the gypsum board layer as the furnace was shut-off which was affected by the average furnace temperature while the base layer was still in place until the end of the test and resulted in a higher temperature between the joist and the base layer that was affected by the temperature trapped in the floor during the test. The temperatures at the centre of joist # 8 at section A-A are also presented in Figure 4-41. The figure shows that the temperature at 10 mm of the centre of the joist was higher than the rest of the joist; however, the maximum temperature measured at the centre of the joist at the termination of the test was 130 °C which shows that the centre of joist # 8 at section A-A did not undergo thermal decomposition. The temperature between the joist and the sub-floor increased slowly and reached 65 °C by

the end of the test.

Figure 4-41 Temperature distributions at Tree # 1 of section A-A

Figure 4-42 shows the temperature distributions at Tree # 1 of section A1-A1. The location of section A1-A1 and the position of the thermocouples at Tree # 1 are shown in Figure 4-19 and Figure 4-20 respectively. The temperature of Tree # 1 at this section followed a similar trend as the temperature at Tree # 1 of section A-A. The temperature between the gypsum board layers started to increase after 1 minute. The calcination of the face layer at this section, as shown by the flattened curve lasted from 3 to 9 minutes. A sudden increase of temperature also occurred between 13 and 14 minutes and reached 1095 °C. The figure also shows that the temperature between the gypsum board and the joist at Tree # 1 of section A1-A1 began to increase approximately 2 minute after the test started. The calcination of the base layer of gypsum board, as shown by the flattened

curve, started at 7 minutes and continued up to 18 minutes. Following the calcination of the base layer the temperature between the joist and the gypsum board increased rapidly and reached 398 °C at 26 minutes. The temperatures at the centre of joist # 8 at section A1-A1 are presented in Figure 4-42. The maximum temperature measured at the centre of the joist at the termination of the test was 125 °C which shows that the centre of joist # 8 at section A1-A1 did not reach thermal decomposition of 200 °C. The temperature between the joist and the sub-floor increased slowly and reached 89 °C by the end of the test.

Figure 4-42 Temperature distributions at Tree # 1 of section A1-A1

The temperature distributions at Tree # 1 of section A2-A2 and the average temperature of the furnace are shown in Figure 4-43. The location of section A2-A2 and the distribution of the thermocouples at Tree # 1 are shown in Figure 4-19 and Figure 4-

20 respectively. The temperature between the joist and the gypsum board is not shown in Figure 4-43 due to thermocouple malfunction. The temperature curves of Tree # 1 at this section followed a similar trend of the temperature curves at Tree # 1 of section A-A.

Figure 4-43 Temperature distributions at Tree # 1 of section A2-A2

The temperature distributions at Tree # 5 of section C-C and the average temperature of the furnace are shown in Figure 4-44. The location of this section on the plan and the distribution of the thermocouples at Tree # 5 are shown in Figure 4-19 and - Figure 4-20 respectively. The temperatures between the joist and the gypsum board are not shown in Figure 4-44 due to thermocouple malfunction. During the test, the temperature at the centre of the joist at this section did not exceed 100 °C because the

location of this section was at the edge of the joist close to the perimeter of the floor. The maximum recorded temperature at 10 mm was 94 °C at 20 minutes.

Figure 4-44 Temperature distributions at Tree # 5 of section C-C

The furnace average temperature (Favg) and the temperature distributions of Tree # 5 at section C1-C1 are shown in Figure 4-45. Thermocouples installed at Tree # 5 of section C1-C1 were similar to those installed at section C-C which are shown in Figure 4-20, however, section C1-C1 was located on joist # 4 as shown in Figure 4-19. The temperature between the gypsum board and the joist started to increase after 3 minutes until it reached 80 °C at 10 minutes when the calcination of the base layer of gypsum board started. The calcination of the base layer continued up to 19 minutes when of the temperature as shown in the figure started to increase rapidly. The maximum temperature recorded was 210 °C at 28 minutes. The temperature distribution at the centre of the joist

at various distances from the bottom of the joist are shown in Figure 4-45. The figure shows that the temperature at 10 mm was slightly higher than the rest of the joist. The maximum temperature recorded at the centre of the joist was 126 °C at 40 minutes indicating that this section did not reach the thermal decomposition temperature of 200 °C by the end of the test.

Figure 4-45 Temperature distributions at Tree # 5 of section C1-C1

Thermocouples installed at Tree # 5 of section C-C were similar to those installed at section C2-C2 as shown in Figure 4-20. The location of section C2-C2 is shown in Figure 4-19. The furnace average temperature (Favg) and the temperature distributions of Tree # 5 at section C2-C2 are shown in Figure 4-46. The temperature between the joist and the gypsum board is not shown in the figure due to thermocouple failure. The figure shows the temperature distribution of the centre of joist # 4 at section C2-C2. The

temperature at 10 mm of the centre of the joist was slightly higher than the temperature at 35 mm and above. The maximum temperature recorded was 142 °C at 32 minutes which shows that the centre of joist # 4 at this section did not reach the thermal decomposition temperature of 200 °C by the end of the test.

Figure 4-46 Temperature distributions at Tree # 5 of section C2-C2

Figure 4-47 shows the temperature distributions at Tree # 8 of section D1-D1 installed at the centre of joist # 12. Thermocouples location installed at Tree # 8 are shown in Figure 4-20. As shown in Figure 4-47, the temperature between the gypsum board and the joist started to increase after 3 minutes and continued to increase slowly until it reached 80 °C around 7 minutes. The calcination of the base layer, as shown by the flattened curve, continued up to 20 minutes. At that time, the temperature started to increase rapidly and reached a maximum of 196 °C at 28 minutes. The temperature at the

centre of the joist as shown in Figure 4-47 was higher at 10 mm. The maximum temperature measured at the centre of joist # 12 at this section was 114 °C at 42 minutes indicating that the centre of joist did not reach the thermal decomposition temperature of 200 °C by the end of the test.

Figure 4-47 Temperature distributions at Tree # 8 of section D1-D1

The furnace average temperature (Favg) and the temperature distributions of Tree # 8 at section D2-D2 are shown in Figure 4-48. Thermocouples installed at Tree # 8 of section D2-D2 were similar to those installed at section D1-D1 which are shown in Figure 4-20. As shown in Figure 4-48, the temperature between the gypsum board and the joist started to increase after 4 minutes of the test and continued to increase slowly until the end of the test. The maximum temperature measured between the joist and gypsum board was 200 °C. The thermocouple at 10 mm from the bottom of the joist

failed to record the temperature at this section. The maximum temperature measured at 35 mm and above of the centre of joist # 12 was 90 °C at 49 minutes.

Figure 4-48 Temperature distributions at Tree # 8 of section D2-D2

The temperatures at the joints of the gypsum board layers were examined through two sections, B1-B1 and B2-B2. As shown in Figure 4-19, section B1-B1 was located at the intersection of the base layer joint and joist # 8 (centre joist) while section B2-B2 was located at the intersection of the face layer joint and joist # 8. Thermocouples, as shown in Figure 4-20, were installed for both sections between the gypsum board layers and between the joist and the gypsum board. Figure 4-49 shows that the temperature between the gypsum board layers at both sections started to increase after 1 minute of the test until reached 80 °C around 3 minutes. At that time the calcination of the face layer started causing a slower temperature increase. The calcination of the face layer continued, as

shown by the flattened curve, up to 8 minutes. When the calcination of the face layer was completed, the temperature between the gypsum board increased rapidly and reached 288 °C at section B1-B1 and 332 °C at section B2-B2 in 13 minutes. A sudden increase of temperature occurred at 13 minutes. The temperature recorded at 14 minutes was 1120 °C at section B1-B1 and 1080 °C at section B2-B2. The temperature followed a similar behaviour as the temperature between gypsum board layers discussed for Tree # 1 of section A-A. The figure also shows that the temperature between the joist and the gypsum board started to increase after 2 minutes until it reached 80 °C at 8 minutes when the calcination of the base layer started. This was followed by a slower increase of temperature until the completion of the calcination of the base layer at 17 minutes. The maximum measured temperature between the joist and the base layer was 442 °C at 21 minutes at section B1-B1 and 321 °C at 27 minutes at section B2-B2.

Figure 4-49 Temperature distributions at Sections B1-B1 and B2-B2

4.6.2 Temperature distributions 10 mm from the surface of joist # 9

Figure 4-50 to Figure 4-52 show the temperature at Tree # 4 of sections A-A, A1-A1, and A2-A2 as located in Figure 4-19. Tree # 4 includes thermocouples installed as shown in Figure 4-20 at 10 mm from the surface of joist # 9 at distances of 10, 35, 60, and 117.5 mm from the bottom of the joist. Figure 4-50 to Figure 4-52 show that the temperatures started to increase after 1 minute for sections A-A and A1-A1 and after 5 minutes for section A2-A2 and followed by a slight increase of temperature. It was also noticed that for all the three sections the temperature at distance of 10 mm from the bottom of the joist was slightly higher than the rest of the joist. Figure 4-50 shows that the maximum temperature recorded at section A-A was 150 °C at 22 minutes. The maximum measured temperature at 35 mm and above was 107 °C by the end of the test.

Figure 4-50 Temperature distributions at Tree # 4 of section A-A

As shown in Figure 4-51, the maximum temperature recorded at 10 mm from the bottom of the joist of section A1-A1 was 180 °C at 32 minutes. While for the rest of the joist, the maximum measured temperature was 117 °C by the end of the test.

Figure 4-52 shows that the maximum temperature recorded at 10 mm from the bottom of the joist of section A2-A2 was 114 °C by the end of the test. While for the rest of the joist, the maximum measured temperature was 102 °C by the end of the test. This shows that at 10 mm from the surface of joist # 9, no thermal decomposition occurred at the three sections.

Figure 4-51 Temperature distributions at Tree # 4 of section A1-A1

Figure 4-52 Temperature distributions at Tree # 4 of section A2-A2

4.6.3 Temperature distributions at the surface of the joists

The temperature distributions at the surface of the joist # 4, # 8 and # 12 are shown in Figure 4-53 to Figure 4-55. As shown in the figures, the temperature at the surfaces of the three joists started to increase after 3 minutes of the test followed by a slow increase until 20 minutes. It was also noticed for all the sections that the maximum temperature measured at the surface of joists did not reach the thermal decomposition temperature of 200 °C.

Figure 4-53 shows the temperature distributions at the surface of joist # 8 which included Tree # 2 of section A-A, section A1-A1, and section A2-A2. The figure also shows the temperature of joist # 8 at Tree # 6 of section C-C. The location of the sections is provided in Figure 4-19 and the distribution of the thermocouples is shown in Figure 4-

20. Figure 4-53 shows that the temperature at the surface of the joist was the same until the furnace was shut-off at 20 minutes. The surface temperatures at the sections after 20 minutes show a large variation with the highest temperature at section A1-A1 and the lowest at the edge of the joist at section C-C.

Figure 4-53 Temperature distributions at Tree # 2 of sections A-A, A1-A1, and A2-A2 and at Tree # 6 of section C-C

Figure 4-54 shows the temperature distributions at the surface of joist # 4. The figure shows the temperature of Tree # 6 at sections C1-C1 and C2-C2 as located in Figure 4-19. Thermocouples distribution of sections C1-C1 and C2-C2 were similar to the thermocouple distributions of section C-C which are shown in Figure 4-20. The measurements of the temperature at 10 mm of section C1-C1 are not shown in Figure 4-

54 due to thermocouple failure. As shown in Figure 4-54, the temperature at the surface of the joist of both sections was almost the same until 22 minutes. At that time, the temperature at 35 mm of section C2-C2 was slightly lower until the end of the test.

Figure 4-54 Temperature distributions at Tree # 6 of sections C1-C1 and C2-C2

Figure 4-55 shows the temperature distributions at the surface of joist # 12. The figure shows the temperature of Tree # 7 at sections D1-D1 and D2-D2 as located in Figure 4-19. Thermocouple distributions of sections D1-D1 and D2-D2 was similar to the thermocouples distributions of section D-D which is shown in Figure 4-20. As shown in Figure 4-55, the temperatures at the surface of the joist of both sections were almost equal until 20 minutes. After 20 minutes, the temperature at section D2-D2 was higher until the end of the test.

Figure 4-55 Temperature distributions at Tree # 7 of sections D1- D 1 and D 2- D2

4.6.4 Temperature distributions at the floor cavity

Figure 4-56 to Figure 4-58 show the temperature distributions at Tree # 3 of section A-A, A1-A1, and A2-A2. Tree # 3 as shown in Figure 4-20 was installed at half the distance between joist # 8 and # 9 and included thermocouples between the gypsum board layers (G.B. Layers), at the bottom of the floor cavity on the surface of the gypsum board (Cavity at G.B.), at mid height of the floor cavity (Cavity at 117.5 mm), at the top of the floor cavity under the sub-floor (Cavity at S.F.). The thermocouples between the sub-floor layers for this test were omitted. The temperature distribution at Tree # 3 of section A-A is shown in Figure 4-56. The measurements of the thermocouple at mid height of the floor cavity are not shown in the figure due to thermocouple failure. The figure shows that the temperature between gypsum board layers started to increase at 1

minute and reached 80 °C at around 2 minutes. At that time, the temperature started to increase slowly as a result of the calcination of the face layer which continued until 9 minutes. The completion of the calcination was followed by a rapid increase of temperature between the gypsum board layers reaching 304°C at 13 minutes. A sudden increase of temperature occurred reaching 1102°C at 14 minutes as a result of the gypsum board fall-off. After that, the temperature between the gypsum board layers behaved similar to the temperature at Tree # 1 of section A-A. The figure shows that the temperature at the bottom of the floor cavity started to increase after 2 minutes of the test until it reached 80°C at 10 minutes when the calcination started. Calcination of the base layer of gypsum board, as shown by the flattened curve, continued up to 18 minutes and then the temperature at the bottom of the floor cavity increased rapidly and reached around 244°C at 24 minutes. The temperature under the sub-floor was lower than the temperature at the bottom of the floor cavity after 17 minutes. The maximum recorded temperature at the top of the floor cavity was 147°C at 29 minutes.

Figure 4-56 Temperature distributions at Tree # 3 of section A-A

Figure 4-57 shows that the temperature distribution at Tree # 3 of section A1-A1 was similar to Tree # 3 of section A-A. The figure shows that the temperature between gypsum board layers started to increase at 1 minute and reached 80°C in around 3 minutes when the calcination of the face layer began. As the calcination of the face layer was completed at 7 minutes, the temperature increased rapidly and reached 314°C at 13 minutes. A sudden increase of the temperature followed reaching 1098°C at 14 minutes. The temperature of the bottom of the floor cavity started to increase after 2 minutes. The calcination of the base layer started at 10 minutes and continued up to 16 minutes. The maximum recorded temperature between the joist and the gypsum board was 290°C at 24 minutes. The maximum temperatures measured at the middle of the floor cavity and under the sub-floor were 198°C at 24 minutes and 169°C at 25 minutes respectively.

Figure 4-57 Temperature distributions at Tree # 3 of section A1-A1

Figure 4-58 shows the temperature distribution at Tree # 3 of section A2-A2. The temperature between gypsum board layers started to increase at 1 minute and reached 80°C in around 2 minutes when the calcination of the face layer began. As the calcination of the face layer was completed at 6 minutes, the temperature increased rapidly and reached 251°C at 13 minutes. A sudden increase of temperature followed reaching 1098°C at 14 minutes followed by a similar behaviour as discussed for Tree # 1 of section A-A. The temperature of the bottom of the floor cavity started to increase after 2 minutes with calcination of the base layer starting at 9 minutes and continued to 16 minutes. The maximum measured temperature at the gypsum board surface was 255°C at 24 minutes. The maximum temperatures measured at the middle of the floor cavity and under the sub-floor were 146°C at 24 minutes and 130°C at 25 minutes.

Figure 4-58 Temperature distributions at Tree # 3 of section A2-A2

4.6.5 Summary of findings for the full-scale test exposed to non-standard fire

Temperatures between the gypsum board layers for sections were fairly similar, as shown in Figure 4-59. The maximum temperature difference did not exceed 100 °C with the highest temperatures at the joints of the face layer and base layer and the lowest at section A1-A1.

Figure 4-59 Temperatures between the gypsum board layers

Unlike the temperature between the gypsum board layers, the temperature between the gypsum board and the joist, as shown in Figure 4-60, varied significantly from one section to another. The highest temperature was recorded at the joint of the base layer. The figure also shows that the joists never reached the thermal decomposition temperature of 200 °C.

Figure 4-60 Temperatures between the gypsum board and the joists

4.7 Full-scale Test: Standard vs Non-Standard Exposure

Figure 4-61 shows a comparison of the average furnace temperatures for both full-scale tests using the standard and non-standard fire exposure. The average temperature of the furnace exposed to the standard fire followed a slow growth rate, which reached 844°C by 30 minutes. The average furnace temperature during the test using a non-standard time-temperature curve began with a fast growth, which reached 851°C in 5 minutes. It then continued to increase slowly and reached temperatures over 1000°C. The furnace was shut-off at 20 minutes. This variation in exposure had a significant impact on the calcination of the gypsum board layers and the thermal decomposition of the wood joists.

Figure 4-61 Average furnace temperatures for full-scale tests

The difference in temperature between the gypsum board layers for both tests was insignificant for the first 5 minutes, although the average furnace temperature at that time was 499 °C for the test exposed to standard fire and 851 °C for the test exposed to non-standard fire. Table 4-3 presents the time of calcination of the face layer and base layer of gypsum board for both tests at different locations in the floor.

Table 4-3: Calcination time of gypsum board layers for both full-scale tests

Section	Location	Standard Exposure		Non-standard Exposure	
		Face Layer (min)	Base Layer (min)	Face Layer (min)	Base Layer (min)
A-A	Joist # 8	***	12-26	3-9	10-18
	Floor cavity	***	19-38	2-9	10-18
A1-A1	Joist # 8	4-12	7-12	3-9	7-18
	Floor cavity	4-12	23-35	3-7	10-16
A2-A2	Joist # 8	4-12	14-35	2-4	***
	Floor cavity	4-12	19-40	2-6	9-16
B1-B1	Joist # 8	4-12	12-23	3-8	8-17
B2-B2	Joist # 8	4-12	12-31	3-8	8-17
C-C	Joist # 8	***	13-40	***	***
C1-C1	Joist # 4	***	13-35	***	10-19
C2-C2	Joist # 4	***	16-41	***	***
D1-D1	Joist # 12	***	12-43	***	7-20
D2-D2	Joist # 12	***	14-40	***	***

*** No measurements

Three locations at different depths of the joists, at centre of the joist; at 10 mm depth from the surface of the joist; and at surface of the joist, were studied to investigate the effect of the standard and the non-standard exposure on the thermal decomposition of the wood joists. At 50 minutes of the standard test, charring occurred only in the first 10 mm from the bottom of the joist at the section located at the centre of the floor. The rest of the joists were charred right after the fall-off of the first piece of the base layer which occurred at 50 minutes and 3 seconds according to the observation (Appendix A) of the test. In contrast, none of the joists of the non-standard test were charred by the time of termination of the test. The maximum temperature measured at the floor cavity was 277 °C at the end of the standard test and 290 °C at 24 minutes for the non-standard test. The average temperature of the five thermocouples on the unexposed side did not vary by

much for the two tests. At the termination of the test, the maximum recorded temperatures on the unexposed side were 40 °C and 55 °C for the tests exposed to standard and non-standard fire respectively.

4.8 Standard Exposure: Intermediate-scale vs Full-scale

Based on the discussion of the temperature distributions provided above, the temperature at four locations of the intermediate- and full-scale floors were compared to determine the effect of the furnace size: between the gypsum board layers, between the joist and the gypsum board, 10 mm from the bottom of the centre of the joist and at the floor cavity. The temperature presented for the full-scale test in this section was at section A-A and A2-A2.

Figure 4-62 shows the temperature distributions between the gypsum board layers at Tree # 1 for both section A2-A2 of the full-scale test and section A-A of the intermediate-scale test. The figure shows that the temperature distributions were similar during the tests except between 15 and 23 minutes. At that time, the temperature of the full-scale test was higher which followed the calcination of the face layer. A considerable high temperature can be shown in the figure for the full-scale test following the fall-off of the first piece of the face layer which occurred at around 45 minutes. The trend of the temperature curve of the intermediate-scale tests shows that that face layer of gypsum board did not fall-off during the test.

Figure 4-62 Temperature distributions between the gypsum board layers, section A2-A2 of the full-scale test and section A-A of the intermediated-scale test

The temperature distributions between the joist and the base layer of gypsum board for both tests are shown in Figure 4-63. The temperature distributions shown in the figure were measured at Tree # 1 of both section A2-A2 of the full-scale test and section A-A of the intermediate-scale test. The figure shows that the maximum temperature during the full-scale test was higher after 25 minutes from ignition. The sudden increase of the temperature in the figure represents the fall-off time of the base layer for the full-scale test which occurred around 50 minutes. The temperature curve of the intermediate-scale test indicates that the gypsum board did not fall-off during the test.

Figure 4-63 Temperature distributions between the gypsum board and the joist, section A2-A2 of the full-scale test and section A-A of the intermediated-scale test

Figure 4-64 shows the temperature at 10 mm from the bottom of the centre of the joist. The temperature distributions were obtained from the thermocouples measurements installed at Tree # 1 of both section A2-A2 of the full-scale test and section A-A of the intermediate-scale test. Both figures show that the intermediate-scale furnace can fairly replicate the full-scale furnace until 50 minutes of the tests. At that time the temperature of the full-scale test was higher as a result of the fall-off of the first piece of the base layer.

Figure 4-64 Temperature distributions at the centre of the joist, section A2-A2 of the full-scale test and section A-A of the intermediated-scale test

A comparison for the temperature at the bottom of the floor cavity for both tests is shown in Figure 4-65. The temperature distributions shown in the figure included the temperature distributions at Tree # 3 of both section A2-A2 of the full-scale test and section A-A of the intermediate-scale test. The temperature distributions at the centre of the joist were similar until 40 minutes following that higher temperature of the intermediate-scale test until the fall-of the base layer for the full-scale test.

Figure 4-65 Temperature distributions at the floor cavity, section A2-A2 of the full-scale test and section A-A of the intermediated-scale test

The comparison of the temperature distributions shown in Figure 4-66 is similar to the comparison of the temperature distributions discussed in Figure 4-63, however, the measurements of temperatures considered for the full-scale test was at Tree # 1 of section A-A. Figure 4-66 shows that the temperature distributions of both the intermediate- and the full-scale test were similar until 25 minutes. After that time, the temperatures of the full-scale test were higher as a result of the early calcination of the base layer (compared to the calcination of the base layer for the intermediate-scale test). This finding might be a result of the effect of loading the full-scale assembly since the intermediate-scale test, as mentioned earlier, was unloaded.

Figure 4-66 Temperature distributions between the gypsum board and the joist, section A-A of the full-scale test and section A-A of the intermediated-scale test

A similar comparison using the measurements of thermocouples at Tree # 1 of section A-A of the full-scale test is shown in Figure 4-67 for the temperature distributions at 10 mm from the bottom of the centre of the joist. The figure shows that the temperature distributions of the full-scale test at section A-A were higher than the temperature distributions of the intermediated-scale test.

The comparisons of the temperature distributions between the joist and gypsum board and at 10 mm from the bottom of the centre of the joist provided in Figure 4-66 and Figure 4-67 showed that the temperature distributions of the full-scale test at section A-A were higher than the temperature distributions of the intermediate-scale test. However, the temperature distributions at the bottom of the floor cavity using thermocouples

measurements at Tree # 3 of section A-A shown in Figure 4-68 did not vary from the comparison provided in Figure 4-65.

Figure 4-67 Temperature distributions at the centre of the joist, section A-A of the full-scale test and section A-A of the intermediated-scale test

Figure 4-68 Temperature distributions at the floor cavity, section A-A of the full-scale test and section A-A of the intermediated-scale test

The discussion above shows that the temperature distributions of the intermediate-scale test compared well with section A2-A2 of the full-scale test. The temperature distributions of the full-scale test at the centre of the floor, however, were higher than the temperature distributions of the intermediated-scale floor. In addition, the results of the intermediate-scale test did not predict well the duration of the test or the fall-off of gypsum board. These results indicate that the intermediate-scale tests can be used to provide an initial assessment of the behaviour of the floors subjected to standard fire. It is, however, necessary to use the full-scale tests for the purpose of evaluating the fire resistance.

5. GYPSUM BOARD FALL-OFF

5.1 General

To facilitate the Canadian construction industry move to performance-based codes, the development of validated fire resistance models becomes essential. Type X gypsum board is typically used to protect the timber or steel frames of floor assemblies from fire exposure. Those boards can provide up to 90% of protection, therefore, understanding gypsum board performance in protecting the assembly is an essential parameter in producing more realistic fire resistance model. One of the important parameters that affect the performance of the assemblies is the “fall-off” of the gypsum board during fires.

This section of the report investigates gypsum board fall-off using eighty full-scale fire resistance floor tests protected by Type X gypsum board which have been conducted at the National Research Council of Canada (NRCC). Details of these tests were presented in Sultan et al [8] (assemblies from FF-01A to FF-29) and Sultan et al [9] (assemblies from FF-30 to FF-82). Four tests (NRC-01, FF-01, FF-03, and FF-05) were omitted from this report due to unavailability of their videotapes. FF-39 was also not included due to malfunction in the data acquisition system. Floor assemblies, 4840 mm long by 3950 mm wide, were constructed using wood joists, wood-I-joists, C-steel joists, and wood truss. One composite steel deck/concrete assembly was also conducted. Details of the assemblies can be found in references [8] and [9]. A typical layout of the floors is

shown in Figure 5-1. The assemblies were constructed so that the impact of the following parameters on the performance of the assemblies could be investigated:

- Number of gypsum board layers;
- Resilient channels installation and spacing;
- Cavity insulation installation and type;
- Sub-floor topping type and Number of layers;
- Frame type;
- Frame spacing;
- Frame depth;
- Wood-I-joist type;
- Wood truss type;
- Method of fastening gypsum board layers;
- Applied load;
- Reproducibility of the test.

As a result of the variation in the above parameters, the fall-off of gypsum board layers varied from one assembly to another. Therefore, a study of the effect of those parameters on the gypsum board fall-off is an important part in understanding the behaviour of gypsum board when exposed to fire.

The investigation of the gypsum board fall-off is achieved by:

- Observation of the eighty full-scale fire resistance tests using videotapes recorded by the East and West view cameras during each test;
- Tabulating data for the fall-off time of gypsum board as shown in Table 5-1;
- Analyze the data summarized in Table 5-1 to determine the impact of the various parameters on gypsum board fall-off time, and to obtain a relation between the fire resistance of the assemblies and the fall-off time of gypsum board;
- Using the results of this analysis to develop criteria for gypsum board fall-off time.

(Dimensions are in millimetres)

Figure 5-1 Typical floor plan (wood joist)

5.2 Tests observations

Two videotapes were observed for each test which had been recorded at the NRCC facilities using the west and east cameras. The position of each camera was adjusted to enable viewing, as much as possible, of the floor during the test. During the first two minutes of the tests, the paper covering the exposed side of the gypsum board was observed burning. The fall-off of the gypsum compound, which covers the joints and the screws, observed around the first twelve minutes. Gypsum board layers calcinated, shrank and fell-off at different times. Different performance was observed for the various types of insulation. Glass fibre batts were melted right after exposure to fire. Rock fibre batts fell-off with a considerable delay when exposed to fire. In contrast, cellulose fibre insulation stayed almost until the last minute of the test. The data of the time to fall-off of the gypsum board layers presented in Table 5-1 are based on the observation of the fall-off of the first piece and last piece of gypsum board panels for assemblies with one layer of gypsum board and also the fall-off of the first piece and last piece of the face layer and the base layer of gypsum board for assemblies with two layers of gypsum board. For some tests, and especially the tests of the non-insulated assemblies or assemblies insulated with glass fibre, flames covered the view of the assemblies; therefore, it prevented the observation of the last piece fall-off. For those tests, the end of the test was assumed to be the fall-off of the last piece.

The results of the eighty full-scale fire resistance floor tests as presented in Sultan et al [8] and Sultan et al [9] are summarized in Table 5-1. The fall-off time of the gypsum board for the assemblies is also presented in this table.

Table S-1: Parameters and Results for test assemblies

Assembly Number	Joist			Ceiling Finish			Sub Floor			Cavity Insulation			Load (N/m ²)	Fire Resistance (min:s)	Mode of failure	Gypsum Board Fall-Off (min:sec)			
	Type	Depth (mm)	Spacing (mm)	Layer Number	Thickness (mm)	Type	Layer Number	Thickness (mm)	Type	Thickness (mm)	Location	Spacing (mm)				First Piece	Last Piece	Face Layer	Base Layer
FF-01A	WJ	235	406	1	12.7	X	1	Ply	15.9	***	***	***	3830	30	Flame	---	---	24.22	31.20
FF-02A	WJ	235	406	1	12.7	X	1	Ply	15.9	***	***	***	3830	45	Flame	---	---	42.07	47.20
FF-03A	WJ	235	406	2	12.7	X	1	Ply	15.9	***	***	***	3830	80	Flame	49.42	57.30	77.43	82.20
FF-04A	WJ	235	406	2	12.7	X	1	Ply	15.9	R	90	B	406	72	Flame	48.19	53.15	56.50	63.43
FF-06	WJ	235	406	2	12.7	X	1	Ply	15.9	G	90	B	406	67	Flame	44.43	48.50	57.30	62.45
FF-07	WJ	235	406	1	12.7	X	1	Ply	15.9	C1	93 ³ /86 ^b		406	59	Flame	---	---	34.00	38.22
FF-08	WJ	235	406	1	12.7	X	1	Ply	15.9	G	90	B	406	36	Flame	---	---	26.14	31.00
FF-09	WJ	235	406	1	12.7	X	1	Ply	15.9	R	90	B	406	60	Flame	---	---	26.35	32.11
FF-10	WIJ ²	240	406	2	12.7	X	1	Ply	15.9	***	***	***	406	69	Struct	47.53	57.59	68.36	70.45
FF-11	WIJ ⁵	240	406	2	12.7	X	1	Ply	15.9	***	***	***	406	74	Struct	49.47	65.15	73.46	76.45
FF-12	WIJ ⁴	240	406	2	12.7	X	1	Ply	15.9	***	***	***	406	80	Flame	54.24	62.43	78.55	82.25
FF-13	WIJ ²	240	406	2	12.7	X	1	Ply	15.9	***	***	***	406	72	Struct	56.06	70.00	69.18	74.20
FF-14	WIJ ²	240	406	1	12.7	X	1	Ply	15.9	***	***	***	406	42	Struct	---	---	40.53	44.00
FF-15	WIJ ²	240	406	2	12.7	X	1	Ply	15.9	G	90	B	406	64	Struct	53.16	59.33	56.50	66.00
FF-16	WIJ ²	240	406	1	12.7	X	1	Ply	15.9	R	90	B	406	46	Struct	---	---	36.36	43.07
NRC-02	WIJ ²	240	406	2	12.7	X	1	Ply	15.9	R	90	B	406	77	Struct	59.28	66.31	67.04	75.18
FF-17	WIJ ²	240	610	2	12.7	X	1	Ply	19	G	90	B	406	75	Struct	59.35	69.24	69.04	74.50
FF-18	WIJ ²	240	610	2	12.7	X	1	Ply	18	G	90	B	406	74	Flame	60.00	65.16	68.16	70.20
FF-19	WIJ ²	240	406	1	12.7	X	1	Ply	15.9	C1	88 ³ /102 ^b		406	52	Struct	---	---	45.10	46.53
FF-20	WIJ ²	240	610	2	12.7	X	1	Ply	19	G	90	B	610	65	Struct	55.41	60.00	59.38	62.01
FF-22	SJ	203	406	2	12.7	X	1	Ply	15.9	***	***	***	406	74.3	Struct	66.26	73.19	73.09	74.00
FF-23	SJ	203	406	2	12.7	X	1	Ply	15.9	G	90	B	406	68	Struct	59.23	64.06	63.26	68.40
FF-24	SJ	203	610	2	12.7	X	1	Ply	15.9	G	90	B	406	69	Struct	59.48	62.06	65.04	67.23
FF-25	SJ	203	406	1	12.7	X	1	Ply	15.9	R	90	B	406	46	Struct	---	---	35.50	43.17
FF-26	SnCon	---	---	2	12.7	X	1	---	---	***	***	***	406	105	Struct	52.52	72.14	74.06	81.48
FF-27	SJ	203	406	2	12.7	X	1	Ply/Con	15.9/38	G	90	B	406	60	Struct	49.26	55.24	53.22	58.05
FF-28	WJ	235	406	2	12.7	X	1	Ply	15.9	***	***	***	406	69	Struct	43.49	60.58	67.09	68.55
FF-29	WJ	235	406	2	12.7	X	1	Ply	15.9	G	90	B	406	69	Struct	45.13	52.54	59.01	62.12
FF-30	WJ	235	406	1	12.7	X	1	Ply	15.9	***	***	***	406	40.49	Struct	---	---	40.43	43.00
FF-31	WJ	235	406	2	12.7	X	1	Ply	15.9	***	***	***	---	67.1	Struct	56.06	61.1	65.32	67.12
FF-32	WJ	184	406	2	12.7	X	1	Ply	15.9	G	89	B	406	67.15	Struct	53.08	57.08	60.10	63.30

Assembly Number	Joist			Ceiling Finish			Sub Floor			Cavity Insulation			Load (N/m ²)	Fire Resistance (min.s)	Mode of failure	Gypsum Board Fall-Off (min. sec)			
	Type	Depth (mm)	Spacing (mm)	Layer Number	Thickness (mm)	Type	Layer Number	Thickness (mm)	Type	Thickness (mm)	Location	Spacing (mm)				First Piece	Last Piece	Face Layer	Base Layer
FF-33	WJ	235	406	1	12.7	X	1	15.9	***	***	***	203	5123	39.55	Struct	---	---	39.35	42.00
FF-34	WJ	235	406	1	15.9	X	1	15.9	R	89	B	203	5075	54.11	Struct	---	---	37.19	45.26
FF-35	WJ	235	406	2	12.7	X	---	15.9/25.4	G	89	B	406	4644	68.27	Struct	53.14	57.50	60.44	64.00
FF-36	WJ	235	406	1	15.9	X	2	15.9	R	178	B	406	4980	58.49	Struct	---	---	31.36	41.34
FF-37	SJ	203	406	1	15.9	X	2	15.9	***	***	***	406	3366	38.49	Struct	---	---	36.30	39.13
FF-38	SJ	203	406	1	15.9	X	2	15.9	R	178	B	406	3318	53.38	Struct	---	---	26.41	38.43
FF-40	SJ	203	406	2	12.7	X	---	51	***	***	***	406	2351	75	Struct	60.39	76.55	72.35	79.12
FF-41	WT ¹	305	406	2	12.7	X	1	15.9	***	***	***	406	5602	69.01	Struct	57.43	66.46	68.12	71.00
FF-42	WT ¹	305	406	2	12.7	X	1	15.9	G	89	B	406	5602	65.41	Struct	53.49	59.35	60.55	65.32
FF-43	SJ	203	406	2	12.7	X	---	51	G	89	B	406	2341	68.25	Struct	54.28	59.41	60.10	66.11
FF-44	SJ	203	406	2	12.7	X	---	51	G	89	B	610	2341	61	Struct	52.32	54.35	53.30	59.15
FF-45	WJ ¹	241	406	1	15.9	X	1	15.9	R	178	B	406	5315	39.31	Struct	---	---	29.58	37.58
FF-46	WT ²	305	406	2	12.7	X	1	15.9	G	89	B	406	4213	67.36	Struct	55.19	59.45	61.41	67.40
FF-47	WT ¹	305	406	2	12.7	X	---	15.9/38	G	89	B	406	5123	72	Struct	52.10	57.02	60.02	63.12
FF-48	WT ¹	305	610	2	12.7	X	1	15.9	G	89	B	406	3783	68.18	Struct	53.50	59.02	62.23	65.54
FF-49	WJ	235	406	1	15.9	X	2	15.9	C1	55 ⁵ /79 ^b	T	406	4980	54.13	Struct	---	---	37.31	44.18
FF-50	SJ	203	406	1	15.9	X	2	15.9	C1	91 ³ /112 ^b	T	406	3285	63.47	Struct	---	---	34.17	45.00
FF-51	SJ	203	406	2	12.7	X	1	15.9	***	***	***	---	3342	65.55	Flame	51.16	61.29	66.39	68.45
FF-52	SJ	203	610	2	12.7	X	1	19	G	89	B	610	2097	52.3	Struct	42.17	49.50	50.14	51.41
FF-53	SJ	203	406	2	12.7	X	---	51	R	89	B	406	2341	70	Struct	51.06	57.17	57.46	64.53
FF-54	SJ	203	610	2	12.7	X	---	51	***	***	***	---	1130	66	Struct	37.38	56.18	60.37	66.04
FF-55	WJ ²	241	610	2	12.7	X	1	19	G	89	B	406	3447	60.59	Struct	48.36	57.28	56.08	60.00
FF-56	WT ³	406	406	2	12.7	X	1	15.9	***	***	***	406	5650	65.05	Struct	54.35	62.08	61.51	64.24
FF-57	WJ ⁶	241	610	1	15.9	X	2	15.9	R	89	B	305	4118	50.17	Struct	---	---	39.08	43.41
FF-58	WT ⁴	330	406	2	12.7	X	1	15.9	G	89	B	406	6847	63.37	Struct	48.50	56.19	54.42	63.11
FF-59	WT ¹	305	610	2	12.7	X	1	19	G	89	B	610	3783	54.35	Struct	40.25	49.02	48.01	52.31
FF-60	WT ¹	305	406	2	12.7	X	1	15.9	***	***	***	---	5602	61.03	Struct	43.15	58.45	59.07	60.55
FF-61	WJ ²	241	406	2	12.7	X	---	15.9/38	G	89	B	406	4596	66.58	Struct	49.39	56.24	57.14	61.46
FF-62	SJ	203	610	2	12.7	X	1	19	***	***	***	---	2123	54.59	Struct	46.15	55.31	54.07	56.00
FF-63	WT ⁵	286	406	2	12.7	X	1	15.9	G	89	B	406	3543	64.04	Struct	51.28	57.23	57.07	62.34
FF-64	WJ	235	610	2	12.7	X	1	19	***	***	***	610	3256	58.55	Struct	47.08	55.23	54.55	61.30

Assembly Number	Joist			Ceiling Finish			Sub Floor			Cavity Insulation			Load (N/m ²)	Fire Resistance (min.s)	Mode of failure	Gypsum Board Fall-Off (min. sec)						
	Type	Depth (mm)	Spacing (mm)	Layer Number	Thickness (mm)	Type	Layer Number	Type	Thickness (mm)	Type	Thickness (mm)	Location				Spacing (mm)	Face Layer			Base Layer		
																	First Piece	Last Piece	First Piece	Last Piece	First Piece	Last Piece
FF-65	SJ	203	610	2	12.7	X	1	Ply	19	C3	94 ^a /100 ^b	T	610	2092	Struct	48.45	52.08	52.39	54.26			
FF-66	WJ	235	406	1	15.9	X	1	Ply	15.9	R	89	B	406	5219	Struct	---	---	36.18	43.18			
FF-67	WJ	235	610	2	12.7	X	1	Ply	19	G	89	B	610	3256	Struct	47.29	51.09	51.46	52.39			
FF-68	WJ	235	406	2	12.7	X	1	Ply	15.9	G	89	B	610	5027	Flame	48.02	53.10	51.58	53.24			
FF-69	WJ	235	610	2	12.7	X	1	Ply	19	R	89	B	610	3256	Struct	49.29	51.51	52.38	56.25			
FF-70	WJ	235	406	2	12.7	X	1	Ply	15.9	C2	235	---	610	4980	Struct	48.02	52.03	52.03	55.41			
FF-71	WT ¹	305	610	2	12.7	X	1	Ply	19	---	---	---	---	3783	Struct	44.41	51.19	54.28	56.13			
FF-72	WT ¹	305	610	2	12.7	X	1	Ply	19	C1	89	T	610	3687	Struct	49.04	54.09	54.18	57.07			
FF-73	WJ	235	610	2	12.7	X	2	Ply	15.9	G	89	B	610	3783	Struct	48.19	51.49	51.49	53.20			
FF-74	SJ	203	610	1	15.9	X	---	SU/Con	51	C1	38 ^a /89 ^b	T	406	3687	Struct	---	---	31.57	40.15			
FF-75	WT ¹	305	610	2	12.7	X	---	Ply/Con	19/38	G	89	B	610	3208	Struct	44.12	50.03	50.28	53.07			
FF-76	WJ ³	241	406	1	15.9	X	2	Ply	15.9	C2	241	---	305	5410	Struct	---	---	38.58	48.32			
FF-77	WJ ²	241	406	2	12.7	X	1	Ply	15.9	---	---	---	---	5506	Struct	52.21	62.02	63.42	63.50			
FF-78	WJ ³	241	406	1	15.9	X	2	Ply	15.9	R	267	B	305	5458	Struct	---	---	33.00	42.16			
FF-79	WT ¹	305	610	2	12.7	X	1	Ply	19	G	89	B	610	3783	Struct	45.31	51.30	51.27	53.57			
FF-80	WT ¹	305	610	2	12.7	X	1	Ply	19	R	89	B	610	3735	Struct	45.10	50.24	50.24	53.10			
FF-81	WJ ³	241	406	2	15.9	X	2	Ply	15.9	R	267	B	305	5363	Struct	56.41	62.48	65.41	76.03			
FF-82	WT ¹	305	406	2	15.9	X	2	Ply	15.9	C2	305	---	406	5793	Struct	50.50	63.13	61.33	68.40			

WJ¹ - 44 mm wide x 38 mm deepWJ² - 38 mm wide and 38 mm deepWJ³ - 58 mm wide and 38 mm deepWJ⁴ - 64 mm wide and 38 mm deepWJ⁵ - 38 mm wide and 64 mm deepWJ⁶ - 63 mm wide and 38 mm deep

C1 - Cellulose Fibre Insulation, Wet Sprayed

C2 - Cellulose Fibre Insulation, Dry Blown

C3 - Cellulose Fibre Insulation, Wet Sprayed with Adhesive

G-Glass fibre batts insulation

R-Rock fibre batts insulation

WT¹ - 89 mm wideWT² - 64 mm wideWT³ - truss oriented verticallyWT⁴ - Finger Jointed wood truss 64 mm wideWT⁵ - Metal web truss 63 mm wide

WJ-Wood joist

WJ-Wood-Ijoist

WT-Wood truss

SJ-Steel joist

a Cellulose Insulation Thickness on under sub-floor

b Cellulose insulation Thickness on joist sides

OSB-Oriented strandboard

B-Bottom

T-Top

Struct-Structure

Ply-Plywood

SI/Con-Steel/Concrete

Ply/Con-Plywood/Concrete

Ply/GC-Plywood/Gypsum-Concrete

5.3 Data analysis

Assemblies were divided into two groups; assemblies with one layer of gypsum board and assemblies with two layers of gypsum board (face layer and base layer). The effects of the various parameters on the fall-off of gypsum board are discussed below. The results shown in this section are based on comparisons between similar assemblies that differ by a single assembly component.

5.3.1 Effect of the Number of Gypsum Board Layers

In this section, the assemblies are classified according to the number of gypsum board layers used. Fall-off of the first piece of the gypsum board for assemblies protected with a single layer permitted heat to be transferred to the assembly and accelerated its failure. In assemblies protected with two layers of gypsum board, heat transfer to the assembly was accelerated after the fall-off of the first piece of the base layer of gypsum board.

Two wood joist assemblies, FF-02A and FF-03A, were studied to determine the effect of the number of gypsum board layers on the fall-off time of gypsum board. Both assemblies were constructed with wood joists that had depth of 235 mm, spaced at 406 mm and resilient channels spaced at 406 mm. The assemblies were fabricated without cavity insulation and had one layer of 15.9 mm thickness plywood sub-floor covering the assemblies on the unexposed side. The assemblies were loaded, using the deflection criteria (L/360) with 3830 N/m². FF-02A was protected on the exposed side with one

layer of 12.7 mm Type X gypsum board layer while FF-03A was protected with two layers of 12.7 mm Type X gypsum board layers.

Figure 5-2 presents the fall-off time for the first and last pieces of gypsum board protecting assembly FF-02A and the first and last pieces for the face and base layers of gypsum board protecting assembly FF-03A. For the assembly protected with a single layer of gypsum board, FF02A, the first and last pieces of gypsum board fell-off at around 42 and 47 minutes while for the assembly protected with two layers of gypsum board, the first and last pieces of the face layer of gypsum board fell-off around 49 and 57 minutes. The delay occurred for the fall-off of the face layer for FF-03A was due to the cooling of the face layer of gypsum board as a result of the moisture produced by the base layer when the free and molecular bound water was driven off from the gypsum board core. After the fall-off of the first piece of the face layer, the frame of the assembly FF-03A was still protected by the base layer until the fall-off of the first piece of the base layer at around 77 minutes. This shows that adding the second layer of gypsum board provided 35 minutes extra protection to the frame of the assembly FF-03A. The last piece of the base layer for FF-03A as shown in Figure 5-2 was recorded at approximately 82 minutes.

Figure 5-2 Effect of the number of layers of gypsum board for wood joist assemblies loaded with deflection criteria

FF-30 and FF-28 are wood joist assemblies fabricated with joists that had depth of 235 mm, spaced at 406 mm and resilient channels spaced at 406 mm. The assemblies were fabricated without cavity insulation and had one layer of 15.9 mm thickness plywood sub-floor covering the assemblies on the unexposed side. The assemblies were loaded, using the bending criteria (100% maximum strength), with 5075 N/m² for FF-28 and 5123 N/m² for FF-30. FF-30 was protected with one layer of 12.7 mm Type X gypsum board layer while FF-28 was protected with two layers of 12.7 mm Type X gypsum board layers.

A comparison for the time to fall-off of gypsum board layers for the assemblies FF-30 and FF-28 is shown in Figure 5-3. The figure shows that the first and last pieces of gypsum board for the assembly protected with a single layer, FF-30, fell-off at around 40 and 43 minutes respectively while for FF-28 the first and last pieces of the face layer were at around 43 and 61 minutes. A delay of 3 minutes resulted for the last assembly

due to delay in calcination of the face layer for the assembly protected with two layers of gypsum board. The first and last pieces of the base layer of gypsum board for FF-28 fell-off at about 67 and 69 minutes. The results show an additional protection of 27 minutes for the frame of the assembly protected with double layers of gypsum board when comparing the fall-off time of the first piece of gypsum board for FF-30 with the that of the first piece of the base layer of gypsum board for FF-28 which results in exposing the frame of the assemblies to the fire.

Figure 5-3 Effect of the number of gypsum board layers of for wood joist assemblies loaded with bending criteria

The effect of the number of layers of gypsum board on the fall-off time of gypsum board layers is studied using two steel joist assemblies, FF-25 and FF-23. The steel joist assemblies had a joist depth of 203 mm and were spaced at 406 mm. The assemblies were fabricated with resilient channels, spaced at 406 mm, and insulated with glass fibre batts. One layer of 15.9 mm thickness plywood sub-floor was covering the

assemblies on the unexposed side. The applied load was calculated using the bending criteria (100% maximum strength), with 2945 N/m^2 . FF-25 was protected with one layer of 12.7 mm Type X gypsum board layer while FF-23 was protected with two layers of 12.7 mm Type X gypsum board layers.

Figure 5-4 presents the fall-off time of the gypsum board layers for the assemblies FF-25 and FF-23. The first and last pieces of gypsum board fell-off at around 35 and 43 minutes for the assembly protected with one layer of gypsum board, FF-25, while the fall-off of the first and last pieces of the face layer of the assembly protected with double layers of gypsum board, FF-23, was recorded at around 59 and 64 minutes. A significant delay of 24 minutes, comparing to the wood joist assemblies discussed above, resulted by adding another layer of gypsum board. The first and last pieces of the base layer fell-off at around 63 and 68 minutes. This shows that the protection time of the frame increased by 28 minutes when adding a layer of 12.7 Type X gypsum board to the steel joist assembly.

Figure 5-4 Effect of the number of gypsum board layers for steel joist assemblies

Two wood-I-joists assemblies with 38 mm wide by 38 mm deep laminated veneer lumber (LVL) flange and 9.5 mm thick plywood web were studied to investigate the effect of the number of the gypsum board layers on the fall-off time of gypsum board layers. The assemblies were fabricated with joists depth of 240 mm which were spaced at 406 mm and resilient channels spaced at 406 mm. The floor cavity was insulated with rock fibre batts with thickness of 90 mm. The unexposed side of the assemblies was covered with one layer of 15.9 mm thickness plywood sub-floor. The applied load was calculated using the bending criteria (100% maximum strength), with 4644 N/m^2 for FF-16 and based on the deflection criteria (74% maximum strength) with 3950 N/m^2 for NRC-02. FF-16 was protected with one layer of 12.7 mm Type X gypsum board layer while NRC-02 was protected with two layers of 12.7 mm Type X gypsum board layers.

Figure 5-5 presents the time to fall-off of gypsum board layers for assemblies FF-16 and NRC-02. The figure shows that the first and last pieces of gypsum board of FF-16 fell-off at around 36 and 43 minutes and the first and last pieces of the face layer of NRC-02 fell-off at around 59 and 66 minutes. Considerable delay of 23 minutes resulted for the fall-off of the first piece of the face layer for NRC-02 due to the cooling provided by the base layer to the face layer when driving off the free and chemically bound water from the gypsum board core. Assembly NRC-02 was protected by the base layer until 67 minutes when the first piece of the base layer fell-off. The result shows that adding a double layer for assembly NRC-02 provided extra protection of 31 minutes for the frame of the assembly. The last piece of the base layer fell-off at around 75 minute.

Figure 5-5 Effect of the number of 12.7 mm thick gypsum board layers for wood-I-joist assemblies

Two wood-I-joists assemblies with 58 mm wide by 38 mm deep LVL flange and 9 mm thick oriented strandboard (OSB) web were studied to investigate the effect of number of layers of gypsum board on the fall-off time of gypsum board layers. The assemblies were fabricated with joists depth of 241 mm which and were spaced at 406 mm. Resilient channels for both assemblies were spaced at 305 mm. The floor cavity was insulated with rock fibre batts of thickness 267 mm. The assemblies were covered with two layers of 15.9 mm thickness plywood sub-floor on the unexposed side. The applied load was calculated using the bending criteria (100% maximum strength) for both assemblies and was 5458 N/m² for FF-78 and 5363 N/m² for FF-81. On the exposed side of the assemblies, assembly FF-78 was protected with one layer of 15.9 mm Type X gypsum board layer while assembly FF-81 was protected with two layers of 15.9 mm Type X gypsum board layers.

Figure 5-6 presents the time to fall-off of gypsum board layers for assemblies FF-78 and FF-81. The figure shows that the first and last pieces of gypsum board of assembly FF-78 fell-off at around 33 and 42 minutes and the first and last pieces of the face layer of FF-81 fell-off at around 57 and 63 minutes. Considerable delay of 24 minutes resulted for the fall-off of the first piece of the face layer for FF-81 due to the cooling provided by the base layer to the face layer. FF-81 was protected by the base layer until 66 minutes when the first piece of the base layer fell-off. The result shows that adding a double layer for assembly FF-81 provided extra protection of 29 minutes for the frame of the assembly. As shown also in the figure, the last piece of the base layer for the assembly FF-81 fell-off at around 76 minute.

Figure 5-6 Effect of the number of 15.9 mm thick gypsum board layers for wood-I-joist assemblies

The data presented above showed that the number of the gypsum board layers had a significant effect on the fall-off time of the gypsum board layers. Exposure of the frames of the assemblies was considerably delayed as a result of doubling the number of

the gypsum board layers. In addition, the delay of the fall-off time of the gypsum board occurred not only for the base layer of gypsum board but also for the face layer as a result of the cooling received from the base layer.

5.3.2 Effect of the Resilient Channels (RC) Installation and Spacing

Resilient channels are long strips of thin galvanized steel, 0.6 mm thick, 14 mm deep by 34 mm wide. The channels have a 58 mm wide web, designed to support gypsum board and one 18 mm wide flattened flange lip connected to the bottom of the joists. The channels are installed perpendicular to the joists to reduce the sound transmission through the floor assemblies. The further apart the channels are the better reduction in the sound transmission; however, the opposite is true for fire resistance. Figure 5-7 shows a typical section of floor assembly with resilient channels.

Figure 5-7 Typical floor section with resilient channels

5.3.2.1 Assemblies with one layer of gypsum board

Four non-insulated wood joist assemblies, FF-01A; FF-02A; FF-30; and FF-33, were studied to investigate the effect of the resilient channels installation characteristics on the fall-off time of gypsum board layers. The assemblies were protected with one layer of 12.7 mm thickness Type X gypsum board on the exposed side and with one layer of 15.9 mm thickness plywood on the unexposed side. The joists had 235 mm depth and they were spaced at 406 mm. The applied load (3830 N/m^2) on the assemblies FF-01A and FF-02A was calculated using the deflection criteria while the load applied (5123 N/m^2) on FF-30 and FF-33 was calculated using the bending criteria. Assembly FF-01A was fabricated without resilient channels (No RC). Resilient channels were installed for FF-02A, FF-30, and FF-33 at spacing of 406, 406, and 203 mm respectively to investigate the effect of the resilient channels spacing on the fall-off time of gypsum board layers.

Figure 5-8 shows the fall-off time of the first and last pieces of gypsum board for all the above four assemblies. The fall-off time for the first and the last pieces of gypsum board for the assembly without resilient channels, FF-01A, occurred at approximately 24 and 31 minutes. In general, the installation of the resilient channels helped the gypsum board panels to stay in place longer and consequently delayed the fall-off time of gypsum board regardless of the installation spacing. As shown in the figure, the first and the last pieces of gypsum board for the assembly with resilient channels, FF-02A, installed at spacing of 406 mm (RC @ 406) fell-off at around 42 and 47 minutes. Increasing the applied load for the assembly FF-30 with resilient channels installed at spacing of 406

mm slightly decreased the fall-off time of first and last pieces of gypsum board to approximately 41 and 43 minutes respectively. The fall-off time of the first and last pieces of gypsum board for the assembly with resilient channels, FF-33, installed at spacing of 203 mm (RC @ 203) was around 39 and 42 minutes respectively. This shows that decreasing the resilient channels spacing from 406 mm to 203 mm does not affect significantly the fall-off of gypsum board. Comparing to the fall-off time of the assembly without resilient channels, a delay was noticed for the fall-off time of the first piece of the gypsum board for both assemblies with resilient channels installed at spacing of 406 mm. Decreasing the resilient channels spacing to 203 mm, however, caused less delay.

Figure 5-8 Effect of resilient channels installation and spacing for non-insulated wood joist assemblies protected with one layer of gypsum board

Two insulated wood joist assemblies, FF-34 and FF-66, were studied to investigate the effect of increasing the resilient channels spacing from 203 to 406 mm for insulated assemblies on the fall-off of gypsum board. The assemblies were protected with one layer of 15.9 mm thick Type X gypsum board on the exposed side and with one layer

of 15.9 mm thickness plywood on the unexposed side. The joists had 235 mm depth and were spaced at 406 mm. The assemblies were constructed with rock fibre cavity insulation of thickness 89 mm. In addition to that, FF-66 had steel mesh installed under the rock fibre insulation. The applied load on the assemblies was calculated using the bending criteria. Assembly FF-34 was loaded with 5075 N/m^2 while assembly FF-66 was loaded with 5219 N/m^2 . Resilient channels were installed for both assemblies and were at spacing of 203 mm for assembly FF-34 and at spacing of 406 mm for assembly FF-66.

Figure 5-9 presents the fall-off time of the first and last pieces of gypsum board for insulated wood joist assemblies, FF-34 and FF-66. The figure shows that the first and last pieces of gypsum board fell-off at around 37 and 45 minutes for assembly FF-34 and 36 and 43 minutes for assembly FF-66. The finding shows that increasing the resilient channels spacing from 203 to 406 mm for insulated assemblies resulted in a small decrease (one minute delay of the first piece) of the fall-off time while as discussed earlier this increase caused a slight increase of the fall-off time for the non-insulated assemblies.

Figure 5-9 Effect of resilient channels spacing for insulated wood joist assemblies protected with one layer of gypsum board

5.3.2.2 Assemblies with two layers of gypsum board

The effect of the resilient channels installation on the fall-off of gypsum board for steel joist assemblies protected with two layers of gypsum board was studied using two steel joist assemblies FF-22 and FF-51. The assemblies were protected with two layers of 12.7 mm thick Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood on the unexposed side. The joists had 203 mm depth and were spaced at 406 mm. There was no cavity insulation installed for these assemblies. The assemblies were loaded with 2945 N/m^2 and 3342 N/m^2 for FF-22 and FF-51 respectively based on bending criteria (100% maximum strength). The resilient channels were installed only for assembly FF-22 at spacing 406 mm while FF-51 was fabricated without resilient channels.

As shown in Figure 5-10, installing resilient channels for FF-22 delayed the fall-off of gypsum board for the face layer and the base layer comparing with FF-51. The first and last pieces of the face layer of gypsum board for the assembly FF-22 were fell-off at approximately 66 and 73 minutes while for FF-51 the fall-off time of the first and last pieces of the face layer of gypsum board for the assembly FF-51 occurred at around 51 and 61 minutes. The fall-off of the first and last pieces of the base layer of gypsum board occurred at 73 and 74 minutes for assembly FF-22 while for assembly FF-51 it was at around 66 and 69 minutes. The behaviour of the assemblies shows significant acceleration for the fall-off of the gypsum board layers for the assembly fabricated without resilient channels.

Figure 5-10 Effect of resilient channels installation for steel joist assemblies protected with two layers of gypsum board

Two assemblies, FF-41 and FF-60, constructed with metal-plate-connected parallel-chord wood trusses were studied to establish the effect of the resilient channels installation on the fall-off of gypsum board for wood truss assemblies. The assemblies were fabricated with 305 mm truss depth spaced at 406 mm. Two layers of 12.7 mm Type X gypsum board protected the exposed side of the assemblies while the unexposed side was covered with one layer of 15.9 mm plywood sub-floor. The assemblies had no cavity insulation and they were loaded based on the bending criteria with 5602 N/m^2 . FF-41 was fabricated with resilient channels installed at spacing of 406 mm while FF-60 was constructed without resilient channels.

Figure 5-11 shows the fall-off time of the gypsum board layers. The figure shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-41 occurred at approximately 58 and 67 minutes and at around 43 and 59 minutes for assembly FF-60. The first and last pieces of the base layer fell-off at around

68 and 71 minutes for assembly FF-41 and 59 and 61 minutes for assembly FF-60. The finding shows that installing resilient channels had significant positive effect on the fall-off of the gypsum board layers.

Figure 5-11 Effect of resilient channels installation for wood truss assemblies with trusses spaced at 406 mm and protected with two layers of gypsum board

Two assemblies, FF-48 and FF-79, constructed with metal-plate-connected parallel-chord wood trusses were studied to establish the effect of the resilient channels spacing on the fall-off of the gypsum board for wood truss assemblies. The assemblies were fabricated with 305 mm truss depth spaced at 610 mm. Two layers of 12.7 mm Type X gypsum board protected the exposed side of the assemblies while the unexposed side was covered with one layer of plywood sub-floor of thickness 15.9 mm for assembly FF-48 and 19 mm for assembly FF-79. The assemblies were insulated with glass fibre batts with thickness of 89 mm and they were loaded based on the bending criteria with 3783 N/m^2 . The assemblies were fabricated with resilient channels installed at spacing of 406 mm and 610 mm for assemblies FF-48 and FF-79 respectively.

Figure 5-12 shows the fall-off time of the gypsum board layers for the wood truss assemblies, FF-48 and FF-79. The figure shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-48 occurred at approximately 54 and 59 minutes and at around 45 and 51 minutes for assembly FF-79. The first and last pieces of the base layer fell-off at around 62 and 66 minutes for assembly FF-48 and at approximately 51 and 54 minutes for assembly FF-79. The finding shows that installing the resilient channels at spacing 406 mm had considerable delay of the fall-off time of the gypsum board layers.

Figure 5-12 Effect of resilient channels installation for wood truss assemblies with trusses spaced at 610 mm and protected with two layers of gypsum board

The performance of four steel joist assemblies FF-24, FF-52, FF-43, and FF-44 protected with two layers of 12.7 mm Type X gypsum board on the exposed side was studied to establish the effect of the resilient channels spacing on the fall-off of gypsum board layers for assemblies covered with plywood sub-floor and assemblies covered with

concrete on top of steel deck sub-floor. All the assemblies were constructed with joists of depth 203 mm and insulated with glass fibre batts thickness of 89 mm. FF-24 and FF 52 were fabricated with joists spaced at 610 mm and covered with one layer of plywood sub-floor on the unexposed side with thickness of 15.9 mm for the assembly FF-24 and 19 mm for the assembly FF-52. FF-43 and FF-44 were fabricated with joists spaced at 406 mm and covered on the unexposed side with 51 mm concrete poured on top of steel deck. All the assemblies were loaded based on the bending criteria with 1796 and 2097 N/m² for the assemblies FF-24 and FF 52 respectively and 2341 N/m² for both assemblies FF-43 and FF-44. Resilient channels were installed at spacing of 406 mm for the assemblies FF-24 and FF-43 while the assemblies FF-44 and FF-52 had resilient channels installed at 610 mm.

Figure 5-13 shows the fall-off time of the gypsum board for the four assemblies. The first and last pieces of the face layer of gypsum board fell-off at roughly 60 and 62 minutes for assembly FF-24 and at about 42 and 50 minutes for assembly FF-52. The fall-off time of the first and last pieces of the base layer of gypsum board also shown in Figure 5-13 and was occurred at about 65 and 67 minutes for assembly FF-24 and at about 50 and 52 minutes for assembly FF-52. The result shows significant acceleration of the fall-off time when increasing the resilient channels spacing from 406 mm to 610 mm. Since the gypsum board layers were fastened to the resilient channels, the reduction in the number of screws fastening the gypsum board resulted when increasing the resilient channels spacing to 610 mm and caused an acceleration of the fall-off of gypsum board layers.

Figure 5-13 also shows the time to fall-off of gypsum board layers for assemblies FF-43 and FF-44. For assembly FF-43, the first and last pieces of the face layer of gypsum board fell-off at nearly 54 and 60 minutes and for FF-44 the fall-off time of the face layer occurred about 52 and 54 minutes. The first and last pieces of the base layer of gypsum board shown in Figure 5-13 occurred at approximately 60 and 66 minutes for assembly FF-43 and it was occurred for assembly FF-44 at about 53 and 59 minutes. The result shows also that increasing the resilient channels spacing from 406 mm to 610 mm accelerated the fall-off time of the gypsum board layers. However, the result shows that the effect of the resilient channels spacing on the fall-off of the gypsum board for steel assemblies covered with steel/concrete sub-floor was less compared to that for the steel assemblies covered with plywood sub-floor.

Figure 5-13 Effect of resilient channels spacing for steel joist assemblies protected with two layers of gypsum board

The behaviour of two wood joist assemblies is discussed to show the effect of the resilient channels installation on the fall-off time of gypsum board. FF-28 and FF-31 are

wood joist assemblies fabricated with joist depth 235 mm spaced at 406 mm. The assemblies were protected with two layers of 12.7 mm Type X gypsum board on the exposed side and covered with one layer of 15.9 mm plywood sub-floor on the unexposed side. The assemblies were constructed without cavity insulation. The applied load on both assemblies was calculated using bending criteria and was 5075 and 5027 N/m² for assemblies FF-28 and FF-31 respectively. The resilient channels were spaced at 406 mm for FF-28 while assembly FF-31 was constructed without resilient channels.

Figure 5-14 shows the fall-off time of the gypsum board layers for assemblies FF-28 and FF-31. The first and last pieces of the face layer of gypsum board occurred at approximately 44 and 61 minutes for assembly FF-28 while for assembly FF-31 it was occurred at 56 and 61 minutes. The first and last pieces of the base layer of gypsum board for FF-28 was recorded at about 67 and 69 minutes, also, for FF-31 it was recorded at around 65 and 67 minutes. The data show that fabrication of the assembly without resilient channels (FF-31) resulted in a delay of the fall-off time of gypsum board.

Figure 5-14 Effect of resilient channels installation for wood joist assemblies protected with two layers of gypsum board.

The performance of the wood joist assemblies FF-29 and FF-68 was studied to investigate the effect of the resilient channels spacing on the fall-off of gypsum board layers for wood joist assemblies. The assemblies were fabricated with joist depth 235 mm spaced at 406 mm and were protected with two layers of 12.7 mm Type X gypsum board on the exposed side. Both assemblies were covered with one layer of 15.9 mm plywood sub-floor on the unexposed side. The floor cavity was insulated with glass fibre cavity insulation of thickness 90 mm. The applied load on both assemblies was calculated using bending criteria and was 5075 and 5027 N/m² for assemblies FF-29 and FF-68 respectively. The resilient channels were spaced at 406 mm for FF-29 and at 610 mm for FF-68.

Figure 5-15 shows that the first and last pieces of face layer of gypsum board for assembly FF-29 was recorded at around 45 and 53 minutes while for FF-68 it was recorded at approximately 48 and 53 minutes. Figure 5-15 shows also the fall-off time of the first and last pieces of the base layer of gypsum board which was occurred at about 59 and 62 minutes for FF-29 and at roughly 52 and 53 minutes for FF-68. The finding shows a slight acceleration of the fall-off of the face layer of gypsum board for the assembly with resilient channels spacing 406 mm (FF-29). However, this assembly (FF-29) had a slightly early fall-off of the face layer comparing to the wood joist assemblies as will be shown in section 5.5.3.1.

Figure 5-15 Effect of resilient channels spacing for wood joist assemblies protected with two layers of gypsum board.

Different assemblies protected with double layers of gypsum board were studied to investigate the effect of the resilient channels characteristics on the fall-off of gypsum. The behaviour of the assemblies shows that installation of the resilient channels improved the behaviour of the gypsum board regardless of the spacing. The presented data also showed that changing the resilient channels spacing from 406 mm to 203 mm had insignificant effect on the fall-off of gypsum board. In contrast, increasing the spacing from 406 mm to 610 mm had a significant negative effect on the fall-off of gypsum board.

5.3.3 Effect of the Cavity Insulation Installation and Type

Three types of cavity insulation were used in the assemblies used in this study: glass fibre batts, rock fibre batts, and cellulose fibre insulation which satisfied the standards CSA A101 [20], CAN/ULC-S703 [21] and CAN/ULC S702 [22] respectively. The cellulose fibre insulation was used as wet sprayed with water for all the assemblies

presented in Sultan et al [8] (assemblies from FF-01A to FF-29) while for the assemblies presented in Sultan et al [9] (assemblies from FF-30 to FF-82), in addition to the wet sprayed cellulose fibre insulation, dry blown-in cellulose fibre insulation was used in assemblies FF-70, FF-76, and FF-82. Wet sprayed cellulose fibre with adhesive was also used in assembly FF-65. The glass and rock fibre batts were supported by the resilient channels and between the joists while the cellulose fibre insulation was at the top of the floor cavity. In some assemblies, cellulose fibre insulation was sprayed on the top of the floor cavity (under the sub-floor) and on the sides of the joists. The wet sprayed cellulose insulation was left to dry for 30 days prior to testing. Other assemblies were insulated with dry blown cellulose fibre insulation which was held in place by a 25 mm hexagonal steel mesh installed above the resilient channels and stapled with 50 mm long staples to the wood frames. Figure 5-16 shows a typical section of a floor assembly insulated with glass or rock fibre batts and Figure 5-17 shows a typical section of a floor assembly insulated with cellulose fibre insulation.

Figure 5-16 Glass or rock fibre insulation location

Figure 5-17 Cellulose fibre insulation location

5.3.3.1 Assemblies with one layer of gypsum board

Four wood joist assemblies, FF-02A, FF-07, FF-08, and FF-09, were studied to determine the effect of the cavity insulation installation and type on the fall-off of gypsum board. The assemblies were fabricated with joists of depth 235 mm and were spaced at 406 mm. One layer of 12.7 mm thickness Type X gypsum board protected the exposed sides of the assemblies while the unexposed sides were covered with one layer of 15.9 mm thickness plywood panels. Resilient channels were installed for the four assemblies at a spacing of 406 mm. The assemblies were loaded with 3830 N/m^2 based on the deflection criteria. FF-02A was fabricated without cavity insulation (Non-insulated), while the assemblies, FF-07; FF-08; and FF-09, were insulated with wet sprayed cellulose fibre, glass fibre, and rock fibre insulation respectively. The thickness of the glass and rock fibre batts was 90 mm while the thickness of the cellulose fibre was 93 mm at the top of the floor cavity and 86 mm on the sides of the joists.

Figure 5-18 shows the time of the fall-off of the first and last pieces of gypsum board protecting the four assemblies. The assemblies insulated with glass and rock fibre batts had an early gypsum board fall-off. The fall-off of the first and last pieces of gypsum board for FF-08 was at approximately 26 and 31 minutes and at around 26 and 32 minutes for FF-09. A delay can be noticed for the assembly insulated with cellulose fibre insulation, the first piece and last pieces of gypsum board for FF-07 fell-off at around 34 and 38 minutes. The first and last pieces of gypsum board fall-off for the non-insulated assembly, FF-02A, occurred at around 42 and 47 minutes. This result shows that the gypsum board fall-off was delayed when using non-insulated assembly regardless

of the type of cavity insulation. This delay is due to the increased heat transfer through the floor cavity in non-insulated assemblies which reduces the temperature of the gypsum board. On the other hand, the installation of the glass and rock fibre batts at the bottom of the floor cavity (on top of the resilient channels) reduces heat transfer and consequently increases the rate of rise of the temperature of the gypsum board resulting in an early fall-off. This reason also applies to the assembly insulated with cellulose fibre; however, there was a delay of the gypsum fall-off since the insulation was sprayed at the top of the floor cavity.

Figure 5-18 Effect of cavity insulation installation and type for wood joist assemblies protected with one layer of gypsum board

The performance of the steel joist assemblies FF-37, FF-38, and FF-50 is studied to investigate the effect of the cavity insulation installation and type on the fall-off of the gypsum board layers. The assemblies were fabricated with a joist depth of 203 mm spaced at 406 mm. One layer of 15.9 mm Type X gypsum board was protecting the assemblies on the exposed side and two layers of 15.9 mm plywood sub-floor were

covering the unexposed side. The assemblies were constructed with resilient channels installed at a spacing of 406 mm. The applied load on the assemblies was calculated using the bending criteria and was 3366, 3318, and 3285 N/m² for the assemblies FF-37, FF-38, and FF-50 respectively. FF-37 was fabricated without cavity insulation while FF-38 was insulated with rock fibre insulation of thickness 178 mm and FF-50 was insulated with cellulose fibre insulation sprayed with a thickness of 91 mm at the top of the cavity and 112 mm at the sides of the joists.

Figure 5-19 shows the fall-off time for the first and last pieces of gypsum board of the steel joist assemblies. The figure shows that the fall-off time of the first and last pieces of gypsum board for the assembly insulated with rock fibre batts, FF-38, occurred at around 27 and 39 minutes while the fall-off time of the first and last pieces of gypsum board for the assembly insulated with cellulose fibre, FF-50, was at about 34 and 45 minutes. The figure also shows the fall-off time of the first and last pieces of the base layer of gypsum board for assembly FF-37, non-insulated assembly, which occurred at about 36 and 39 minutes. The comparison of the results shows that increasing the thickness of the cellulose fibre insulation at the joists delays the fall-off time of the last piece of the gypsum board. The data also show that increasing the thickness of rock fibre insulation accelerated the fall-off of the first piece of gypsum board.

Figure 5-19 Effect of cavity insulation installation and type for steel joist assemblies protected with one layer of gypsum board

Two wood-I-joist assemblies, FF-76 and FF-78, were studied to investigate the effect of the installation of full cavity insulation on the fall-off time of gypsum board. The assemblies were made of joists with a depth of 241 mm and were spaced at 406 mm. The wood-I-joists were constructed from 38 mm thick by 58 mm width laminated veneer lumber (LVL) flanges and 9 mm oriented strandboard web. The assemblies were protected with one layer of 15.9 mm thick Type X gypsum board on the exposed side and covered with two layers of 15.9 mm thick plywood sub-floor. The load applied on both assemblies was calculated based on the bending criteria and was 5410 and 5458 N/m² for FF-76 and FF-78 respectively. Resilient channels were installed for both assemblies at a spacing of 305 mm. The floor cavity was insulated with dry blown cellulose fibre with a thickness of 241 mm for assembly FF-76 and with rock fibre batts with a thickness of 241 mm for FF-78.

Figure 5-20 shows that the first and last pieces of gypsum board for assembly FF-76 was recorded at around 39 and 48 minutes while for assembly FF-78 it was recorded at approximately 33 and 42 minutes. The result shows that installing full floor cavity insulation with rock fibre batts accelerated the fall-off of both the first and last pieces of gypsum board compared to the assembly which was fully insulated with dry blown cellulose fibre. This result shows that not only the location of the insulation affected the fall-off of gypsum board but also its thermal properties.

Figure 5-20 Effect of full cavity insulation type for wood-I-joist assemblies protected with one layer of gypsum board

The effect of the cavity insulation installation and type on the fall-off time of the gypsum board layers was studied using three wood-I-joist assemblies, FF-14, FF-16 and FF-19. All the assemblies were fabricated with a joist depth of 240 mm spaced at 406 mm and resilient channels were installed at a spacing of 406 mm. The wood-I-joists for the three assemblies had 38 mm width and a 38 mm depth laminated veneer lumber (LVL) flange and a 9.5 mm thick plywood web. The assemblies were protected with one

layer of Type X 12.7 mm thick gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side. The applied load was calculated using the deflection criteria for assemblies FF-14 and FF-19 and was 4597 N/m² (93% maximum strength) and 4046 N/m² (74 % maximum strength) respectively while for FF-16 it was calculated based on the bending criteria (100% maximum strength) and was 4644 N/m². The floor cavity of assembly FF-16 was insulated with rock fibre batts with a thickness of 90 mm. Wet sprayed cellulose fibre was used in assembly FF-19 with a thickness of 102 mm at the sides of the joists and 88 mm at the top of the floor cavity. FF-14 was fabricated without cavity insulation.

Figure 5-21 presents the fall-off time of the first and last pieces of gypsum board for the assemblies FF-14, FF-16 and FF-19. The first and last pieces of gypsum board fell-off at around 41 and 44 minutes for the non-insulated assembly, FF-14, while the fall-off of the first and last pieces of the gypsum board for the insulated assemblies FF-16 was recorded at around 36 and 43 minutes. A delay was noticed for the fall-off of gypsum board for the assembly insulated with cellulose fibre, FF-19, and occurred at about 45 and 47 minutes. Compared to the records of the non-insulated assembly, the result shows an early fall-off of the gypsum board for the assembly insulated with rock fibre due to the installation of the insulation at the bottom of the floor cavity that increases the temperature of the gypsum board. Using the cellulose fibre insulation for assembly FF-19 resulted in a delay of the fall-off time, however, the fall-off time exceeded that for the non-insulated assembly. The behaviour of this assembly (FF-19) was unique comparing to the performance of the other assemblies protected with a single

layer of gypsum board as shown in section 5.5.2. This might be related to the manufacture process or handling of the construction materials.

Figure 5-21 Effect of cavity insulation type and thickness for wood-I-joist assemblies protected with one layer of gypsum board

5.3.3.2 Assemblies with two layers of gypsum board

Three wood joist assemblies, FF-03A, FF-04A, and FF-06, were studied to investigate the effect of the floor cavity insulation installation and type on the fall-off of the gypsum board layers. The assemblies were loaded with 3830 N/m^2 based on the deflection criteria. The joists for all the three assemblies were spaced at 406 mm and had a depth of 235 mm. Two layers of 12.7 mm Type X gypsum board protected the assemblies' exposed side while the unexposed side was covered with one layer of 15.9 mm thick plywood sub-floor. Resilient channels were installed at a spacing of 406 mm. FF-03A was fabricated without cavity insulation while FF-04A and FF-06 were insulated with rock fibre batts and glass fibre batts with 90 mm insulation thickness.

Figure 5-22 shows that the fall-off time of the first piece of the face of gypsum board for the three assemblies FF-03A, FF-04A, and FF-06 occurred at about 50, 48, and 45 minutes respectively whereas the fall-off time for the last pieces of the face layer of gypsum board was recorded at approximately 57, 53, and 49 minutes. The fall-off time of the first and last pieces of the base layer of gypsum board for the assemblies is shown in Figure 5-22. For assembly FF-03A it occurred at around 78 and 82 minutes while for assemblies FF-04A and FF-06 it was at approximately 57 and 64 minutes, and at roughly 57 and 63 minutes. This shows an early fall-off of the gypsum board layers for the insulated assemblies comparing to the fall-off time of the assembly constructed without cavity insulation due to the installation of the insulation at the bottom of the floor cavity that increases the temperature of the gypsum board.

Figure 5-22 Effect of cavity insulation installation and type for wood joist assemblies loaded based on the deflection criteria

Two wood joist assemblies, FF-28 and FF-29, were studied to investigate the effect of the floor cavity insulation installation and type on the fall-off of the gypsum board layer. The assemblies were loaded with 5075 N/m^2 based on the bending criteria. The joists for both assemblies were spaced at 406 mm and had a depth of 235 mm. Two layers of 12.7 mm Type X gypsum board were protecting the assemblies' exposed side while the unexposed side was covered with one layer of 15.9 mm thick plywood sub-floor. Resilient channels were installed at a spacing of 406 mm. Assembly FF-28 was fabricated without cavity insulation while assembly FF-29 was insulated with glass fibre batts with 90 mm insulation thickness.

Figure 5-23 shows that the fall-off time of the first and last pieces of the face layer for the non-insulated assembly, FF-28, occurred at roughly 44 and 61 minutes while for the assembly insulated with glass fibre batts, FF-29, it was recorded at 45 and 52 minutes. Although there was a delay of 1 minute for the fall-off time of the first piece of the face layer for the assembly insulated with glass fibre, the face layer of the non-insulated assembly stayed longer in place until 61 minutes and consequently affected the fall-off of the base layer. The first and last pieces of the base layer of the gypsum board for the assemblies, as shown in Figure 5-23, fell-off at about 67 and 69 minutes for the non-insulated assembly and at approximately 59 and 62 minutes for the insulated assembly. The comparison of the records shows that an early fall-off for the first piece of the face layer for the non-insulated assembly. As pointed earlier, a delay was noticed in the fall-off of the first piece of gypsum board for assembly FF-29 comparing to the assemblies insulated with glass fibre batts.

Figure 5-23 Effect of cavity insulation installation for wood joist assemblies loaded based on the bending criteria

The effect of the cavity insulation installation and type on the fall-off of gypsum board was studied using three wood joist assemblies, FF-64, FF-67 and FF-69, fabricated with resilient channels installed at spacing 610 mm. The assemblies had joists with a depth of 235 mm spaced at 610 mm. The assemblies were covered with one layer of 19 mm thickness plywood sub-floor on the unexposed side and protected with two layers of 12.7 mm Type X gypsum board layers on the exposed side. The load applied on the assemblies was calculated using the bending criteria (100% maximum strength) and was 3256 N/m². Assembly FF-64 was constructed without cavity insulation while assembly FF-67 was insulated with glass fibre batts (89 mm thickness) and FF-69 was insulated with rock fibre batts (89 mm thickness).

Figure 5-24 shows the fall-off time of the first and last pieces of the gypsum board for the wood joist assemblies, FF-64, FF-67 and FF-69. The fall-off of the first and last pieces of the face layer of gypsum board occurred at approximately 47 and 55

minutes for FF-64, and at roughly 47 and 51 minutes for assembly FF-67 while for assembly FF-69 it occurred at approximately 49 and 52 minutes. The first and last pieces of the base layer of gypsum board for FF-64 fell-off at roughly 55 and 61 minutes and for FF-67 was recorded at about 52 and 52 minutes, also, for FF-69 it was recorded at around 52 and 56 minutes. The finding shows that the type of insulation, glass fibre or rock fibre, has a small effect on the fall-off of gypsum board layers for the studied wood joist assemblies.

Figure 5-24 Effect of cavity insulation type for wood joist assemblies with resilient channels and joist spaced at 610 mm and loaded based on the bending criteria

Three wood-I-joist assemblies, FF-13; FF-15; and NRC-02, protected with two layers of 12.7 mm thick Type X gypsum board were studied to investigate the effect of the floor cavity insulation installation and type on the fall-off of gypsum board layers. The wood-I-joists had 38 mm wide by a 38 mm thick flange and a 9.5 mm thick oriented strandboard web. The joists had a depth of 240 mm for all the assemblies and they were spaced at 406 mm. The butt ends of the gypsum board base layer for these assemblies

were fastened to the resilient channels while the butt ends of the face layer were fastened to the base layer with Type G screws 38 mm long. The assemblies were fabricated with one layer of 15.9 mm thick plywood sub-floor on the unexposed side and resilient channels spaced at 406 mm. The applied load on the assemblies was calculated using the bending criteria for assemblies FF-13 and was 3926 N/m^2 whereas for FF-15 and NRC-02 it was determined based on the deflection criteria (74% maximum strength) and was 3950 N/m^2 . The floor cavity of the assemblies was insulated with glass fibre batts (90 mm thickness) for FF-15 and with rock fibre batts for NRC-02 (90 mm thickness) while assembly FF-13 was non-insulated.

Figure 5-25 shows the fall-off time of the gypsum board layers for assemblies FF-13, FF-15 and NRC-02. The first and last pieces of the face layer of gypsum board occurred at approximately 56 and 70 minutes for the non-insulated assembly, FF-13, while for assembly with glass fibre cavity insulation, FF-15, it occurred at roughly 53 and 59 minutes. As shown in Figure 5-25, the first and last pieces of the face layer of gypsum board for assembly NRC-02 was recorded at approximately 59 and 66 minutes. The result shows that the first piece of the face layer of gypsum board for the non-insulated assembly fell-off before the assembly insulated with rock fibre batts, nevertheless, the face layer stayed in place longer. Figure 5-25 also presents the first and last pieces of the base layer of gypsum board of the assemblies. The fall-off time was at bout 69 and 74 minutes for FF-13, at roughly 57 and 66 minutes for FF-15, and at approximately 67 and 75 minutes for NRC-02. The records show a considerable early fall-off of both layers of gypsum board occurred for the assembly insulated with glass fibre batts. It was also

noticed that the non-insulated assembly, FF-13, has relatively early fall-off of the first piece of the face layer.

Figure 5-25 Effect of cavity insulation for wood-I-joist assemblies with two layers of gypsum board

The behaviour of the wood truss assemblies, FF-41 and FF-42, were studied to investigate the effect of the floor cavity insulation installation on the fall-off of the gypsum board layers. The assemblies were built with metal-plate-connected nominal 4x2 (305 mm deep by 89 mm wide by 38 mm thick) chord with metal-plate connected parallel-chord oriented horizontally on flat. The depth of the trusses was 305 mm and spaced at 406 mm. Both assemblies were protected with two layers of 12.7 mm thick Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood on the unexposed side. The applied load was calculated based on the bending criteria and was 5602 N/m^2 . Assemblies FF-41 and FF-42 were fabricated with resilient channels installed at a spacing of 406 mm. Assembly FF-41 was non-insulated while

assembly FF-42 was insulated with glass fibre batts in the floor cavity with a thickness of 90 mm.

Figure 5-26 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for the non-insulated assembly occurred at about 58 and 68 minutes while it was at approximately 54 and 59 minutes for the assembly insulated with glass fibre batts. The figure also shows that the first and last pieces of the base layer of gypsum board fell-off at about 68 and 71 minutes for assembly FF-41 and around 61 and 65 minutes for assembly FF-42. This finding shows that the addition of insulation increased the fall-off time for both layers of gypsum board for wood truss assemblies.

Figure 5-26 Effect of cavity insulation installation for wood truss assemblies with trusses spaced at 406 mm

Three wood truss assemblies, FF-72; FF-79; and FF-80, were studied to investigate the effect of floor cavity type on the fall-off of gypsum board layer. The

assemblies were loaded with 3687, 3783, 3735 N/m² respectively based on the bending criteria. The joists for all the three assemblies were spaced at 610 mm and had depth of 305 mm. The assemblies were built with metal-plate connected nominal 4x2 (305 mm deep by 89 mm wide by 38 mm thick) parallel-chord oriented horizontally on flat. Two layers of 12.7 mm thick Type X gypsum board were protecting the assemblies' exposed side while the unexposed side was covered with one layer of 19 mm thick plywood sub-floor. Resilient channels were installed at a spacing of 610 mm. The floor cavity was insulated with wet sprayed cellulose fibre insulation with 66 mm thickness on top of the cavity and 64 mm on the sides of the joists for assembly FF-72 while assemblies FF-79 and FF-80 were insulated with glass and rock fibre respectively with 90 mm thickness for both assemblies.

Figure 5-27 shows that the fall-off time of the first piece of the face of gypsum board for the three assemblies FF-72, FF-79, and FF-80 occurred at about 49, 45, and 45 minutes respectively whereas the last pieces of the face layer of gypsum board were recorded at approximately 54, 51, and 50 minutes. This result shows acceleration for the fall-off of the first piece of the face layer for the assemblies insulated with glass and rock fibre batts comparing to the assembly insulated with cellulose fibre. The fall-off of the first and last pieces of the base layer of gypsum board for the assemblies is shown in Figure 5-27. For assembly FF-72 it occurred at around 54 and 57 minutes while for FF-79 it was at approximately 51 and 54 minutes, and for FF-80 it was at about 50 and 53 minutes. This shows a minor difference between the fall-off time of the base layer for the

assemblies insulated with rock fibre and glass fibre batts and a delay for the assembly insulated with cellulose fibre insulation.

Figure 5-27 Effect of cavity insulation type for wood truss assemblies with trusses and resilient channels spaced at 610 mm

The effect of the floor cavity insulation installation on the fall-off of gypsum board layers for steel joist assemblies with a joist depth of 203 mm and protected with two layers of 12.7 mm Type X gypsum board on the exposed side is shown in Figure 4-28 to Figure 4-30. Two assemblies, FF-22 and FF23, was fabricated with joists spaced at 406 mm were covered with two layers of 15.9 mm thick plywood sub-floor on the unexposed side. Resilient channels were installed for both assemblies at a spacing of 406 mm. The assemblies were loaded with 2945 N/m² based on the bending criteria. The floor cavity was insulated with glass fibre batts for assembly FF-24 while assembly FF-23 was fabricated without cavity insulation.

The fall-off time of the gypsum board layers for FF-22 and FF-23 is shown in Figure 4-28. The figure shows that the first and last pieces of the face layer of gypsum board fell-off at about 66 and 73 minutes for assembly FF-22 whereas for assembly FF-23 the fall-off time occurred at approximately 59 and 64 minutes. The figure also shows that the fall-off time of the first and last pieces of the base layer of gypsum board for the non-insulated assembly occurred at 73 and 74 minutes and for the assembly insulated with glass fibre batts at 63 and 69 minutes. The result shows that the addition of insulation decreases the fall-off time.

Figure 5-28 Effect of cavity insulation installation for steel joist assemblies with two layers of gypsum board

Two steel joist assemblies, FF-52 and FF-65, constructed with joists spaced at 610 mm were covered with two layers of 19 mm thick plywood sub-floor on the unexposed side. Resilient channels were installed for both assemblies at a spacing of 610 mm. The applied load on the assemblies was determined using the bending criteria and was 2097 and 2092 N/m² for assemblies FF-52 and FF-65 correspondingly. The floor cavity was

insulated with glass fibre batts of thickness 89 mm for assembly FF-52 and with wet sprayed cellulose fibre with adhesive insulation sprayed with thickness of 94 mm on top of the floor cavity and 100 mm on the sides of the joists for FF-65.

Figure 5-29 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for the assembly insulated with glass fibre occurred at about 42 and 50 minutes while for the assembly insulated with wet sprayed cellulose fibre the fall-off time was at approximately 49 and 52 minutes. The figure also shows that the first and last pieces of the base layer of gypsum board fell-off at about 50 and 52 minutes for assembly FF-52 and around 52 and 54 minutes for assembly FF-65. The result shows that the fall-off time of the gypsum board layer for the assembly insulated with glass fibre batts is less than the fall-off time of the assembly insulated with wet sprayed cellulose fibre insulation with adhesive.

Figure 5-29 Effect of cavity insulation type for steel joist assemblies with joists and resilient channels spaced at 610 mm

Three steel joist assemblies, FF-40; FF-43; and FF-53, fabricated with joists spaced at 406 mm and were covered with a steel/concrete sub-floor (51 mm thick) were also studied to investigate the effect of the floor cavity insulation installation and type on the fall-off of the gypsum board layer. Resilient channels were installed at a spacing of 406 mm. FF-40 was loaded with 2351 N/m^2 while FF-43 and FF-53 were loaded with 2341 based on the bending criteria. The floor cavity for assemblies FF-43 and FF-53 was insulated with glass and rock fibre batts respectively while FF-40 had no cavity insulation.

Figure 5-30 shows the fall-off time for the first and last pieces of the face and base layers of gypsum board for the three steel joist assemblies. For the face layer, the time to fall-off of the first and last pieces was occurred at around 60 and 77 minutes for the non-insulated assembly, 54 and 60 minutes for the assembly with glass fibre batts, and at about 51 and 57 minutes for the assembly insulated with rock fibre batts. The fall-off time of the first piece and last pieces of the base layer of gypsum board for the assemblies is also shown in Figure 5-30 and was recorded for FF-40 at about 72 and 79 minutes and at approximately 60 and 66 minutes for assembly FF-43 whereas for assembly Ff-53 it was around 58 and 65 minutes. The result shows that the addition of insulation decreases the fall-off times. However, in contrast with the earlier assemblies, the fall-off time of gypsum board when using rock fibre batts was less than the fall-off time when using glass fibre batts.

Figure 5-30 Effect of cavity insulation installation and type for steel joist assemblies covered with steel-concrete sub-floor

Several assemblies protected with one and two layers of gypsum board were studied to investigate the effect of cavity insulation installation and type on the fall-off time of gypsum boards. In general, gypsum board fell-off first for the assemblies with glass fibre batts installed in the floor cavity followed by the assemblies insulated with rock fibre except the case of the steel joists presented in Figure 5-30 where the assemblies were covered with steel/concrete sub-floor. A considerable delay in the fall-off time resulted from using cellulose fibre insulation. The results also show that the gypsum board fell-off last for the non-insulated assemblies comparing to the insulated assemblies regardless the type of insulation.

5.3.4 Effect of Sub-floor

5.3.4.1 Effect of sub-floor topping

A series of tests was studied to investigate the effect of sub-floor topping on the fall-off of gypsum board. Two sub-floor materials were used, softwood plywood (CSP) tongue and groove, 15.9 mm and 19.0 mm thick, and oriented strand-board (OSB) tongue and groove, 15.9 mm thick. In the figures and summary table, ply refers to the former type of sub-floor. Two sub-floor topping materials were used, gypsum-concrete topping and concrete topping. The Gypsum-Concrete topping was poured on top of the plywood sub-floor (Ply/GC) while the concrete was used on both plywood sub-floor (Ply/Con) and on steel deck (St/Con).

Two wood joist assemblies (FF-29 and FF-35) protected with two layers of 12.7 mm thick Type X gypsum board were studied to investigate the effect of sub-floor topping (Ply versus Ply/GC) on the fall-off time of gypsum board. For both assemblies, the joists had depth of 235 mm and were spaced at 406 mm. The assemblies were fabricated with resilient channels spaced at 406 mm and insulated with glass fibre batts cavity insulation 89 mm thick. The applied load on the assemblies was calculated using the bending criteria (100% maximum strength) and was 5075 and 4644 N/m² for assemblies FF-29 and FF-35 respectively. One layer of 15.9 mm thick plywood covered assembly FF-29 on the unexposed side while assembly FF-35 was covered with a 25 mm thick Gypsum-Concrete topping poured on top of the 15.9 mm thick plywood sub-floor.

The Gypsum-Concrete was a mix of Portland cement, sand, water and gypsum at a density of 1957 kg/m^3 and cured for 60 days.

Figure 5-31 presents the effect of adding gypsum-concrete topping on top of plywood sub-floor on the fall-off of gypsum board layers for wood joist assemblies. The figure shows that the fall-off time of the first and last pieces of the face layer of gypsum board occurred at around 45 and 53 minutes for the assembly covered with plywood sub-floor, FF-29, while for the assembly covered with Gypsum-Concrete on top of the plywood sub-floor, FF-35, it occurred at approximately 53 and 58 minutes. The figure also shows the fall-off time of the first and last pieces of the base layer of gypsum board for the assemblies and it was recorded for FF-29 at around 59 and 62 minutes and for FF-35 at about 61 and 64 minutes. The result shows that the addition of Gypsum-Concrete topping delays significantly the fall-off of the face layer and has less impact on the fall-off of the base layer. The result occurred due to the decrease of heat transferred to the unexposed side as a result of adding Gypsum-Concrete on top of the plywood sub-floor.

Figure 5-31 Effect of Gypsum-Concrete sub-floor topping for wood joist assemblies protected with two layers of gypsum board

Two wood-I-joist assemblies, FF-15 and FF-61, protected with two layers of 12.7 mm thick Type X gypsum board were studied to investigate the effect of the sub-floor topping (Ply versus Ply/Con) on the fall-off time of gypsum board layers. The assemblies had joists of depths of 240 and 241 mm spaced at 406 mm. The assemblies were fabricated with resilient channels spaced at 406 mm and insulated with glass fibre batts cavity insulation 90 mm thick. FF-15 was loaded with 3950 N/m^2 based on the deflection criteria while FF-61 was loaded with 4596 N/m^2 based on the bending criteria (100% maximum strength). One layer of 15.9 mm thickness plywood covered assembly FF-15 on the unexposed side while the unexposed side of the assembly FF-61 was covered with a 38 mm thick concrete topping poured on top of the 15.9 mm thick plywood sub-floor. The concrete was normal weight concrete with coarse aggregate having a concrete strength of 25 MPa after 28 days.

Figure 5-32 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for the assembly covered with plywood sub-floor, FF-15, occurred at around 53 and 59 minutes and at approximately 49 and 56 minutes for the assembly covered with concrete on top of the plywood sub-floor, FF-61. The figure also shows the fall-off time of the first and last pieces of the base layer of gypsum board for the assemblies and it was recorded for FF-15 at around 57 and 66 minutes and for FF-61 at about 57 and 62 minutes. Addition of the concrete resulted in decreasing of the fall-off time for the both layers of gypsum board. However, the effect on the fall-off time of the first piece of the base layer of gypsum board was insignificant.

Figure 5-32 Effect of concrete sub-floor topping for wood-I-joist assemblies protected with two layers of gypsum board

Two wood truss assemblies, FF-79 and FF-75, protected with two layers of 12.7 mm thick Type X gypsum board were studied to investigate the effect of sub-floor topping (Ply versus Ply/Con) on the fall-off time of gypsum board layers. For both assemblies, the trusses had depth of 305 mm and spaced at 610 mm. The assemblies were fabricated with resilient channels spaced at 610 mm and insulated with glass fibre batts cavity insulation 89 mm thick. The applied load on both assemblies was determined using the bending criteria and was 3783 N/m^2 and 3208 N/m^2 for FF-79 and FF-75 respectively. One layer of 19 mm thickness plywood covered assembly FF-79 on the unexposed side while the unexposed side of the assembly FF-75 was covered with 38 mm thick concrete topping poured on top of the 19 mm thick plywood sub-floor. The concrete was normal weight concrete with coarse aggregate having a concrete strength of 25 MPa after 28 days.

The fall-off time of the first and last pieces of gypsum layers is presented in Figure 5-33. The figure shows that the first and last pieces of the face layer of gypsum board for the assembly covered with plywood sub-floor fell-off at around 45 and 51 minutes and at approximately 44 and 50 minutes for the assembly covered with concrete on top of the plywood sub-floor. The figure also shows fall-off of the first and last pieces of the base layer of gypsum board for the assemblies which was recorded for FF-79 at around 51 and 54 minutes and for FF-75 at about 50 and 53 minutes. The result shows that the addition of concrete topping on the unexposed side does not have a significant impact on the fall-off time.

Figure 5-33 Effect of concrete sub-floor topping for wood truss assemblies with trusses and resilient channels spaces at 610 mm and protected with two layers of gypsum board

Three steel joist assemblies, FF-23; FF-27; and FF-43, protected with two layers of 12.7 mm thick Type X gypsum board were studied to investigate the effect of sub-floor topping (Ply versus Ply/Con and St/Con) on the fall-off time of gypsum board layers. The assemblies had joists of depth 203 mm spaced at 406 mm. Resilient channels were installed for the three assemblies at a spacing of 406 mm and glass fibre batts of 90

mm thick was insulating the floor cavity. The applied load on the assemblies was determined using the bending criteria and was 2945 N/m^2 , 1915 N/m^2 , and 2341 N/m^2 for FF-23, FF-27, and FF-43 respectively. One layer of 15.9 mm thickness plywood sub-floor covered assembly FF-23 on the unexposed side while the unexposed side of the assembly FF-27 was covered with a 38 mm thick concrete topping poured on top of a plywood sub-floor. FF-43 was covered with 51 mm concrete topping poured on top of a steel deck sub-floor. The concrete was normal weight concrete with coarse aggregate which having a concrete strength of 25 MPa after 28 days.

The fall-off time of the first and last pieces of gypsum layers is presented in Figure 5-34. The figure shows that the first and last pieces of the face layer of gypsum board for the assembly covered with plywood sub-floor fell-off at around 59 and 64 minutes and at approximately 49 and 55 minutes for the assembly covered with concrete on top of the plywood sub-floor while the fall-off time for the first and last pieces of the face layer of gypsum board for the assembly covered with concrete on top of steel deck occurred at roughly 54 and 60 minutes. The figure also shows the fall-off time of the first and last pieces of the base layer of gypsum board for the assemblies was recorded for FF-23 at around 63 and 69 minutes, for FF-27 at about 53 and 58 minutes, and for assembly FF-43 at approximately 60 and 66 minutes. The result shows that the addition of concrete on top of both plywood sub-floor and steel deck decreases the fall-off time of gypsum board, however, the impact was less on top of the steel deck.

Figure 5-34 Effect of concrete topping on plywood or steel deck for steel joist assemblies protected with two layers of gypsum board

Two non-insulated steel joist assemblies, FF-22 and FF-40, had steel joists spaced at 406 mm and resilient channels installed at spacing 406 mm. The applied load on the assemblies was determined using the bending criteria and was 2945 and 2351 N/m² for assemblies FF-22 and FF-40 respectively. The exposed side for both assemblies was protected with two layers of 12.7 mm thick Type X gypsum board. The unexposed side was covered with one layer of 15.9 mm thick plywood sub-floor for assembly FF-22 and with 51 mm thick concrete poured on top of steel deck for assembly FF-40.

Figure 5-35 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for the assembly covered with plywood sub-floor occurred at about 66 and 73 minutes while it was at approximately 60 and 77 minutes for the assembly covered with concrete on top of steel deck. The figure also shows that the first and last pieces of the base layer of gypsum board fell-off at about 73 and 74 minutes for assembly

FF-22 and around 73 and 79 minutes for assembly FF-40. This shows that addition of concrete on top of steel deck decreases the fall-off time of the first piece of the face layer, however, the effect was insignificant on the fall-off of the first piece of the base layer of gypsum board.

Figure 5-35 Effect of steel-concrete sub-floor for steel joist assemblies with joists and resilient channels spaced at 610 mm and protected with two layers of gypsum board

Two non-insulated steel joist assemblies, FF-62 and FF-54, fabricated with steel joists spaced at 610 mm and constructed without resilient channels were studied to investigate the impact of the sub-floor topping on the fall-off of gypsum board. The applied load on the assemblies was determined using the bending criteria and was 2123 and 1130 N/m² for assemblies FF-62 and FF-54 respectively. The exposed side for both assemblies was protected with two layers of 12.7 mm thick Type X gypsum board whereas the unexposed side was covered with one layer of 19 mm thick plywood sub-floor for assembly FF-62 and with concrete on top of steel deck of thickness 51 mm for assembly FF-54.

Figure 5-36 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for the assembly covered with plywood sub-floor occurred at about 46 and 55 minutes and at approximately 37 and 56 minutes for the assembly covered with concrete on top of steel deck. The figure also shows that the first and last pieces of the base layer of gypsum board fell-off at about 54 and 56 minutes for assembly FF-62 and around 60 and 66 minutes for assembly FF-54. This shows that the addition of concrete on top of steel deck accelerates the fall-off for first piece of the face layer of gypsum board; however, it delays the fall-off of the first piece of the base layer of gypsum board. The impact of the concrete topping on the fall-off of the base layer is unique for assembly FF-54 as will be discussed later in section 5.5.3.4.

Figure 5-36 Effect of steel-concrete sub-floor for steel joist assemblies without resilient channels protected with two layers of gypsum board

Assemblies with different construction elements were studied to determine the effect of the sub-floor topping on the fall-off of gypsum board. In general, adding Gypsum-Concrete on top of plywood sub-floor improved the performance of the fall-off

of gypsum layers especially for the first piece of the face layer. On the other hand, using concrete topping either on top of plywood sub-floor or on top of steel deck had negative effect of the fall-off of the gypsum board layers, although, the impact was not the same on all the assemblies.

5.3.4.2 Effect of the number of sub-floor layers

Wood joist assemblies, FF-67 and FF-73, were studied to investigate the effect of increasing the number of sub-floor layers on the fall-off of gypsum board. The assemblies were made of joists with 235 mm depth and spaced at 610 mm. The floor cavity for both assemblies was insulated with glass fibre batts with a thickness of 89 mm and the resilient channels were installed at a spacing of 610 mm. Both assemblies were loaded based on the bending criteria with 3256 N/m² for FF-67 and with 3783 N/m² for FF-73. The exposed side of the assemblies was protected with two layers of 12.7 mm thick Type X gypsum board while the unexposed side was covered with one layer of 19 mm thick plywood sub-floor (S-1) for the assembly FF-67 and two layers of 15.9 mm thick plywood sub-floor for the assembly FF-49.

Figure 5-37 presents the effect of the number of sub-floor layers on the fall-off of gypsum board for wood joist assemblies. The figure shows that the fall-off time of the first and last pieces of the face layer of gypsum board occurred at around 47 and 51 minutes for the assembly covered with one layer of 19 mm plywood sub-floor, FF-67, while for the assembly covered with two layers of 15.9 mm plywood sub-floor, FF-73, it

occurred at approximately 48 and 52 minutes. The figure also shows the fall-off times for the first and last pieces of the base layer of gypsum board for the assemblies which was recorded for FF-67 at around 52 and 52 minutes and for FF-73 at about 52 and 53 minutes. The result shows that increasing the number of sub-floor layers has insignificant effect on the fall-off of both layers of gypsum board.

Figure 5-37 Effect of the number of sub-floor layers for wood joist assemblies protected with two layers of gypsum board

5.3.5 Effect of Frame Type

5.3.5.1 Assemblies with one layer of gypsum board

Figure 5-38 to Figure 5-39 show the effect of frame type on the fall-off of gypsum board for different assemblies protected with one layer of gypsum board. Wood joist and steel joist assemblies, FF-36 and FF-38, insulated with rock fibre batts with thickness of 178 mm and protected with one layer of 15.9 mm thick Type X gypsum board on the exposed side were studied to investigate the effect of the frame type on the fall-off of

gypsum board. The wood joist assembly FF-36 was fabricated with joists depth of 235 mm and the steel joist assembly FF-38 had joists of depth 203 mm. The joists and resilient channels were spaced at 406 mm for both assemblies. Two layers of 15.9 mm thick plywood sub-floor were covering the unexposed side of the assemblies. Based on the bending criteria, assembly FF-36 was loaded with 4980 N/m^2 and assembly FF-38 was loaded with 3318 N/m^2 .

Figure 5-38 shows the effect of the joist type on the fall-off of gypsum board. The figure shows that the fall-off time of the first and last pieces of gypsum board for the wood joist assembly occurred at around 32 and 42 minutes while for the steel joist assembly it was recorded at roughly 27 and 39 minutes. The result shows a decrease in the fall-off time of the gypsum board layers when using steel frame.

Figure 5-38 Effect of joist type for wood and steel assemblies insulated with rock fibre batts and protected with one layer of gypsum board

The performance of the wood joist (FF-49) and the steel joist (FF-50) assemblies insulated with cellulose fibre with thickness 89 mm and protected with one layer of 15.9 mm thick Type X gypsum board on the exposed side were studied to investigate the effect of the frame type on the fall-off of gypsum board when cellulose fibre is used. FF-49 and FF-50 were fabricated with wood joists of depth 235 mm and steel joists of depth 203 mm with joists spacing of 406 mm for both assemblies. Resilient channels were spaced at 406 mm. Two layers of 15.9 mm thick plywood sub-floor were covering the unexposed side of the assemblies. FF-49 and FF-50 were loaded with 4980 and 3285 N/m² respectively based on the bending criteria.

Figure 5-39 shows that the fall-off time of the first and last pieces of gypsum board for the wood joist assembly occurred at around 37 and 44 minutes while for the steel joist assembly it was at approximately 34 and 45 minutes. The result shows a small acceleration of the fall-off time of the first piece of gypsum board for the steel joist assembly.

Figure 5-39 Effect of frame type for wood and steel assemblies insulated with cellulose fibre insulation and protected with one layer of gypsum board

Two non-insulated assemblies fabricated with wood-I-joists (FF-14) and wood joists (FF-30) protected with one layer of 12.7 mm thick Type X gypsum board on the exposed side were studied to investigate the effect of the frame type on the fall-off of gypsum board. The joists had a depth of 240 mm for the wood-I-joists and 235 mm for the wood joists with joists spacing of 406 mm for both assemblies. Resilient channels were installed at a spacing of 406 mm for both assemblies. One layer of 15.9 mm thick plywood sub-floor was covering the unexposed side of the assemblies. The applied load was calculated using the deflection criteria (93% maximum strength) for the wood-I-joist assembly and was 4597 N/m² and using the bending criteria (100% maximum strength) for the wood joist assembly and was 5123 N/m².

The fall-off time of the first and last pieces of gypsum board for the assemblies is presented in Figure 5-40. The first and last pieces of gypsum board for the wood-I-joist assembly fell-off at around 41 and 44 minutes whereas for the wood joist assembly it was at roughly 41 and 43 minutes. The result shows insignificant effect of the joist type on the fall-off time of gypsum board for the non-insulated assemblies.

Figure 5-40 Effect of frame type for the non-insulated wood-I-joist and wood joist assemblies protected with one layer of gypsum board

The discussion above shows the impact of the frame type on the fall-off of gypsum board for assemblies protected with single layer of gypsum board. Compared to the fall-off time of the wood joist assemblies, the records show an acceleration of 3 to 5 minutes of the fall-off of the first piece gypsum board for the steel joist assemblies. The records also show no difference between the fall-off time of the first piece of gypsum board of the wood joist and the wood-I-joist assemblies protected with a single layer of gypsum board.

5.3.5.2 Assemblies with two layers of gypsum board

The effect of the frame type on the fall-off of gypsum board is studied using wood joist assembly, FF-04A, and wood-I-joist assembly, NRC-02. The assemblies were protected with two layers of 12.7 mm thick Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side. Resilient channels were installed at a spacing of 406 mm for both assemblies and the

floor cavity was insulated with rock fibre batts of thickness 90 mm. The applied load on both assemblies was calculated using the deflection criteria and was 3830 N/m^2 for FF-04A and 3950 N/m^2 for NRC-02. The joists were spaced at 406 mm with a depth of 235 mm for the wood joist and 240 mm for the wood-I-joist.

Figure 5-41 shows the fall-off time of the first and last pieces of the gypsum board layers for the assemblies. The first and last pieces of the face layer of the wood joist assembly, FF-04A, fell-off at around 48 and 53 minutes while for the wood-I-joist at approximately 59 and 66 minutes. The fall-off of the first and last pieces of the base layer of gypsum board as recorded in Figure 5-41 occurred at about 57 and 64 minutes for FF-04A and at roughly 67 and 75 minutes for NRC-02. The result shows that delay in the fall-off of both layers of gypsum board occurred when using wood-I-joist.

Figure 5-41 Effect of joist type for assemblies insulated with rock fibre batts and protected with two layers of gypsum board

The performance of the wood joist FF-69 and the wood truss assemblies FF-80 is studied to investigate the effect of the frame type on the fall-off of the gypsum board layers for assemblies insulated with rock fibre insulation. The assemblies were fabricated with a frame depth of 235 mm for the wood joist assembly and 305 mm for the wood truss assembly and spaced at 610 mm. Resilient channels were spaced at 610 mm for both assemblies. The assemblies were protected with two layers of 12.7 mm Type X gypsum board on the exposed side and covered with one layer of 19 mm plywood sub-floor on the unexposed side. The floor cavity for both assemblies was insulated with rock fibre cavity insulation with a thickness of 89 mm. The applied load on the assemblies was calculated using bending criteria and was 3256 and 3735 N/m² for assemblies FF-69 and FF-80 respectively.

Figure 5-42 shows that the first and last pieces of face layer of gypsum board for the wood joist assembly FF-69 fell-off at around 49 and 52 minutes while for FF-80 it fell-off at approximately 45 and 50 minutes. Figure 5-42 shows also the fall-off time of the first and last pieces of the base layer of gypsum board which occurred at about 52 and 56 minutes for FF-69 and at about 50 and 53 minutes for FF-80. The result shows that the fall-off of the gypsum boards occurs earlier when using wood truss than when using wood joists.

Figure 5-42 Effect of the frame type for assemblies with frame and resilient channels spaced at 610 mm, insulated with rock fibre batts, and protected with two layers of gypsum board

Two non-insulated assemblies fabricated without resilient channels and with wood joists (FF-31) and steel joists (FF-51) were studied to investigate the effect of the frame type on the fall-off of gypsum board. The assemblies were protected with two layers of 12.7 mm thick Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side. The joists had a depth of 203 mm for the steel joists and 235 mm for the wood joists with joists spacing of 406 mm for both assemblies. Resilient channels were installed at a spacing of 406 mm for both assemblies. The applied load was calculated using the bending criteria for both assemblies and was 5027 N/m² on the wood joist assembly and 3342 N/m² on the steel joist assembly.

Figure 5-43 shows the fall-off time of the gypsum board layers. The figure shows that the fall-off time of the first and last pieces of the face layer of gypsum board for the wood joist assembly, FF-31, occurred at approximately 56 and 61 minutes and at around 51 and 61 minutes for the steel joist assembly FF-51. The first and last pieces of the base layer fell-off at around 65 and 67 minutes for assembly FF-31 and 66 and 69 minutes for assembly FF-51. The result shows that using a steel joist resulted in a decrease of the fall-off time of the first piece of the face layer. The impact on the base layer, however, was insignificant.

Figure 5-43 Effect of the frame type for assemblies without cavity insulation or resilient channels and protected with two layers of gypsum board

Four assemblies fabricated with wood joists of depth 235 mm (FF-29), wood-I-joist of depth 240 mm (FF-15), wood truss of depth 286 mm (FF-42), and steel joist of depth 203 mm (FF-23) were studied to investigate the effect of the frame type on the fall-off of gypsum board layers. All the frames were spaced at 406 mm and were protected

with two layers of 12.7 mm thick Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood on the unexposed side. The assemblies were fabricated with resilient channels installed at 406 mm and with glass fibre batts insulation of thickness 89 mm in the floor cavity. The applied load on the assemblies was calculated using deflection criteria for the wood-I-joist assemblies with 3950 N/m^2 while the wood joist, wood truss, and steel joist assemblies were loaded with 5075, 5602, 2945 N/m^2 respectively.

Figure 5-44 shows the fall-off time of the gypsum board for the four assemblies. The fall-off of the first and last pieces of the face layer of gypsum board occurred at around 45 and 53 minutes for the wood joist assembly, FF-29, 53 and 59 minutes for the wood-I-joist assembly, FF-15, 54 and 59 minutes for the wood truss assembly, FF-42, and at roughly 59 and 64 for the steel joist assembly, FF-23. The first and last piece of the base layer as recorded in Figure 4-46 fell-off at approximately 59 and 62 minutes for FF-29, 57 and 66 minutes for FF-15, 61 and 65 minutes for FF-42, and at about 63 and 69 minutes for FF-23. The results show that wood-I-joist assemblies behave similar to wood truss assemblies while wood joist assemblies have an early fall-off time. Unlike the earlier steel assemblies, the insulated steel assembly have a delay in the fall-off time of the gypsum board layers comparing to the other assemblies.

Figure 5-44 Effect of the frame type for assemblies insulated with glass fibre batts and protected with two layers of gypsum board

Non-insulated assemblies fabricated with wood joist of depth 235 mm (FF-28), wood truss of depth 305 mm (FF-41), and steel joist of depth 203 mm (FF-22) were studied to investigate the effect of the frame type on the fall-off of gypsum board layers. All the frames were spaced at 406 mm and were protected with two layers of 12.7 mm thick Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood on the unexposed side. The assemblies were fabricated with resilient channels installed at 406 mm. Based on the bending criteria, the applied load on the assemblies was 5075, 5602, 2945 N/m² for the wood joist, the wood truss, and the steel joist assemblies respectively.

Figure 5-45 shows the fall-off time of the gypsum board for the four assemblies. The fall-off of the first and last pieces of the face layer of gypsum board occurred at around 44 and 61 minutes for the wood joist assembly, FF-28, 58 and 67 minutes for the

wood truss assembly, FF-41, and at roughly 66 and 73 for the steel joist assembly, FF-22. The first and last piece of the base layer, as shown in Figure 5-45, fell-off at approximately 67 and 69 minutes for FF-28, at roughly 68 and 71 minutes for FF-41, and at about 73 and 74 minutes for FF-22. The result shows that for non insulated assemblies using the steel joists significantly delayed the fall-off time. In contrast, using the wood joist accelerated the fall-off time. The finding also shows that there is no difference in the fall-off time of the base layer when using either wood joist or wood truss frame.

Figure 5-45 Effect of the frame type for non-insulated assemblies protected with two layers of gypsum board

Four assemblies fabricated with wood joist of depth 235 mm (FF-67), wood-I-joist of depth 240 mm (FF-20), wood truss of depth 305 mm (FF-79), and steel joist of depth 203 mm (FF-52) were studied to investigate the effect of the frame type on the fall-off of gypsum board layers. All the frames and resilient channels were spaced at 610 mm. The assemblies were fabricated with glass fibre batts insulation with a thickness of 89

mm and were protected with two layers of 12.7 mm thick Type X gypsum board on the exposed side and covered with one layer of 19 mm thick plywood on the unexposed side. The applied load on the assemblies was calculated using deflection criteria for the wood-I-joist assembly with 3112 N/m^2 while the other three assemblies were loaded based on the bending criteria with 3256 N/m^2 for the wood joist assembly, 3783 N/m^2 for the wood truss assembly, and with 2079 N/m^2 for the steel joist assembly.

Figure 5-46 shows the fall-off time of the gypsum board for the four assemblies. The fall-off time of the first and last pieces of the face layer of gypsum board occurred at around 47 and 51 minutes for the wood joist assembly, FF-67, 56 and 60 minutes for the wood-I-joist assembly, FF-20, 45 and 51 minutes for the wood truss assembly FF-79 and at roughly 42 and 50 minutes for the steel joist assembly FF-52. The first and last piece of the base layer as shown in Figure 5-46 occurred at approximately 52 and 52 minutes for FF-67, 59 and 62 minutes for FF-20, 51 and 54 minutes for FF-79 and at about 50 and 52 minutes for FF-52. The results show that for insulated assemblies, wood-I-joists have the longest fall-off time of the gypsum board, while the steel joist assembly have the shortest fall-off time.

Figure 5-46 Effect of the frame type for assemblies with frame and resilient channels spaced at 610 mm, insulated with glass fibre batts, and protected with two layers of gypsum board

Wood joist, wood-I-joist, steel joist, and wood truss assemblies protected with double layers of gypsum board were studied to show the impact of the frame type on the fall-off of the gypsum board layers. The following discussion presents a comparison of the gypsum board fall-off of the different assemblies to that of the wood joist assemblies. In general, using wood-I-joist delayed the fall-off of the first piece of both layers of gypsum board. Using wood truss and steel joist assemblies also delayed the fall-off of the first piece of both layers of gypsum board except for the assemblies where the joists and resilient channels spacing was 610 mm. For those assemblies, using wood trusses or steel joists accelerated the fall-off of the first piece of the face layer of gypsum board and had minor impact on the fall-off of the first piece of the base layer.

5.3.6 Effect of Frame Spacing

The results presented in Figure 5-47 to Figure 5-51 for wood joist, steel joist, and wood truss assemblies shows the effect of the frame spacing (F.S.) on the fall-off of gypsum board layers. The fall-off time of gypsum board is shown in Figure 5-47 for two wood joist assemblies, FF-67 and FF-68, protected with two layers of 12.7 mm Type X gypsum board and covered with one layer of plywood sub-floor on the unexposed side of thickness 19 mm for FF-67 and 15.9 mm for FF-68. The assemblies were fabricated with glass fibre insulation of thickness 89 mm and resilient channels installed at 610 mm. The applied load for both assemblies was determined using the bending criteria and was 3256 N/m² and 5027 N/m² for FF-67 and FF-68 respectively. Both assemblies were constructed with joists of depth 235 mm; however, the joists for FF-67 were spaced at 610 mm while for FF-68 the joists were spaced at 406 mm. Figure 5-47 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-67 was recorded at around 47 and 51 minutes while for FF-68 it was recorded at approximately 48 and 53 minutes. Figure 5-47 shows also the fall-off of the first and last pieces of the base layer of gypsum board which occurred at about 52 and 53 minutes for FF-67 and at about 52 and 53 minutes for FF-68. The results show that the joist spacing has insignificant impact on the fall-off gypsum board for wood joist assemblies.

Figure 5-47 Effect of joist spacing for wood joist assemblies protected with two layers of gypsum board

Two steel joist assemblies, FF-23 and FF-24, protected with two layers of 12.7 mm Type X gypsum board and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side were studied to investigate the effect of the joist spacing on the fall-off of gypsum board for insulated steel joist assemblies. The assemblies were fabricated with glass fibre insulation of thickness 90 mm and resilient channels installed at 406 mm. The applied load for both assemblies was determined using the bending criteria and was 2945 N/m^2 and 1796 N/m^2 for FF-23 and FF-24 respectively. Both assemblies were constructed with joists of depth 203 mm and spaced at 406 mm for FF-23 and at 610 mm for FF-24.

Figure 5-48 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-23 was recorded at around 59 and 64 minutes while for FF-24 it was recorded at approximately 60 and 62 minutes. Figure 5-48 shows also the fall-off of the first and last pieces of the base layer of gypsum board which occurred at

bout 63 and 69 minutes for FF-23 and at bout 65 and 67 minutes for FF-24. For insulated steel joist assemblies, the finding shows that the joist spacing has insignificant impact on the fall-off of the first piece of the face layer of gypsum board; however, increasing the joist spacing delays the fall-off time of first piece of the base layer.

Figure 5-48 Effect of joist spacing for insulated steel joist assemblies protected with two layers of gypsum board

Two non-insulated steel joist assemblies, FF-51 and FF-62, protected with two layers of 12.7 mm Type X gypsum board and covered with one layer of plywood sub-floor on the unexposed side of 15.9 mm thick for assembly FF-51 and 19 mm thick for assembly FF-62 were studied to investigate the effect of the joist spacing on the fall-off of gypsum board for non-insulated steel joist assemblies. The assemblies were fabricated without cavity insulation or resilient channels. The applied load for both assemblies was determined using the bending criteria and was 3342 N/m² and 2123 N/m² for FF-51 and

FF-62 respectively. Both assemblies were constructed with joists of depth 203 mm and spaced at 406 mm for FF-51 and at 610 mm for FF-62.

Figure 5-49 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-51 was recorded at around 51 and 61 minutes while for FF-62 it was recorded at approximately 46 and 56 minutes. The fall-off of the first and last pieces of the base layer of gypsum board is also shown in Figure 5-49 which occurred at about 66 and 69 minutes for FF-51 and at about 54 and 56 minutes for FF-62. For the non-insulated steel joist assemblies, the result shows that increasing the joist spacing decreased the fall-off time of both layers of gypsum board.

Figure 5-49 Effect of joist spacing for non-insulated steel joist assemblies protected with two layers of gypsum board

Two insulated wood truss assemblies, FF-42 and FF-48, protected with two layers of 12.7 mm Type X gypsum board and covered with one layer of 15.9 mm thick plywood

sub-floor on the unexposed side were studied to investigate the effect of the joist spacing on the fall-off time of gypsum board. The assemblies were fabricated using glass fibre cavity insulation of thickness 89 mm and with resilient channels installed at 406 mm. The applied load for both assemblies was determined using the bending criteria and was 5602 N/m² and 3783 N/m² for FF-42 and FF-48 respectively. Both assemblies were constructed with joists of depth 305 mm and spaced at 406 mm for FF-42 and at 610 mm for FF-48.

Figure 5-50 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-42 was recorded at around 54 and 59 minutes while for FF-48 it was recorded at approximately 54 and 59 minutes. Figure 5-50 shows also the fall-off of the first and last pieces of the base layer of gypsum board which occurred at about 61 and 65 minutes for FF-42 and at about 62 and 66 minutes for FF-48. The records show insignificant effect of the joist spacing on the fall-off of the gypsum board layers.

Figure 5-50 Effect of joist spacing for insulated wood truss assemblies protected with two layers of gypsum board

Two non-insulated wood truss assemblies, FF-60 and FF-71, protected with two layers of 12.7 mm Type X gypsum board and covered with one layer of plywood sub-floor on the unexposed side of thickness 15.9 mm for FF-60 and 19 mm for FF-71 are used to investigate the effect of the joist spacing on the fall-off of gypsum board layers. The assemblies were fabricated without cavity insulation or resilient channels. The applied load for both assemblies was determined using the bending criteria and was 5602 N/m² and 3783 N/m² for FF-60 and FF-71 respectively. Both assemblies were constructed with joists of depth 305 mm and spaced at 406 mm for FF-60 and at 610 mm for FF-71.

Figure 5-51 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-60 was recorded at around 43 and 59 minutes while for FF-71 it was at approximately 45 and 51 minutes. Figure 5-51 shows also the fall-off of the first and last pieces of the base layer of gypsum board which occurred at about 59 and 61 minutes for FF-60 and at about 54 and 56 minutes for FF-71. The result shows that increasing the joist spacing for the studied wood truss assemblies has insignificant effect on the fall-off of the first piece of gypsum board; however, it decreases the fall-off time of the base layer of gypsum board.

Figure 5-51 Effect of joist spacing for non-insulated wood truss assemblies protected with two layers of gypsum board

The data presented above show that the frame spacing has an insignificant impact on the fall-off of the gypsum board except for the steel joist assemblies with joists spaced at 610 mm and fabricated without resilient channels. For those assemblies increasing the joists spacing from 406 mm to 610 mm accelerated the fall-off of the gypsum board layers, however, the effect was less on the fall-off of the base layer. A delay for the fall-off of the first piece of the base layer also was noticed when increasing the joist spacing from 406 to 610 mm for the wood truss assemblies fabricated without resilient channels

5.3.7 Effect of Frame Depth

Figure 5-52 shows the effect of frame depth (F.D) on the fall-off of gypsum board for wood joist assemblies. The wood joist assemblies FF-29 and FF-32 were protected with two layers of 12.7 mm Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side. The floor cavity

was insulated with glass fibre batts with thickness of 89 mm. Resilient channels were installed at spacing of 406 mm for both assemblies. The assemblies were loaded based on the bending criteria with 5075 N/m^2 for FF-29 and 3304 N/m^2 for FF-32. Both assemblies were made of wood joists spaced at 406 mm with depth of 235 mm for FF-29 and 184 mm for FF-32.

The first and last pieces of the face layer as shown in Figure 5-52 fell-off at around 45 and 53 minutes for the assembly with 235 mm joist depth, FF-29, and at roughly 53 and 57 minutes for the assembly with 184 mm joist depth, FF-32. The fall-off time of the first and last pieces of the base layer, as shown in Figure 5-52, occurred at about 59 and 62 minutes for FF-29 and at approximately 60 and 62 minutes for FF-32. The result shows that decreasing the joist depth from 235 to 184 mm increases the fall-off time of the gypsum board layers.

Figure 5-52 Effect of joist depth for wood joist assemblies protected with two layers of gypsum board

5.3.8 Effect of Wood-I-Joist Type

Three wood-I-joist assemblies, FF-10; FF-11; and FF-12, protected with two layers of 12.7 mm thick Type X gypsum board were studied to investigate the effect of the wood-I-joist type on the fall-off of gypsum board layers. The assemblies were fabricated with joists of depth 240 mm that were spaced at 406 mm, resilient channels spaced at 406 mm, and without floor cavity insulation. The unexposed side for all the assemblies was covered with one layer of 15.9 mm thick plywood sub-floor. All the assemblies were loaded based on the deflection criteria with 3926, 3830, 4405 N/m² for FF-10, FF-11, and FF-12 respectively. Assembly FF-10 was fabricated with 38 mm wide by 38 mm deep LVL flanges (FL.D-1) while assembly FF-11 was constructed with 38 mm wide by 64 mm deep lumber flanges (FL.D-2) and assembly FF-12 was constructed with 64 mm wide by 38 mm deep lumber flanges (FL.D-3).

As shown in Figure 5-53, the fall-off time of the first and last pieces of the face layer of gypsum board for the assembly FF-10 was recorded at approximately 48 and 58 minutes whereas for the assembly FF-11 it was at about 50 and 65 minutes and at roughly 54 and 62 minute for the assembly FF-12. The Figure also shows that the first and last pieces of the base layer of gypsum board fell-off at roughly 68 and 71 minutes for assembly FF-10, 74 and 77 minutes for assembly FF-11, and at bout 79 and 82 minutes for assembly FF-12. The performance of the assemblies show that the gypsum board layers for the assembly with flange dimension FL.D-1 fell-off first followed that the assembly with FL.D-2 and delay, except for the last piece of the face layer, occurred in the fall-off of both layers of gypsum board for the assembly with flange dimension FL.D-

3. The result shows that increasing both the depth and the width of the flange for the wood-I-joist assemblies increases the fall-off time of the gypsum board layers, however, the impact of the width is more on the fall-off time.

Figure 5-53 Effect of wood-I-joist type for assemblies protected with two layers of gypsum board

5.3.9 Effect of wood Truss Type

Two wood truss assemblies, FF-42 and FF-46, were studied to investigate the effect of the parallel-chord wood truss type size on the fall-off of gypsum board. The assemblies were protected with two layers of 12.7 mm thick gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side. Resilient channels were installed in both assemblies at a spacing of 406 mm and the floor cavity was insulated with glass fibre batts of thickness 89 mm. The applied load on both assemblies was determined using the bending criteria with 5602 and 4213 N/m² for FF-42 and FF-46 respectively. The assemblies were constructed with

metal-plate connected parallel-chord wood trusses spaced at 406 mm with parallel-chord oriented horizontally on flat nominal size of 4x2, 305 mm deep by 89 mm wide by 38 mm thick, for assembly FF-42 and nominal size of 3x2, 305 mm deep by 64 mm wide by 38 mm thick.

Figure 5-54 shows the fall-off time of the gypsum board layers for the wood truss assemblies, FF-42 and FF-46. The figure shows that the first and last pieces of the face layer of gypsum board fell-off at approximately 54 and 59 minutes for the assembly with nominal 4x2 chord, FF-42, and at about 55 and 60 minutes for the assembly with nominal 3x2 chord, FF-46. The fall-off of the first and last pieces of the base layer, as shown in Figure 5-54, was recorded in around 61 and 65 minutes for FF-42 and at approximately 62 and 68 minutes for FF-46. The results show an insignificant effect of the parallel-chord size on the fall-off of the gypsum board.

Figure 5-54 Effect of the parallel-chord wood truss size for wood truss assemblies protected with two layers of gypsum board

Two non-insulated wood truss assemblies FF-41 and FF-56 were used to investigate the effect of the parallel-chord orientation on the fall-off of gypsum board. The assemblies were protected with two layers of 12.7 mm Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side. Resilient channels were installed at a spacing of 406 mm in both assemblies. The assemblies were loaded based on the bending criteria with 5602 N/m^2 and 5650 N/m^2 for FF-41 and FF-56 respectively. The assemblies were constructed with metal-plate connected parallel-chord wood trusses spaced at 406 mm with parallel-chord of size nominal 4x2, 305 mm deep by 89 mm wide by 38 mm thick oriented horizontally on flat for assembly FF-41 and vertically on edge for assembly FF-56.

The first and last pieces of the face layer as shown in Figure 5-55 fell-off at around 58 and 68 minutes for the assembly with chord oriented horizontally, FF-41, and at roughly 54 and 62 minutes for the assembly with chord oriented vertically, FF-56. The first and last pieces of the base layer also shown in Figure 5-55 occurred at about 68 and 71 minutes for FF-41 and at approximately 62 and 64 minutes for FF-56. The finding shows that using vertical oriented chord accelerates the fall-off of the gypsum board.

Figure 5-55 Effect of parallel-chord wood truss orientation for wood truss assemblies protected with two layers of gypsum board

Two insulated wood truss assemblies FF-63 and FF-58 were used to investigate the effect of the parallel-chord type on the fall-off of gypsum board. The assemblies were protected with two layers of 12.7 mm Type X gypsum board on the exposed side and covered with one layer of 15.9 mm thick plywood sub-floor on the unexposed side. Resilient channels were installed at a spacing of 406 mm for both assemblies and the floor cavity was insulated with glass fibre batts with a thickness of 89 mm. The assemblies were loaded based on the bending criteria with 3543 N/m^2 and 6847 N/m^2 for FF-63 and FF-58 respectively. FF-63 was constructed with metal-plate connected parallel-chord wood trusses spaced at 406 mm with parallel-chord of size nominal 4x2, 286 mm deep by 89 mm wide by 38 mm thick oriented horizontally on flat while FF-58 was constructed with finger joint trusses.

The first and last pieces of the face layer, as shown in Figure 5-56, fell-off at around 51 and 57 minutes for the assembly with metal-plate connected parallel-chord, FF-63, and at roughly 49 and 56 minutes for the assembly with finger joint trusses, FF-58. The first and last pieces of the base layer also shown in Figure 5-56 occurred at about 57 and 62 for FF-63 and at approximately 55 and 63 minutes for FF-58. The result shows that using finger joint trusses slightly accelerates the fall-off of gypsum board.

Figure 5-56 Effect of parallel-chord wood truss web type for wood truss assemblies protected with two layers of gypsum board

5.3.10 Effect of Method of Fastening Gypsum Board Layers

Figure 5-57 and Figure 5-58 show the effect of the method of fastening the gypsum board layers on the fall-off of gypsum board panels for wood-I-joist assemblies protected with two layers of gypsum board. Four methods of fastening were used to investigate the effect on the fall-off of gypsum board:

- MF-1, fastening the butt ends for both layers of gypsum board to the resilient channels at a spacing of 406 mm with screws 38 mm from the board butt edges for assembly with joists spaced at 406 mm.
- MF-2, fastening the butt ends of the base layer to the resilient channels at spacing of 406 mm with screws 38 mm from the board edge while fastening the butt ends of the face layer to the base layer with type G screws, 38 mm long for assembly with joists spaced 406 mm.
- MF-3, fastening the butt ends of the base layer to the resilient channels at spacing 406 mm with screws 38 mm from the board butt edges while fastening the face layer to the base layer with type G screws, 38 mm long for assembly with joists spaced 610 mm.
- MF-4, fastening the butt ends of the base layer to the resilient channels at spacing 406 mm with screws 10 mm from the board butt edges while fastening the butt ends of the face layer to the base layer with type G screws, 38 mm long for assembly with joists spaced 610 mm.

Two non-insulated wood-I-joist assemblies, FF-10 and FF-13, were studied to investigate the effect of the method of fastening the gypsum board layers on the fall-off of gypsum board. The assemblies were fabricated with joist depth of 240 mm spaced at 406 mm and resilient channels installed at 406 mm. The assemblies were protected with

two layers of 12.7 mm Type X gypsum board on the exposed side and covered with one layer of 15.9 mm plywood sub-floor on the unexposed side. The applied load on both assemblies was calculated using deflection criteria and was 3926 N/m^2 . The gypsum board layers of the assembly FF-10 were fastened according to method 1 (MF-1) while that for the assembly FF-13 were fastened with method 2 (MF-2).

Figure 5-57 shows that the fall-off time of the first and last pieces of the face layer of gypsum board for assembly FF-10 was recorded at around 48 and 58 minutes while for FF-13 it was recorded at approximately 56 and 70 minutes. Figure 5-57 shows also the fall-off time of the first and last pieces of the base layer of gypsum board which occurred at about 68 and 71 minutes for FF-10 and at about 69 and 74 minutes for FF-13. The result shows that fastening the butt ends for both layers of gypsum board to the resilient channels at spacing 406 mm (MF-1) has an earlier fall-off of the first piece of the face layer of gypsum board than the assembly, FF-13, where only the butt ends of the base layer fastened to the resilient channels while the face layer was fastened to the base layer (MF-2). However, the effect is insignificant on the fall-off of the first piece of the base layer of gypsum board.

Figure 5-57 Effect of method of fastening gypsum board for non-insulated wood-I-joist assemblies protected with two layers of gypsum board

The effect of method of fastening the gypsum board on the fall-off of the gypsum board layers was also studied using two insulated wood-I-joist assemblies FF-17 and FF-18. The assemblies were fabricated with joist depth 240 mm spaced at 610 mm and resilient channels installed at 406 mm. The floor cavity for both assemblies was insulated with glass fibre batts of thickness 90 mm. The assemblies were protected with two layers of 12.7 mm Type X gypsum board on the exposed side and covered with one layer of 19 mm plywood sub-floor on the unexposed side. The applied load on both assemblies was calculated using deflection criteria and was 2969 N/m² for assembly FF-17 and 2490 N/m² for assembly FF-18. The gypsum board layers of FF-17 were fastened according to method 3 (MF-3) while that for FF-18 were fastened with method 4 (MF-4).

Figure 5-58 presents the fall-off time of the first and last pieces of the gypsum board layer. The figure shows that the first and last pieces of the face layer of gypsum board for assembly FF-17 fell-off at around 59 and 69 minutes while for FF-18 the fall-

off time was recorded at approximately 60 and 65 minutes. The fall-off of the first and last pieces of the base layer of gypsum board as recorded in Figure 5-58 occurred at bout 69 and 75 minutes for FF-17 and at bout 68 and 70 minutes for FF-18. The result shows insignificant difference of the fall-off time of gypsum board layers between the two fastening methods.

Figure 5-58 Effect of method of fastening gypsum board for insulated wood-I-joist assemblies protected with two layers of gypsum board

5.3.11 Effect of Applied Load

The load is applied on the assemblies using a steel frame with thirty hydraulic jacks. The jacks transfer the load to the assemblies by three circular steel pads with a diameter of 178 mm and thickness of 12.7 mm. The loading frame is shown in Figure 3-7. All the studied wood joist assemblies were loaded using the deflection criteria ($L/360$) except assemblies FF-28 and FF-29 which were loaded using the bending criteria (100% maximum strength). The load applied on the steel and wood truss assemblies was

determined using the bending criteria. Wood-I-joist assemblies were loaded based on the bending criteria except the following assemblies which were loaded based on the deflection criteria: FF-11 (94% maximum strength), FF-15 and FF-19 (74% maximum strength), FF-14 and FF-17 (93% maximum strength).

5.3.11.1 Assemblies with one layer of gypsum board

The effect of increasing the applied load on the fall-off of gypsum board for wood joist assemblies protected with single layer of gypsum board on the exposed side is shown in Figure 5-59. The figure shows the effect of loading the assemblies with the bending criteria versus the deflection criteria on the fall-off of gypsum board for wood joist assemblies protected with one layer 12.7 mm thick Type X gypsum board. The assemblies, FF-02A and FF-30, were fabricated with joists of depth 235 mm and spaced at 406 mm. Resilient channels were installed for both assemblies at a spacing of 406 mm. The assemblies were covered with one layer of 15.9 mm thick plywood on the unexposed side and constructed without floor cavity insulation. FF-02A was loaded with 3830 N/m² based on the deflection criteria while FF-30 was loaded with 5123 N/m² based on the bending criteria.

Figure 5-59 shows the fall-off time of the gypsum board for the assemblies FF-02A and FF-30. The fall-off of the first and last pieces of gypsum board occurred at around 42 and 47 minutes for the assembly loaded based on the deflection criteria, FF-02A, while for the assembly loaded based on the bending criteria, FF-30, it was at

roughly 41 and 43 minutes. The result shows that increasing the applied load for the studied wood joist assemblies had no major impact on the fall-off time of the first piece of gypsum board for the wood joist assemblies protected with a single layer of gypsum board.

Figure 5-59 Effect of the applied load for wood joist assemblies protected with one layer of gypsum board

5.3.11.2 Assemblies with two layers of gypsum board

The effect of the applied load on the fall-off of gypsum board layers for non-insulated wood joist assemblies protected with two layers of 12.7 mm thick Type X gypsum board is studied using the assemblies FF-03A and FF-28. The assemblies were constructed with joists of depth 235 mm spaced at 406 mm. Resilient channels were installed at a spacing of 406 mm. The unexposed side of the assemblies was covered with one layer of 15.9 mm thick plywood sub-floor. FF-03A was loaded with 3830 N/m² based on the deflection and FF-28 with 5075 N/m² based on the bending criteria.

Figure 5-60 shows the fall-off time of the first and last pieces of gypsum board layers for the assemblies. The first and last pieces of the face layer of gypsum board fell off at about 50 and 57 minutes for the assembly loaded with 3830 N/m^2 , FF-03A, while for the assembly loaded with 5075 N/m^2 , FF-28, it occurred at about 44 and 61 minutes. The records of the first and last pieces of the base layer of gypsum board are also shown in Figure 5-60 and occurred at approximately 78 and 82 minutes for assembly FF-03A and at around 67 and 69 minutes for assembly FF-28. Increasing the load on the assemblies resulted in a reduction of the fall-off time of the first piece of both layers of gypsum board for wood joist assemblies protected with double layers of gypsum board.

Figure 5-60 Effect of the applied load for non-insulated wood joist assemblies protected with two layers of gypsum board

The effect of the applied load on the fall-off of gypsum board layers for wood joist assemblies insulated with glass fibre batts with 90 mm thickness and protected with two layers of 12.7 mm thick Type X gypsum board is studied using the assemblies FF-06

and FF-29. The assemblies were constructed with joists of depth 235 mm spaced at 406 mm. Resilient channels were installed at a spacing of 406 mm. The unexposed side of the assemblies was covered with one layer of 15.9 mm thick plywood sub-floor. Based on the deflection criteria, assembly FF-06 was loaded with 3830 N/m^2 and based on the bending criteria assembly FF-29 was loaded with 5075 N/m^2 .

Figure 5-61 shows the fall-off time of the first and last pieces of gypsum board layers for the assemblies. The first and last pieces of the face layer of gypsum board fell-off at about 45 and 49 minutes for the assembly loaded with 3830 N/m^2 , FF-06, while for the assembly loaded with 5075 N/m^2 , FF-29, it occurred at about 45 and 53 minutes. The records of the first and last pieces of the base layer of gypsum board are also show in Figure 5-61 and occurred at approximately 57 and 63 minutes for assembly FF-06 and at around 59 and 62 minutes for assembly FF-29. The results show that increasing the load has a minor impact on the fall-off of the gypsum board layers.

Figure 5-61 Effect of the applied load for wood joist assemblies insulated with glass fibre batts and protected with two layers of gypsum board

5.3.12 Effect of Reproducibility Tests

Two wood truss assemblies, FF-59 and FF-79, protected with two layers of 12.7 mm thick Type X gypsum board were studied to investigate the variation of fall-off times for similar assemblies. Both assemblies were constructed with trusses 305 mm in depth and spaced at 610 mm. The assemblies were fabricated with resilient channels spaced at 610 mm and insulated with glass fibre batts cavity insulation 89 mm thick. The applied load on both assemblies was determined using the bending criteria and was 3783 N/m². One layer of 19 mm thick plywood covered the unexposed side for both assemblies. The assemblies were constructed with metal-plate connected parallel-chord wood trusses spaced at 406 mm with parallel-chord oriented horizontally on flat of nominal size 4x2, 305 mm deep by 89 mm wide by 38 mm thick.

The fall-off time of the first and last pieces of gypsum layers is presented in Figure 5-62. The figure shows that the first and last pieces of the face layer of gypsum board for the assembly FF-59 fell-off at around 40 and 49 minutes and at approximately 45 and 51 minutes for the repeated assembly, FF-79. The figure also shows the records for the first and last pieces of the base layer of gypsum board for the assemblies which was recorded for FF-59 at around 48 and 52 minutes and for FF-79 at about 51 and 54 minutes. The result shows a delay for the fall-off of the first piece of the face layer by 5 minute and for the fall-off of the first piece of the base layer by 3 minutes. Although, the two assemblies were similarly fabricated the results of the fall-off time were different. This performance shows that in addition to the different discussed parameters which affect the fall-off of the gypsum board layers, material handling such as gypsum board

can also affect the behaviour of the assemblies which could cause crack or damage for the board edge. As a result of this finding in the subsequent analysis on the impact of various parameters, variations of 5 minutes in the fall-off time can be then considered insignificant.

Figure 5-62 Effect of test repeatability for wood truss assemblies protected with two layers of gypsum board

5.4 Fire Resistance vs Gypsum Board Fall-off

Gypsum board can provide up to 90% of the assemblies' protection, therefore, its fire resistance depends on how long gypsum panels remain in place. Figure 5-63 shows a plot for the fire resistance and the fall-off of the first piece of gypsum board for the assemblies protected with a single layer of gypsum board. The data are also presented in Table 5-1. The findings show that assemblies fabricated without cavity insulation had fire resistance fairly close to the fall-off time of the first piece of gypsum board except assembly FF-01 which was constructed without resilient channels.

Figure 5-63 Variations between fire resistance and first piece gypsum board fall-off for all assemblies protected with one layer of gypsum board

Similar behaviour was observed for assemblies protected with double layers of gypsum board. Figure 5-64 shows that the assemblies fabricated without cavity insulation had fire resistance very close to its fall-off time of the first piece of the base layer of gypsum board except for FF-64 which was fabricated with resilient channels installed at a spacing of 610 mm and FF-26 that was constructed with steel deck\concrete.

Figure 5-64 Variations between fire resistance and first piece of base layer fall-off for all assemblies with two layers of gypsum board

5.5 Developing Criteria for the Fall-off time of Gypsum Board

5.5.1 General

The investigation of the different parameters discussed above showed the impact of these parameters on the performance of the assemblies and consequently on the behaviour of the gypsum board which provided the protection to the assemblies. This impact was considered by investigating the fall-off time of gypsum board for different assemblies. The findings show that the impact on the fall-off of gypsum board was different for the assemblies protected with single layer and double layers. Although, the recorded results presented the fall-off time of the first and last pieces of gypsum board for the assemblies protected with a single layer and the fall-off time of the first and last

pieces of the face and base layer of gypsum board for assemblies protected with double layer, the discussion in this section will focus only on the fall-off time of the first pieces of both layers. Furthermore, the manufacturing process, handling the construction materials, and fabrication of the assemblies might cause errors which affect the fall-off and will not be relevant in this analysis. Those assemblies would be exempted from the criteria developed below.

5.5.2 Assemblies with single layer of gypsum board

Eleven wood joist, five steel joist, and seven wood-I-joist floor assemblies fabricated with different parameters and protected with a single layer of gypsum board were investigated to determine criteria for the fall-off time of the first piece of gypsum board. In order to develop a correlation for the effect of the different parameters, a reference assembly was chosen in this analysis. The reference assembly has the following characteristics:

- Wood joist assembly;
- Joists depth is 235 mm;
- Joists spacing is 406 mm;
- Protected with single layer of 12.7 mm Type X gypsum board on the exposed side;
- Protected with single layer of 15.9 mm thick plywood sub-floor on the unexposed side;

- Resilient channels installed at 406 mm;
- No cavity insulation;
- The assembly is loaded based on the bending criteria (100% maximum strength).

The reference assembly corresponds to assembly FF-30 which was fabricated with the parameters considered above. The first piece of gypsum board for assembly FF-30 fell-off at 40 minutes and 43 seconds. Therefore, the base time for the fall-off of the first piece of gypsum board is 41 minutes.

The following procedure is used to develop an equation to predict the fall-off of the first piece of gypsum board for assemblies protected with single layer of gypsum board:

1. The base time of 41 minutes is used as the reference time for all the assemblies protected with single layer of gypsum board shown in Table 5-1;
2. Consider assemblies that differ by a single parameter to determine the impact of that parameter on the fall-off time;
3. Evaluate the impact of non-tested parameters which are used in combination with tested parameters;
4. Finally, formulate an equation that includes the effects of the parameters considered in this study.

The effect of parameters is considered in this analysis when their impact on the fall-off time was more than two minutes. Based on the findings of the impact of various parameters on the fall-off time of the first piece of gypsum board for the assemblies protected with a single layer the following equation was developed,

$$t_F = t_B + t_{SJ} + t_{WJ} + t_{Insl} + t_{RC} + t_{SFT} \quad 5-1$$

where, t_F is the fall-off time of the first piece of gypsum board;

t_B is the base time (41 minutes);

t_{SJ} is the effect of steel joist;

t_{WJ} is the effect of wood-I-joist flange width;

t_{Insl} is the effect of insulation;

t_{RC} is the effect of resilient channels;

t_{SFT} is the effect of sub-floor topping.

The values for the terms in equation 5-1 are taken from Table 5-2 when the associated parameter is present. If the parameter is not present the values is considered as zero.

Table 5-2: Values for variables in Equation 5-1

Parameters		Time (minutes)
Steel Joist (t_{SJ})		-5
Wood-I-Joist flange width ≥ 58 mm (t_{WIJ})		3
Cavity Insulation (t_{insl})	Glass fibre insulation	-15
	Rock fibre insulation (90 mm)	0 for SJ or -5
	Rock fibre insulation (178 or 241 mm)	-10
	Cellulose fibre insulation	0 for $b^* > 100$ mm or -5
No Resilient channels (t_{RC})		-15
Sub-floor topping-St/Con (t_{SFT})		-5

* b is the thickness of the insulation on the sides of the joist

Applying the developed equation on assembly FF-01A (as an example) yielded a calculated fall-off time of 26 minutes. For this assembly, the only parameter that differs from the reference assembly was its fabrication without resilient channels (t_{RC}) which resulted in an early fall-off time of 15 minutes (as provided in Table 5-2). Table 5-3 shows the effect of the different parameters and the calculated fall-off time compared to the experimental fall-off time for the assemblies protected with a single layer of gypsum board.

Table 5-3: Calculated and experimental fall-off of time of the first piece of gypsum board

Assembly No.	t_B	t_{insl}	t_{SJ}	t_{SFT}	t_{RC}	t_{WIJ}	t_F	Experimental time	Difference %
FF-01A	41				-15		26	24.22	5.70
FF-02A	41						41	42.07	-2.54
FF-07	41	-5					36	34.00	5.88
FF-08	41	-15					26	26.14	-0.54
FF-09	41	-5					36	26.35	35.10
FF-14	41						41	40.53	0.17
FF-16	41	-5					36	36.36	-0.99
FF-19	41	0					41	45.10	-9.09
FF-25	41		-5				36	35.50	0.28
FF-30	41						41	40.43	0.42
FF-33	41						41	39.35	3.18
FF-34	41	-5					36	37.19	-3.20
FF-36	41	-10					31	31.36	-0.77
FF-37	41		-5				36	36.30	-0.83
FF-38	41	-10	-5				26	26.41	-1.55
FF-45	41	-10					31	29.58	3.45
FF-49	41	-5					36	37.31	-3.51
FF-50	41	0	-5				36	34.17	5.36
FF-57	41	-5				3	39	39.08	-0.20
FF-66	41	-5					36	36.18	-0.50
FF-74	41	-5	-5				31	31.57	-1.81
FF-76	41	-5				3	39	38.58	0.01
FF-78	41	-5		-5		3	34	33.00	3.03

The result shows that the maximum difference between the calculated and the experimental time was 6 % except for assemblies FF-09 and FF-19. The reason of the behaviour of these two assemblies might be related to the manufacture process or the material handling. Figure 5-65 shows a plot for the calculated time versus the experimental time.

Figure 5-65 Calculated time vs experimental time for assemblies protected with single layer of gypsum board

5.5.3 Assemblies with double layers of gypsum board

Fifty three different floor assemblies fabricated with wood joist, steel joist, wood-I-joist and wood truss and protected with double layers of gypsum board were studied to investigate the criteria for the fall-off of the first piece of both the face and the base layer of gypsum board. The behaviour of the assemblies protected with double layers was more complicated than that of the assemblies protected with single layer. In addition to the effect of the different parameters on the fall-off of gypsum board discussed above, the protection of the face layer to the base layer and the cooling provided by the base layer to the face layer, as a result of the moisture produced by the base layer when the free and molecular bound water was driven off from the gypsum board core, yielded to different performance of the gypsum board and consequently affected its fall-off time.

An assembly with the following characteristics is considered as a reference assembly similar to the methodology used for the assemblies protected with single layer:

- Frames spaced at 406 mm;
- Protected with double layers of 12.7 mm Type X gypsum board on the exposed side;
- Protected with one layers of 15.9 mm thick plywood sub-floor on the unexposed side;
- Resilient channels installed at 406 mm;
- No cavity insulation;
- The assembly is loaded based on the bending criteria (100% maximum strength).

The procedure used for developing an equation that predicts the fall-off of the first piece of the face and the base layers of gypsum board for assemblies protected with double layers of gypsum board is similar to the procedure followed for assemblies protected with single layer of gypsum board. The effect of the different parameters, however, varied with the frame type. Therefore, base time and fall-off time are considered for each frame type separately.

5.5.3.1 Wood joist assemblies

The records of fourteen wood joist assemblies protected with double layers of gypsum board were studied to develop criteria for the fall-off time of the first piece of the

face and base layer of gypsum board. In addition to the fourteen assemblies, the wood joist assembly presented in section 4.5 which is listed as Carl-01 in Table 5-5 is considered in this analysis. As a result of the findings of the impact of various parameters on the fall-off time of the first piece of gypsum board for the wood joist assemblies protected with double layers the following equation was developed,

$$t_F = t_B + t_{JD} + t_{SFT} + t_{Insl} + t_{RC} + t_L \quad 5-2$$

Where, t_F is the fall-off time of the first piece of gypsum board layers;

t_B is the base fall-off time;

t_{JD} is the effect of decreasing the joist depth for wood joist assemblies;

t_{SFT} is the effect of the sub-floor topping;

t_{Insl} is the effect of the insulation;

t_{RC} is the effect of the resilient channels;

t_L is the effect of the applied load.

The values for the terms in equation 5-2 are taken from Table 5-4 when the associated parameter is present. If the parameter is not present the values is considered as zero.

Table 5-4: Values for variables in Equation 5-4

Wood Joist			Face Layer	Base Layer
Base time (minutes) (t_B)			45	67
Joist Depth (t_{JD})			8	N/A
Sub-floor topping (Ply/GC) (t_{SFT})			8	N/A
Cavity Insulation (t_{Inst})	Glass fibre	Defl. Criteria	-5	-20
		Bending	N/A	-5
	Rock fibre	Defl. Criteria	N/A	-20
		Bending	N/A	-5
	Cellulose fibre (C2)		N/A	-5
Resilient Channels (t_{RC})	No RC		N/A	-15
	RC @ 610		3	-10
Load (deflection) (t_L)			5	10

The effect of the different parameters was applied, using Equation 5-2, to the wood joist assemblies as shown in Table 5-5 and Table 5-6. The Tables also shows a comparison between the actual and the estimated fall-off time.

Table 5-5: Calculated and experimental fall-off time for wood joist assemblies, face layer

Assembly	t_B	t_L	t_{insl}	t_{JD}	t_{SFT}	t_{RC}	t_F	Experimental time	Difference %
Carl-01	45						45	45.37	-0.82
FF-03A	45	5					50	49.42	0.36
FF-04A	45	5					50	48.19	2.93
FF-06	45	5	-5				45	44.43	0.38
FF-28	45						45	43.49	2.55
FF-29	45						45	45.13	-0.29
FF-31	45						45	56.06	-19.73
FF-32	45			8			53	53.08	-0.15
FF-35	45				8		53	53.14	-0.26
FF-64	45					3	48	47.08	1.10
FF-67	45					3	48	47.29	0.66
FF-68	45					3	48	48.02	-0.04
FF-69	45					3	48	49.29	-2.62
FF-70	45					3	48	48.02	-0.04
FF-73	45					3	48	48.19	-0.39

Table 5-6: Calculated and experimental fall-off time for wood joist assemblies, base layer

Assembly	t_B	t_L	t_{insl}	t_{JD}	t_{SFT}	t_{RC}	t_F	Experimental time	Difference %
Carl-01	67					-15	52	50.03	3.14
FF-03A	67	10					77	77.43	-0.56
FF-04A	67	10	-20				57	56.5	0.18
FF-06	67	10	-20				57	57.3	-0.52
FF-28	67						67	67.09	-0.13
FF-29	67		-5				62	59.01	4.39
FF-31	67					-15	52	65.32	-20.39
FF-32	67		-5				62	60.1	2.50
FF-35	67		-5				62	60.44	1.92
FF-64	67					-10	57	54.55	3.76
FF-67	67		-5			-10	52	51.46	0.27
FF-68	67		-5			-10	52	51.58	0.04
FF-69	67		-5			-10	52	52.38	-1.49
FF-70	67		-5			-10	52	52.03	-0.06
FF-73	67		-5			-10	52	51.49	0.21

The result shows a maximum variation of 5 % between the calculated and experimental fall-off time of the first piece of the face layer and the fall-off of the first piece of the base layer. Assembly FF-31 was exempted from the results since it is the only assembly that delays the fall-off time for absence the resilient channels. The fall-off time for this assembly was discussed in section 5.3.2.2 and shown in Figure 5-14. Figure 5-66 and Figure 5-67 show a plot for the experimental and the calculated fall-off time of the face and base layer respectively.

Figure 5-66 Calculated time vs experimental fall-off time for wood joist assemblies, face layer

Figure 5-67 Calculated time vs experimental fall-off time for wood joist assemblies, base layer

5.5.3.2 Wood truss assemblies

Sixteen wood truss assemblies were studied to develop the criteria for the fall-off of gypsum board. In addition to the characteristics of the reference assembly mentioned above, metal-plate connected parallel-chord wood trusses with parallel-chord nominal size of 4x2, 305 mm deep by 89 mm wide by 38 mm thick, oriented horizontally on flat was considered as the reference assembly for the wood truss assemblies. Based on the findings of the impact of various parameters on the fall-off time of the first piece of gypsum board for the wood truss assemblies protected with double layers the following equation was developed,

$$t_F = t_B + t_{FS} + t_{Insl} + t_{RC} + t_{WTO} \quad 5-3$$

where, t_F is the fall-off time of the first piece of gypsum board layers;

t_B is the base fall-off time;

t_{FS} is the effect of frame spacing;

t_{Insl} is the effect of insulation;

t_{RC} is the effect of resilient channels;

t_{WTO} is the effect of wood truss orientation.

The values for the terms in equation 5-3 are taken from Table 5-7 when the associated parameter is present. If the parameter is not present the values is considered as zero.

Table 5-7: Values for variables in Equation 5-3

Wood Truss		Face Layer	Base Layer
Base time (minutes) (t_B)		57	68
Frame spacing (610 mm) (t_{FS})		N/A	-5*
Cavity Insulation (t_{insl})	Glass fibre	-5	-10
	Rock fibre	-5	-10
	Full cavity of cellulose	-5	-5
Resilient Channels (t_{RC})	No RC	-15	-10
	RC @ 610	-10	-10
Wood Truss orientation (Vertical) (t_{WTO})		-4	-6

* Only for assembly without resilient channels

The effect of the different parameters was applied, using Equation 5-3 to the wood truss assemblies as shown in Table 5-8 and Table 5-9. A comparison for the actual and estimated fall-off time is also shown in the tables.

Table 5-8: Calculated and experimental fall-off time for wood truss assemblies, face layer

Assembly	t_B	t_{insl}	t_{WTO}	t_{RC}	t_F	Experimental time	Difference %
FF-41	57				57	57.43	-0.75
FF-42	57	-5			52	53.49	-2.79
FF-46	57	-5			52	55.19	-5.78
FF-47	57	-5			52	52.10	-0.19
FF-48	57	-5			52	53.50	-2.80
FF-56	57		-4		53	54.35	-2.48
FF-58	57	-5			52	48.50	6.39
FF-59	57	-5		-10	42	40.25	3.35
FF-60	57			-15	42	43.15	-2.67
FF-63	57	-5			52	51.28	0.62
FF-71	57			-15	42	44.41	-5.43
FF-72	57			-10	47	49.04	-4.16
FF-75	57	-5		-10	42	44.12	-4.81
FF-79	57	-5		-10	42	45.31	-7.31
FF-80	57	-5		-10	42	45.10	-6.87
FF-82	57	-5			52	50.50	2.18

Table 5-9: Calculated and experimental fall-off time for wood truss assemblies, base layer

Assembly	t_B	t_{insl}	t_{FS}	t_{WTO}	t_{RC}	t_F	Experimental time	Difference %
FF-41	68					68	68.12	-0.18
FF-42	68	-10				58	60.55	-4.21
FF-46	68	-10				58	61.41	-5.55
FF-47	68	-10				58	60.02	-3.37
FF-48	68	-10				58	62.23	-6.80
FF-56	68			-6		62	61.51	0.15
FF-58	68	-10				58	54.42	5.84
FF-59	68	-10			-10	48	48.01	-0.02
FF-60	68				-10	58	59.07	-1.81
FF-63	68	-10				58	57.07	0.93
FF-71	68		-5		-10	53	54.28	-2.36
FF-72	68				-10	58	54.18	6.31
FF-75	68	-10			-10	48	50.28	-4.53
FF-79	68	-10			-10	48	51.27	-6.38
FF-80	68	-10			-10	48	50.24	-4.46
FF-82	68	-5				63	61.33	2.07

The result shows a maximum variation of 7 % between the estimated and actual fall-off time of the first piece of the face layer and the fall-off of the first piece of the base layer. The comparison between the experimental and calculated fall-off time is shown in Figure 5-68 and Figure 5-69.

Figure 5-68 Calculated time vs experimental fall-off time for wood truss assemblies, face layer

Figure 5-69 Calculated time vs experimental fall-off time for wood truss assemblies, base layer

5.5.3.3 Wood-I-joist assemblies

Thirteen wood-I-joist assemblies were studied to determine criteria for the fall-off of gypsum board. In addition to the characteristics of the reference assembly mentioned earlier, the wood-I-joist reference assembly is fabricated with 38 mm wide by 38 mm deep flange. Based on the finding of the analysis provided earlier of the impact of various parameters on the fall-off time of the first piece of gypsum board for the wood-I-joist assemblies protected with double layers the following equation was developed,

$$t_F = t_B + t_{SF} + t_{SFT} + t_{Insl} + t_{RC} + t_{MF-1} + t_{FD} \quad 5-4$$

Where, t_F is the fall-off time of the first piece of gypsum board layers;

t_B is the base fall-off time;

t_{SF} is the effect of sub-floor type;

t_{SFT} is the effect of sub-floor topping ;

t_{Insl} is the effect of insulation;

t_{RC} is the effect of resilient channels;

t_{MF-1} is the effect of method of fastening gypsum board layers;

t_{FD} is the effect of flange dimension.

The values for the terms in equation 5-4 are taken from Table 5-10 when the associated parameter is present. If the parameter is not present the values is considered as zero.

Table 5-10: Values for variables in Equation 5-4

Wood-I-joist type		Face Layer	Base Layer
Base time (minutes) (t_B)		60	70
Sub-floor type (OSB) (t_{SF})		-10	-15
Sub-floor topping (Ply/Con) (t_{SFT})		-5	N/A
Cavity Insulation (t_{insl})	Glass fibre	-5 ^{*1}	-13 ^{*1}
	Rock fibre (Full cavity)	-5	-5
Resilient Channels (t_{RC})	No RC	-7	-7
	RC @ 610	-5	-10
MF-1 (t_{MF-1})		-10	N/A
Flange dimension (t_{FD})		5 for FD-3 ^{*3}	5 for FD-2 ^{*2} 10 for FD-3 ^{*3}

^{*1} only for assemblies with joists spacing 406 mm

^{*2} FD-2 is 38 mm wide and 64 mm deep

^{*3} FD-3 is 64 mm wide and 38 mm deep

The effect of the different parameters was applied, using Equation 5-4, to the wood-I-joist assemblies as shown in Table 5-11 and Table 5-12.

Table 5-11: Calculated and experimental fall-off time for wood-I-joist assemblies, face layer

Assembly	t_B	t_{insl}	t_{SF}	t_{SFT}	t_{RC}	t_{MF-1}	t_{FD}	t_F	Experimental time	Difference %
FF-10	60					-10		50	47.53	4.36
FF-11	60					-10		50	49.47	0.26
FF-12	60					-10	5	55	54.24	0.66
FF-13	60							60	56.06	6.31
FF-15	60	-5						55	53.16	2.71
NRC-02	60							60	59.28	0.54
FF-17	60							60	59.35	0.42
FF-18	60							60	60.00	0.00
FF-20	60				-5			55	55.41	-0.74
FF-55	60		-10					50	48.36	2.56
FF-61	60	-5		-5				50	49.39	0.43
FF-77	60				-7			53	52.21	0.75
FF-81	60	-5						55	56.41	-2.50

Table 5-12: Calculated and experimental fall-off time for wood-I-joist assemblies, base layer

Assembly	t_B	t_{insl}	t_{SF}	t_{RC}	t_{FD}	t_F	Experimental time	Difference %
FF-10	70					70	68.36	1.81
FF-11	70				5	75	73.46	1.55
FF-12	70				10	80	78.55	1.34
FF-13	70					70	69.18	0.61
FF-15	70	-13				57	56.50	0.18
NRC-02	70					70	67.04	3.82
FF-17	70					70	69.04	0.81
FF-18	70					70	68.16	2.11
FF-20	70			-10		60	59.38	0.37
FF-55	70		-15			55	56.08	-1.93
FF-61	70	-13				57	57.14	-0.25
FF-77	70			-7		63	63.42	-0.66
FF-81	70	-5				65	65.41	-0.63

The result shows a maximum variation of 5 % between the estimated and actual fall-off time of the first piece of the face layer and the fall-off of the first piece of the base layer. A slight higher difference can be noticed for assembly FF-13 due to the early fall-off time of the first piece of the face layer. The fall-off time of this assembly was discussed in section 5.3.3.2 for the wood-I-joist assemblies. The experimental and calculated fall-off time are shown in Figure 5-70 and Figure 5-71.

Figure 5-70 Calculated time vs experimental fall-off time for wood-I-joist assemblies, face layer

Figure 5-71 Calculated time vs experimental fall-off time for wood-I-joist assemblies, base layer

5.5.3.4 Steel joist assemblies

The effect of the parameters on the fall-off time of thirteen steel joist assemblies was studied to obtain criteria for the fall-off time of gypsum board. A base fall-off time

of 65 minutes was considered for the first piece of the face layer and 73 minutes was estimated for the first piece of the base layer. Based on the analysis of the impact of various parameters on the fall-off time of the first piece of gypsum board for the steel joist assemblies protected with double layers the following equation was developed,

$$t_F = t_B + t_{FS} + t_{SFT} + t_{Insl} + t_{RC} \quad 5-5$$

where, t_F is the fall-off time of the first piece of gypsum board layers;

t_B is the base fall-off time;

t_{FS} is the effect of frame spacing;

t_{SFT} is the effect of sub-floor topping ;

t_{Insl} is the effect of insulation;

t_{RC} is the effect of resilient channels;

The values for the terms in equation 5-5 are taken from Table 5-13 when the associated parameter is present. If the parameter is not present the values is considered as zero.

Table 5-13: Values for variables in Equation 5-5

Steel joist assemblies		Face Layer	Base Layer
Base time (minutes) (t_B)		65	73
Frame spacing (610 mm) (t_{FS})		- 5 * ¹	- 10 * ¹
Sub-floor topping (t_{SFT})	Ply/Con	-10	-10
	St/Con	-5	N/A
Cavity Insulation (t_{insl})	Glass fibre	-5	-10
	Rock fibre	-10	-15
	Cellulose	N/A	-10
Resilient Channels (t_{RC})	No RC	-15	-7
	RC @ 610	- 15 * ²	-10

*¹ only for assemblies without resilient channel*² N/A for assembly with st/con sub-floor

The effect of the different parameters was applied, using Equation 5-5 to the steel joist assemblies as shown in Table 5-14 and Table 5-15. The tables also show a comparison for the calculated and experimental fall-off times.

Table 5-14: Calculated and experimental fall-off time for steel joist assemblies, face layer

Assembly	t_B	t_{insl}	t_{FS}	t_{SFT}	t_{RC}	t_F	Experimental time	Difference %
FF-22	65					65	66.26	-1.90
FF-23	65	-5				60	59.23	0.62
FF-24	65	-5				60	59.48	0.20
FF-27	65	-5		-10		50	49.26	0.69
FF-40	65			-5		60	60.39	-0.65
FF-43	65	-5		-5		55	54.28	0.59
FF-44	65	-5		-5		55	52.32	4.36
FF-51	65				-15	50	51.16	-2.27
FF-52	65	-5			-15	45	42.17	5.76
FF-53	65	-10		-5		50	51.06	-2.08
FF-54	65		-5	-5	-15	40	37.38	5.94
FF-62	65		-5		-15	45	46.15	-2.49
FF-65	65				-15	50	48.45	3.20

Table 5-15: Calculated and experimental fall-off time for steel joist assemblies, base layer

Assembly	t_B	t_{insl}	t_{SF}	t_{RC}	t_{FD}	t_F	Experimental time	Difference %
FF-10	70					70	68.36	1.81
FF-11	70				5	75	73.46	1.55
FF-12	70				10	80	78.55	1.34
FF-13	70					70	69.18	0.61
FF-15	70	-13				57	56.50	0.18
NRC-02	70					70	67.04	3.82
FF-17	70					70	69.04	0.81
FF-18	70					70	68.16	2.11
FF-20	70			-10		60	59.38	0.37
FF-55	70		-15			55	56.08	-1.93
FF-61	70	-13				57	57.14	-0.25
FF-77	70			-7		63	63.42	-0.66
FF-81	70	-5				65	65.41	-0.63

The result shows a maximum variation of 7 % between the estimated and actual fall-off time of the first piece of the face layer and the fall-off of the first piece of the base layer. The experimental and calculated fall-off time are shown in Figure 5-72 and Figure 5-73.

Figure 5-72 Calculated time vs experimental fall-off time for steel joist assemblies, face layer

Figure 5-73 Calculated time vs experimental fall-off time for steel joist assemblies, base layer

6. SUMMARY AND CONCLUSIONS

6.1 Summary

This research was carried out to provide an understanding of the performance of gypsum board protecting floor assemblies when exposed to fire. The study included comparisons of tests for intermediate- and full-scale floor assemblies when exposed to standard and non-standard time-temperature relationships and development of criteria for the fall-off time of gypsum board in full-scale standard fire resistance tests.

Two intermediate-scale fire resistance tests on floor assemblies exposed to standard and non-standard time-temperature curve were carried out to provide a comparison of the effect of the time-temperature relationship on the performance of the gypsum board. Two full-scale fire resistance tests on floor assemblies using standard and non-standard exposure were conducted to provide an insight into the behaviour of these systems when exposed to those standard and non-standard fires.

Criteria for predicting the fall-off time of the gypsum board layers protecting floor assemblies when exposed to fire have been developed. The criteria are based on the investigation of the effect of floor components on the fall-off time of gypsum board. This investigation was conducted using the results of eighty full-scale fire resistance tests on floor assemblies conducted at the National Research Council of Canada facilities.

6.2 Conclusions

From the analysis of the intermediate- and full-scale tests results and the observation of the fall-off time of the gypsum board the following conclusions can be drawn:

- The non-standard exposure shows that the calcination and fall-off time of gypsum board protecting full-scale floor assemblies is highly dependent on the severity of the fire exposure.
- The temperatures at the center of the assembly of the full-scale test were higher than the temperature of the intermediate-scale tests. Temperatures in the assemblies at other locations compare well. The difference in temperature between intermediate- and full-scale tests show that the intermediate-scale test should not be used to determine the fire resistance rating for assemblies. This test should only be used development work.
- Sealing the joist for the intermediate-scale test results in an early charring of the wood joists for the standard test. In contrast, the effect of sealing the joist of the non-standard test was insignificant.
- The parameters that affect significantly the fall-off time of gypsum board protecting floor assemblies are the number of gypsum board layers, installation of resilient channels and installation and type of floor cavity insulation. As expected, assemblies with two layers of gypsum board have longer fall-off times than assemblies with a single layer. The installation of resilient channels also delayed the fall-off time of the gypsum board regardless of the spacing.

- Installation of cavity insulation accelerates the fall-off time of the gypsum board regardless of the type of the insulation.
- Five correlations were developed that provide the fall-off time of the first piece of gypsum board layers. One correlation yields the fall-off time of the first piece of gypsum board for assemblies protected with single layer of gypsum board while four correlations give the fall-off time of the first piece of the face and the base layer of gypsum board for assemblies protected with double layers. The fall-off times computed using the developed correlations compare well with the experimental values for the assemblies considered in this study.
- The fire resistance time for non-insulated floor assemblies fabricated with resilient channel spaced at 406 mm is very close to the fall-off time of the first piece of gypsum board for assemblies protected with single layer of gypsum board.
- The fire resistance time of non-insulated floor assemblies protected with a double layer of gypsum boards fabricated with resilient channels spaced at 406 mm is very close to the fall-off time of the first piece of the base layer of gypsum board.

7. RECOMMENDATIONS

Many sophisticated computer models have been developed to predict the fire resistance and heat transfer of wall assemblies, however, the passive effort on the development of the computer model that predicts the fire resistance and heat transfer of floor assemblies can seldom be found. Therefore, it is recommended to develop a computer model that serves this topic. The results of the tests presented in this study can be used for validation of such model.

It is evident from the experimental results presented in this study that the behaviour of the gypsum board is highly dependent on the severity of fire exposure. Since this behaviour impacts the fire resistance of building systems it is necessary to model the actual fire scenario to evaluate the fire resistance requirements for building elements.

This study also shows that the behaviour of the gypsum board depends on the variation of the assembly's component. To improve the predictions of the fall-off time of the gypsum board layers, further research is recommended to make a full assessment of the effect of the following parameters on the fall-off of gypsum board:

- Lining thickness;
- Frame depth for different types of frame;
- Frame spacing;
- Thickness of the cavity insulation;
- Applied load on the assemblies;

- Types of the wood-I-joists and wood-I-trusses;

The investigations of the impact of the different floor components on the fall-off of gypsum board presented in this study were all based on exposing the assemblies to a standard time-temperature curve. The extent to which their fire performance is varied when exposed to non-standard fire should be experimentally evaluated.

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A. APPENDIX A: TESTS OBSERVATIONS AND PHOTOS

Full-scale Exposed to Standard Fire

Using video cameras, it was observed during the test that the paper lining was ignited in the first few minutes followed that by the fall-off of the filler compound (gypsum mix) which covered the gypsum board joints of the two adjacent panels and the screws at around 7 minutes from the ignition and was completely fallen at around 20 minutes. The gypsum board layers at that time were still intact. The face layer of gypsum board started to crack and peel-off at around 44 minutes. The fall-off of the first piece of the face layer was witnessed at 45 minutes and 37 seconds. The base layer was then swollen and its joints started to open. The fall-off of the first piece of the base layer was recorded at 50 minutes and 3 seconds. At 52 minutes a cracking sound was heard followed by flames penetration. Assessment of the floor after the fire was extinguished revealed that the floor was failed structurally. The middle of the joists was broken and all the joists were charred as shown in Figure A-1. Another observation made at the termination of the test was that the middle of the sub-floor was broken as shown in Figure A-2.

Appendix A: Tests observations and photos

Figure A-1 Wood joists after the test

Figure A-2 Sub-floor after the test

Full-scale Exposed to Non-standard Fire

Similar to the standard test, the paper lining was ignited in the first few minutes followed by the fall-off of the filler compound (gypsum mix) which covered the gypsum board joints of the two adjacent panels and the screws. Cracks were observed in the face layer at approximately 10 minutes. As a result of the fast growth of temperature and the early completion of the calcination of the face layer, small pieces started to fall-off and was observed as a powder at around 11 minutes. The fall-off of the first big piece was witnessed at 13 minutes and 27 seconds. As mentioned earlier, the furnace was shut-off at 20 minutes which resulted in darkness in the furnace and it was unable to complete the video recording of the test. Inspection of the gypsum board after the fires were extinguished revealed that although the base layer of gypsum board had remained intact as shown in Figure A-3, it had become considerably brittle due to the loss of the chemically bound water through calcination of the gypsum. Simultaneously, the base layer could be easily removed to expose the joists. The joists after suppressing the fire were still undamaged with some char at the bottom of the joists as shown in Figure A-4.

Figure A-3 Base layer of gypsum board after the test

Figure A-4 Wood joists after the test