Hybrid Fire Testing for Performance Evaluation of Structures in Fire - Part 2: Application

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Part 2 Application

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ABSTRACT

A hybrid fire testing (HFT) approach was carried out by means of both computer simulation and experimentation using the National Research Council Canada's (NRC) testing facilities in Ottawa. Fire structural performance of a 3D full-scale 6-storey building structure was tested for a fire compartment scenario in the main floor of the building. The column in the designated fire compartment was exposed to the fire in a column furnace and the rest of the building was simulated using a numerical modeling. The methodology of the HFT and its numerical verifications were developed and described in a previous report. This report includes application of the HFT and its displacement results for fire structural performance of the whole 6-storey building. It also includes results of a separate column tested in fire using the traditional fire resistance standard test method. The second column specimen was identical to that of the column tested using the HFT. A comparison is provided between the results of the standard test and the HFT.

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INTRODUCTION

Hybrid fire testing (HFT) is a new method for assessing fire performance of structures (Mostafaei and Mannarino 2009, Mostafaei, 2010 and Mostafaei, 2011). Traditionally, fire resistance rates of structural elements, e.g. columns, have been measured using a prescriptive test method, which assessed the fire endurance of the structural elements separated from the rest of the structure. In other words, performance of the whole building in fire was estimated based on a single element testing method. To assess performance of the whole building in fire, a realistic method is to test the whole building physically in the fire. However, such a method is very expensive to apply, since the entire building needs to be constructed and tested. On the other hand, there is less flexibility provided using the direct full-scale test method. For instance, if the test needs to be carried out for a new variable, e.g. for structural elements with different configurations or material properties, this would require building a new full-scale building specimen.

Using HFT, performance of the whole building could be simulated with a very reasonable cost, almost the same as the current standard tests, however with more reliable results than the prescriptive methods. The method is also flexible; various building structural configurations and properties could be tested by building only the structural elements that are tested in the furnace.

The HFT methodology was presented previously (Mostafaei, 2011). This report describes implementation of the HFT for a full-scale building. For this purpose, a 6-storey reinforced concrete building with a fire compartment in the centre of the first floor was tested by the Fire Research Program of NRC using the HFT method. The column in the fire compartment was tested in the NRC's column furnace facility and the rest of the building was simulated using the SAFIR software (SAFIR 2005). The results of the test were compared to that of the test of an identical column, tested using the prescriptive test method.

HFT implemented in this study includes load and deformation interactions between the test and analysis. Both the furnace test specimen and the rest of the structure were exposed to the CAN/ULC-S101 standard fire, for the purpose of comparison with the results of a column specimen tested previously using the prescriptive test method. In case of a real fire test, interactions in HFT must include temperature component in addition to the load and deformation. That is to measure temperatures during the test and impose the rest of structures to the same temperatures in the analysis.

Two identical column specimens used in this study were constructed in 1996; only one of them was tested previously, in 1999, however the second specimen was still available. These two specimens were part of a previous NRC experimentation program for fire endurance assessment of the high strength columns (Kodur, et al. 2001). However, the experimental program was terminated and neither the results for the first test were published nor the second column tested. Since both column specimens were identical and made from the same concrete batch, for the sake of comparison, the second column specimen was selected for the HFT test. This report includes the results of both tests.

THE 6-STOREY BUILDING SPECIMEN

A 6-storey reinforced concrete building specimen was designed based on the Canadian Building Code and Concrete Design Standard for a hybrid fire test. Further details of the design were described in the HFT Methodology report (Mostafaei 2011). Figure 1 shows the overall 3D structural frame configuration of the building.

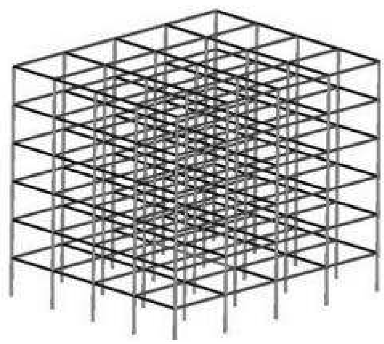

FIGURE 1. The 6-Storey Reinforced Concrete Building Structure Specimen.

Figure 2 shows both the floor plan of the building and the elevation of the main frame as well as the location of the fire compartment on the first floor. The main frames of the building are in the direction with the shorter spans (5.0 m), as shown in Figure 2. The frames perpendicular to the main frames are considered secondary frames. The floor loads are considered to be carried only by the main frames.

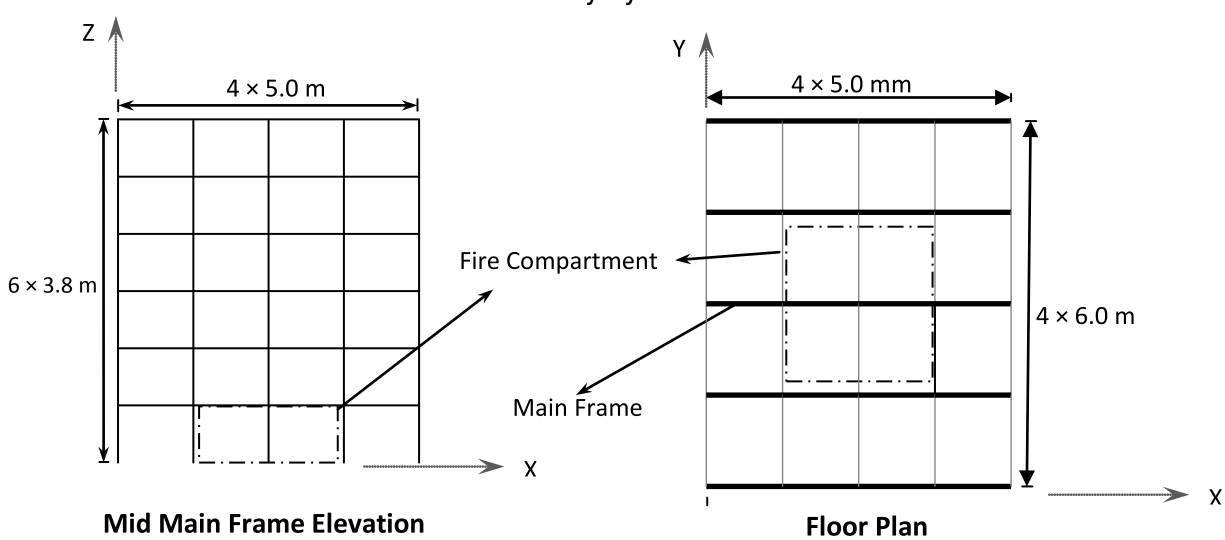

FIGURE 2. The Elevation and Floor Plan of the 6-Storey Reinforced Concrete Building.

The applied axial load for the previous column test, carried out using the traditional prescriptive method, was a constant load that was 2000 kN. For the sake of comparison, the applied load on the 6-storey frame test was adjusted in order to achieve the same level of axial load in the centre column of the first floor; however, the building code requirements for load combinations were also satisfied. As for the results, the applied load obtained for the main interior frames at the roof level was 43.7 kN/m and the main interior frames at the other levels was 68.5 kN/m. The end frames were subjected to half of the above loads accordingly.

Columns section

Cross section and details of the reinforcements for both column specimens, as well as the rest of the columns in the 6-storey building specimen are shown in Figure 3. Concrete compressive strength, for both column specimens, were 96 MPa obtained based on three cylinder compression tests, carried out before the fire tests. The concrete was made of siliceous aggregates with a mix of steel fibre, 42 kg/m^3.

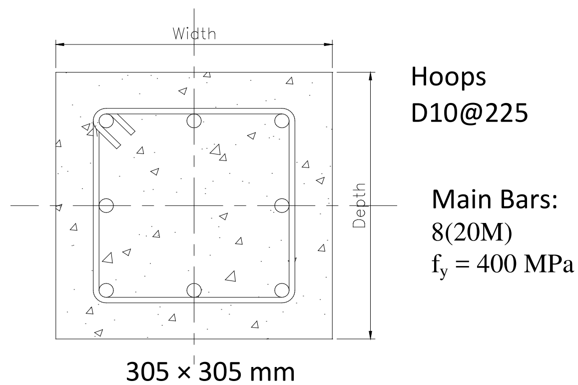

FIGURE 3. Cross Section of Columns at all Levels.

Beam sections

The same concrete properties were considered for beams as that for the columns. Figure 4 shows the cross section for the beams of the main frames with material properties for concrete and steel. Figure 5 illustrates the cross section for beams in the secondary frames. In order to include contribution of the floor slabs in the building response, all beams were designed as T beams. For simplicity, end beams were modeled with the same cross sections as that of the interior beams (a balcony type).

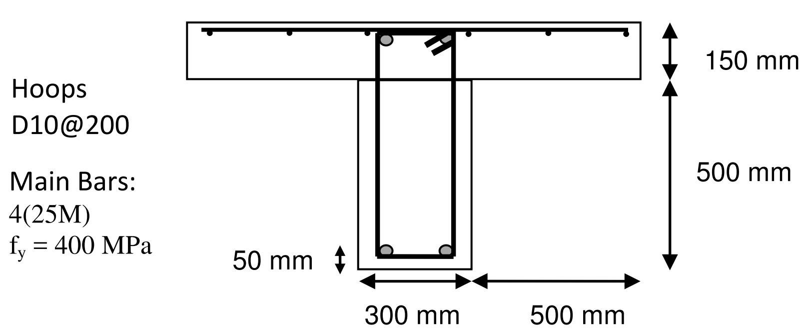

FIGURE 4. Cross Section of Beams in the Main Frames.

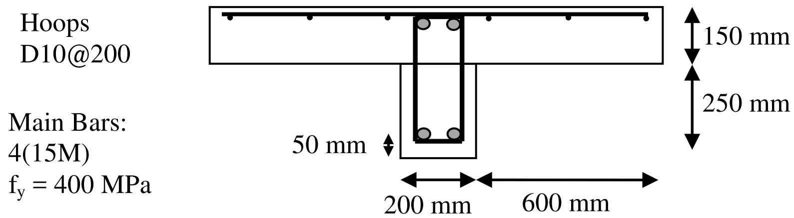

FIGURE 5. Cross Section of Beams in the Secondary Frames.

SPECIFICATIONS OF THE COLUMN SPECIMEN

The column specimens were 3810 mm long from end plate to end plate and were of square cross-section with dimensions of 305 mm × 305 mm.

Cement

Normal Type I Portland cement was used for constructing the two column specimens.

Aggregate

The concrete was made of fine aggregates and siliceous coarse aggregates. Typically a concrete made of normal weight coarse aggregate, consisting mainly silica and silicates (quartz), is referred to as siliceous aggregate concrete. On the other hand, concrete made of coarse aggregate, consisting mainly of calcium carbonate or a combination of calcium and magnesium carbonate (for example limestone and dolomite), is referred as to carbonate aggregate concrete (Kodur et al. 2001).

Reinforcement

Deformed bars were used as main bars and transverse reinforcements. The main bars of the column included 8 steel bars of 20 mm, symmetrically located on the cross section. The percentage of the main bars in the cross-section of Columns HS21 was 2.58. The ties were of 10 mm diameter with spacing of 225 mm. The ties were lapped with 135^{o} bends at the ends. Figures 3, 6 and 7 show the reinforcing details of the columns with the arrangement of the main reinforcing bars and ties. The main bars were welded to steel end plates. Both longitudinal and transverse bars had yield strength of 400 MPa. The clear concrete cover from the ties to the cross section edges was 38 mm.

Concrete Mix

The volume of the concrete batch was 4m^3, which was adequate for 4 specimens. The concrete mix included 2000.00 kg cement (normal type I), 4400.00 kg coarse aggregate (granite- siliceous aggregate), 168.00 kg silica fume (force 10,000 D), 2800.00 kg fine aggregate, 560.00 kg (360L) water, 168 kg steel fibre (based on 42 kg/m^3), 0.28 water-cement ratio, 5.8 L (290 ml/100 kg cement) water reducing/retarding admixture, 18 L superplasticizer, Daracem 100, added at NRC (9 L was added also at plant). The 28-day and 90-day average cylinder compressive strengths were 66.4 MPa and 87.20 MPa respectively. The average cylinder compressive strengths just before the two tests were 96MPa; three cylinder compressive specimens were tested on August 3, 1999 and three cylinder compressive specimens were tested on June 17, 2011.

Specimens' Instrumentation

Figure 6 shows locations of the thermocouples on the column cross section, at the centre high of the column. Thermocouples are made of Type K chromel-alumel 0.91 mm thick for measuring temperatures for both concrete and steel at the locations shown in Figure 6.

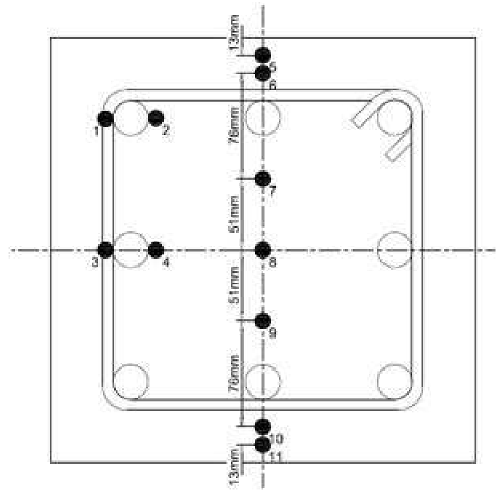

FIGURE 6. Column Cross-Section and Location of Thermocouples.

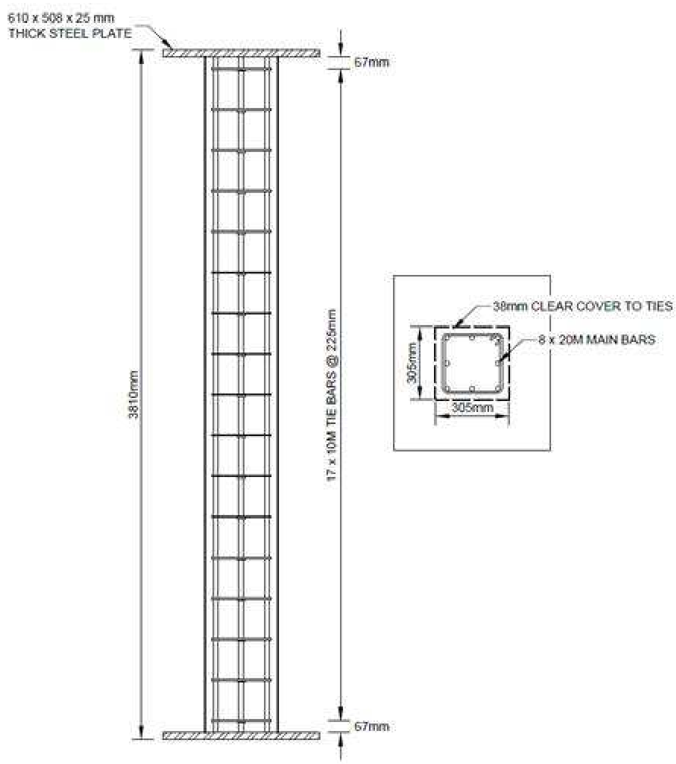

FIGURE 7. Reinforcement and Details of the Column Specimen.

Curing

Both concrete columns were constructed from the same batch of concrete. The column specimens' moist cured in their forms for approximately seven days. The first column specimen was tested three years after it was cast and the second column was tested 15 years after construction. No information was found for the relative humidity of the first test. For the HFT specimen, the internal relative humidity of column was 90.1% while the ambient relative humidity was 54%.

COLUMN TEST FACILITY

The tests were carried out using the NRC's full-scale column furnace facility in Ottawa. The furnace is capable of applying axial loads up to 9790 kN (2200 kips), lateral loads up to 110 kN (25 kips) in a North-South direction, lateral loads up to 310 kN (70 kips) in a East-West direction and e-centric loading. E-centric hydraulic jacks are placed one at the top and one at the bottom of the column at a distance of 508 mm from the axis of the column. The capacity of the top hydraulic jack is 587 kN and the bottom hydraulic jack is 489 kN. Further details are provided by Lie, T.T. (1980).

During the test the axial load was controlled by servocontrollers and measured with pressure transducers with ~4.0 kN accuracy at lower load levels and relatively better accuracy at higher loads. Lateral loads are controlled and measured with load cells.

Lateral, axial displacements and top and bottom rotations are measured using transducers with an accuracy of ~0.002 mm. The end plate column's rotations were calculated based on the plates' displacement at a distance of 500 mm from the centre of the column axis.

The furnace is designed to produce conditions that a structural element could be exposed to a fire, e.g. standard fire. Figure 8 shows the column furnace chamber.

The furnace chamber has a floor area of 2600 x 2600 mm and height of 4300 mm. The chamber is insulated from inside to efficiently transfer the heat to the column specimens. Part of the column specimens at the top and bottom are insulated to keep the heat away from the test apparatus. Therefore, only 3200 mm of the column specimen is exposed to fire during the test. The furnace has 32 propane gas burners arranged at different elevations each with four burners. The total capacity of the burners is 4700 kW. Each burner can be controlled individually. The pressure in the furnace chamber is monitored and set to be fairly lower than atmospheric pressure.

Eight Type K chromelalumel thermocouples, located 305 mm from the column specimen at different heights, measure the furnace temperatures during the tests. The furnace temperature is controlled based on the average of the temperatures measured by these thermocouples.

FIGURE 8. NRC's Column Furnace Facility.

HFT EXPERIMENTATION

Figure 9 illustrates the HFT implemented for the 6-storey building specimen. The column specimen, which was tested in the furnace, was the centre column on the first floor of the building, in the centre of the fire compartment. The rest of the building structure, including beams and the floor in the fire compartment, were simulated using the SAFIR software (the new version, which was released in 2011). The HFT was carried out for the building as described in this section.

Numerical simulation assumptions

Mechanical properties of the concrete and steel reinforcement for all sections were considered identical as that of the column specimens. The numerical analyses were carried out using the SAFIR software. Beams and columns were simulated using fibre models and therefore shear responses of the elements were considered negligible. All the connections were considered moment resisting connections.

The fire compartment was considered in the centre of the building; therefore, lateral deformations due to thermal expansion were ignored. This assumption was verified in a previous report (Mostafaei 2011). Therefore, the interaction components between the column specimen and the frame were the column end's axial load and axial deformation in the analysis. In the analysis, all the beams in the fire compartment were exposed to the same fire as that for the column specimens.

Fire Exposure

At the start of the test the measured ambient temperature was 23.4 ^{o}C. The average temperatures in the fire compartment, both in the furnace and in the simulation, during the test were controlled based on the CAN/ULC-S101 standard temperature-time curve.

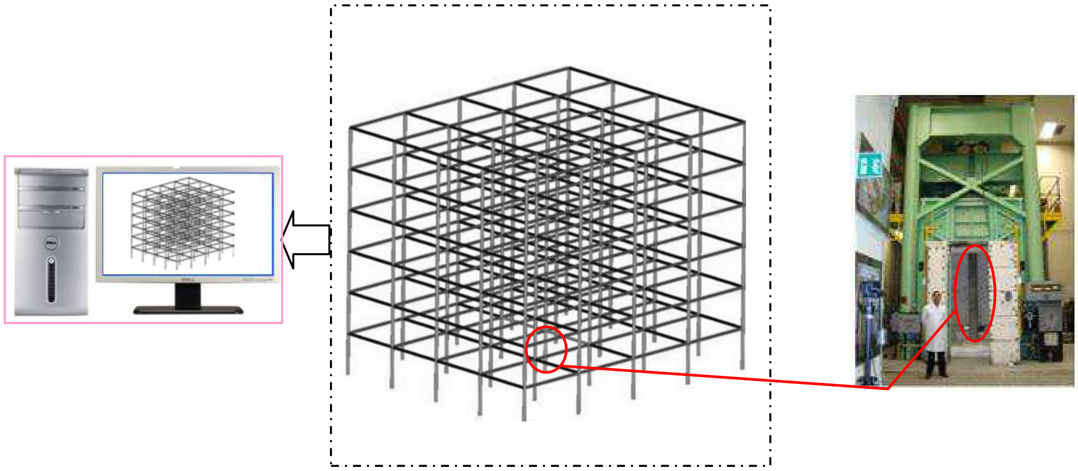

FIGURE 9. The HFT Implementation for the 6-Storey Reinforced Concrete Building Specimen.

Load and support conditions of the specimen

For the column in the furnace, no rotation or lateral displacements were imposed at the top and bottom of the specimen. For the rest of the building, at the point where the column specimen is connected to the frame, no rotation was permitted. However, the frame was free to displace in the two horizontal directions. The vertical displacement was controlled based on the result of the column vertical movement in the furnace. The initial axial load on the column specimen was calculated from the analysis of the building under the applied load at the ambient temperature, which was 2000 kN. That provided a stress on the column cross section, which was about 22% of the concrete compressive strength. The initial axial load was applied on the column specimen, before the fire started, gradually reaching its value in a 30 minute time period. The test started 1 hour and 50 minutes after the initial load was applied.

Data recording during the test

Temperatures in the furnace and designated locations in concrete and steel bars, axial deformation and axial load of the column specimens, and time were recorded, during the test. Axial and shear loads, and moments for all the building elements and support reactions, displacements in three main directions for all the connections and nodes of the building specimen were determined during the test and recorded at each time step.

The HFT process

The simplified HFT process, described by Mostafaei (2011), was implemented for this experimentation.

Here are the steps for implementation of the simplified HFT:

Step 1: Run the analysis for the entire structure, with the column specimen included in the analysis, for the ambient temperature and obtain the axial load and vertical deformation of the centre column on the first floor, referred as the column specimen.

Step 2: Run another analysis for the structure, but this time without the column specimen. When the frame is subjected to the vertical deformation obtained in Step 1, at the location of the column specimen being separated. Then obtain the corresponding load reaction. If the load reaction is different from the axial load obtained in Step 1, then an adjustment in deformation may be needed to minimize such difference, as described by Mostafaei (2011). Normally the difference is very small and it can be ignored. The initial axial load and deformation for the column specimen obtained for this test were 2000 kN and -0.00133 m respectively.

Step 3: For the column specimen in the furnace, apply the initial column's axial load, obtained from Steps 1 and 2, gradually, based on the rate required by the CAN/ULC-S101 standard. Once stabilized, the test is now ready to start. Figure 10 shows the column specimen at this stage before the test.

Step 4: Start the fire in the furnace for the column specimen

Step 5: Read axial deformation of the column specimen in the furnace at each time increment. Then run the analysis for the rest of the building structure, while it is subjected to this axial deformation, at the point where the column specimen is being separated and obtain the corresponding load reaction.

Note: Figure 11 shows the computer used for numerical simulation of the building as well as the new digital controlling system of the column, used for the HFT.

Step 6: Adjust the axial load for the column specimen in the furnace with the load obtained from analysis in Step 5.

Step 7: Repeat Steps 5 and 6 for each time increment, Δt, for the entire period of the test including the cooling phase. Δt depends on the level of the acceptable error.

For the purpose of this test, Δt was approximately 5 minutes, which provided a reasonable accuracy.

FIGURE 10. The Full-Scale Column Specimen Prior to the HFT Test.

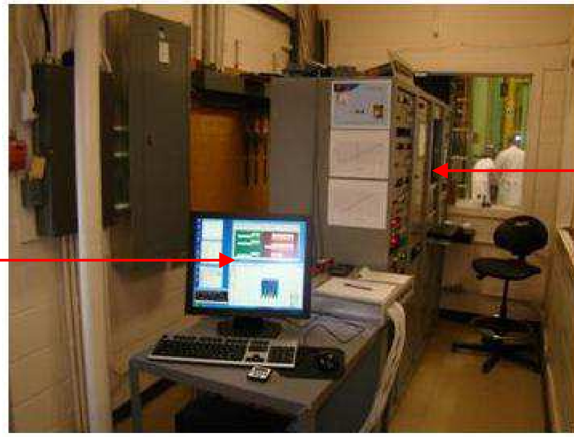

FIGURE 11. The Furnace Controlling System and the 3D Computer Simulator of the Rest of the Building Used for the HFT Test.

HFT TEST RESULTS AND VALIDATION

Observations

During the test, column specimens were observed closely for spalling or any damage. Figure 12 shows one of the furnace observation windows covered by protected glass. Observation remarks for the column specimen are provided in Table 1. Figures 13 and 14 illustrate the column specimen 4 hours and 20 hours after the fire exposure was stopped, respectively.

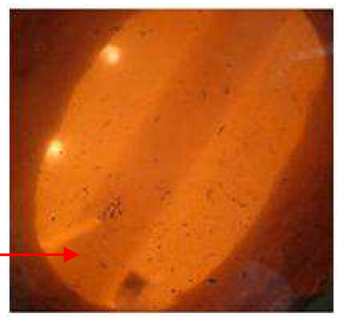

FIGURE 12. Observation of the Column Specimen During the HFT Test Through the Furnace Protected Glass.

FIGURE 13. Column Specimen just after Opening the Furnace Doors (after 4 Hours Fire Exposure).

Table 1. Observations Recorded for the Column Specimen During the Test.

Time	Remarks
June 23, 2011 6:40 am	Arrived to NRC's building M-59 Fire Lab.
6:41 am	Start measuring humidity at the lower end of the column specimen.
6:47 am	Start pre-loading the column at a rate of 60 psi/minute at steps of 50psi.
7:19 am	Reached 580 psi or 2000 kN axial load.
8:06 am	Measured humidity in column 90.1% and outside 54%.
8:54 am	Doors of the furnace were closed.
9:08 am	Fire started in the furnace.
9:23 am	Spalling started at the south face, this would be the open face of the column when casting concrete in the formwork.
9:40 am	Spalling at south-east corner.
10:00 am	Spalling at south-east corner continued, other faces of the column still looked intact.
10:38 am	Axial deformation starts to fall, all faces of the column are still intact except the south face. But the south face has not changed since the initial spalling.
10:48 am	On the west face of the column spallings are observed.
10:55 am	South face at the bottom, more spallings occurred.
11:15 am	Vertical cracks started at the west and south faces.
11:35 am	Vertical cracks on the east face started, larger cracks on the north face but cracks on the west faces are intact.
11:45 am	A new vertical crack was observed on the east face.
12:10 am	More cracks on the south face.
12:20 – 13:10	Not much change was observed.
13:10	The fire was stopped after 4 hours. The furnace doors opened. However, the measurements and recording continued for the cooling phase.
14:00	Column continued to shrink and axial load continued to drop.
16:06	Axial load reaches its minimum axial load capacity of the hydraulic system. A minimum constant axial load (172 kN) was continued to be applied to the column.
16:23	Hydraulic jacks turned off. The data acquisition was set to continue measuring temperature for another 8 hours.
17:00	Everyone left the lab but measuring temperatures continued.
June 24, 2011 00:29	The data acquisition automatically stopped measuring data.
08:09 am	Arriving to the fire lab.
08:39 am	Started the data acquisition system then started hydraulic jacks and loaded the column back to the last applied axial load (172 kN).
09:11 am	Column was unloaded and data acquisition system was turned off.
June 27, 2011 08:45 am	Started data acquisition system, then started hydraulic jacks and loaded the column back to the last applied axial load (172 kN).
10:18 am	Column was unloaded and data acquisition system was turned off.
June 29, 2011 10:18 am	Started data acquisition system, then started hydraulic jacks and loaded the column back to the last axial load (172 kN).
10:18 am	Test continued for the seismic resistance evaluation of the column after fire.

FIGURE 14. Column Specimen 20 Hours after Stopping Fire Exposure.

Furnace Temperature

Average furnace temperatures were controlled to follow the CAN/ULC-S101 standard temperature curve. Figure 15 shows the average temperature in the furnace and the standard curve for the 4 hour duration of the test, which illustrates a consistent correlation. Table 2 provides the S101 temperatures and the furnace temperatures during the test. The same temperature curve was used to simulate fire on the beams, in the fire compartment, in the numerical simulation.

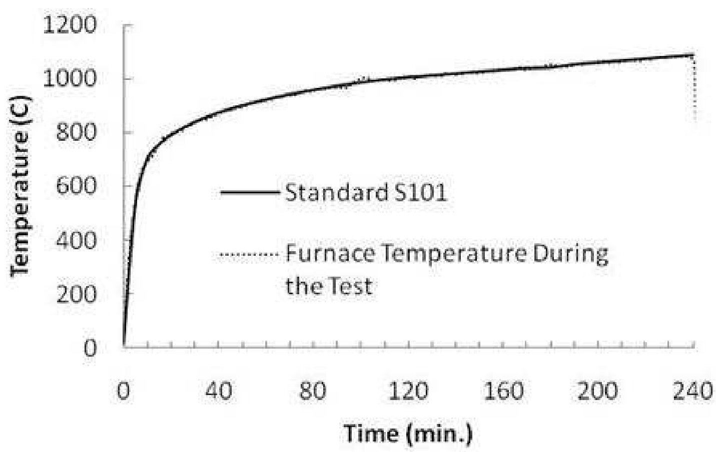

FIGURE 15. Comparison between Average Furnace Temperature during the Test and the Standard S101 Temperature Curve.

Temperature Response of the Column Specimen

During the test, temperatures were measured in concrete and steel bars. Tables 3 and 4 provide the test data for these temperatures. Figure 16 illustrates temperatures in cover concrete, thermocouple no. 5 in Figure 6, and temperatures in the centre of the concrete, thermocouple no. 8 in Figure 6, compared with the average temperatures in the furnace, during the fire and the cooling phase. The results show that the temperature in the cross of the concrete reaches the ambient temperature after almost 4 days. It also indicates the temperature in the centre of the concrete cross section increased even up to 1 hour after the fire exposure stopped.

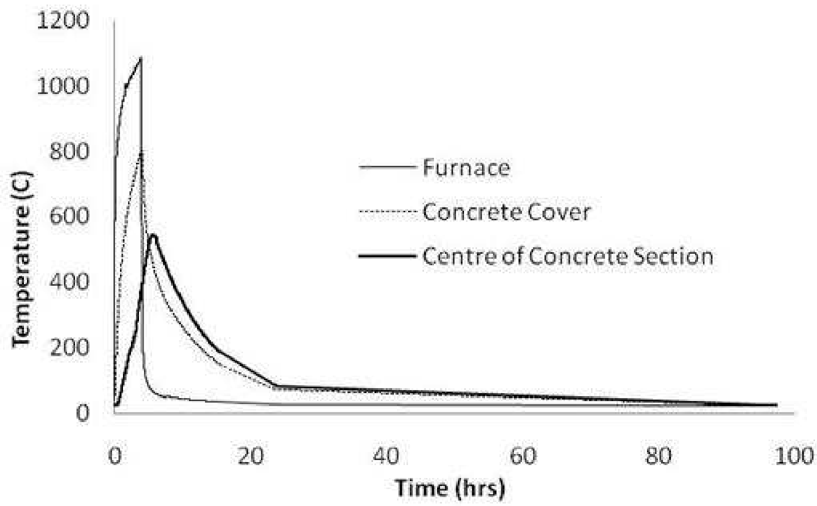

FIGURE 16. Temperatures in Furnace, Cover Concrete and Centre of The Concrete Section of the Column Specimen.

Axial deformation of the column specimen

Axial deformation of the column was measured during the first 8 hours of the test and then it was imposed to the rest of the building being simulated by the computer. Figure 17 illustrates axial deformation of the column during the fire test and the cooling phase for up to 6 days. Axial deformation at the time when the fire exposure stopped was -6 mm. However, 20 hours after the fire stopped, its value increased significantly and reached about -26 mm. This is in agreement with the significant temperature reduction in concrete, as shown in Figure 16, during the first 20 hours of the cooling phase. For the following 5 days the column was experiencing a slower but continuing creep. The test was stopped at day 6. A future test is recommended to find out when the concrete creep stops and becomes stable. Table 5 provides data for the axial deformation.

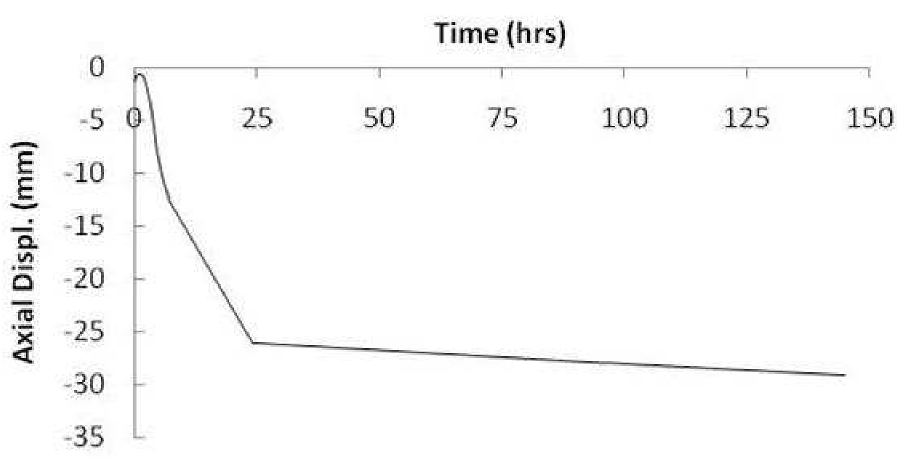

FIGURE 17. Axial Displacement Response of the Column Specimen.

Axial load of the column specimen

Axial load of the column was controlled by the numerical simulation. As the axial deformation of the column specimen changed during the test, an analysis was carried out using the current value of the axial deformation and time to determine axial load of the column specimen for the next step. In the prescriptive method, axial load is considered constant. However, in the HFT, the axial load is changing based on the interactions between the column specimen and the rest of the building. Figure 18 shows axial load of the column specimen during the fire exposure and cooling phase. Initially, axial load was increased slightly, from its initial value of 2000kN up to 2130kN, due to thermal expansion of the column and its interaction with the frame. However, axial load was then reduced due to reduction of the axial deformation of the column as the result of its interaction with the rest of the building. In other words, the frame of the building carries more load than that before fire to compensate the loss of the carrying load by the column specimen. In fact, after 8 hours, the column axial deformation increased significantly (its absolute value) so that the axial load in the column specimen reached a zero load. In other words, the column could not carry any load, since it is significantly shorter than its initial length and lost its interaction with the frame. In other words, the frame carries the entire load. No numerical simulation was carried out after the 8 hours, however, for the purpose of the experimentation, a minimum axial load (172kN) was applied on the column specimen and the test continued for 6 more days to measure the concrete creep and temperatures. The column then was loaded axially up to its initial applied load, which was 2000kN. It failed at about 2200kN axial load. This was done as part of a separate experimentation, for assessment of residual lateral load capacity, the results of which will be published separately. Further information on the seismic load will be proved in a separate report. Table 5 provides data for the axial load. A future HFT test could include a corner column or a weaker frame, where the frame could not compensate loss of axial load in the column specimen, which could result in failure of the building structure.

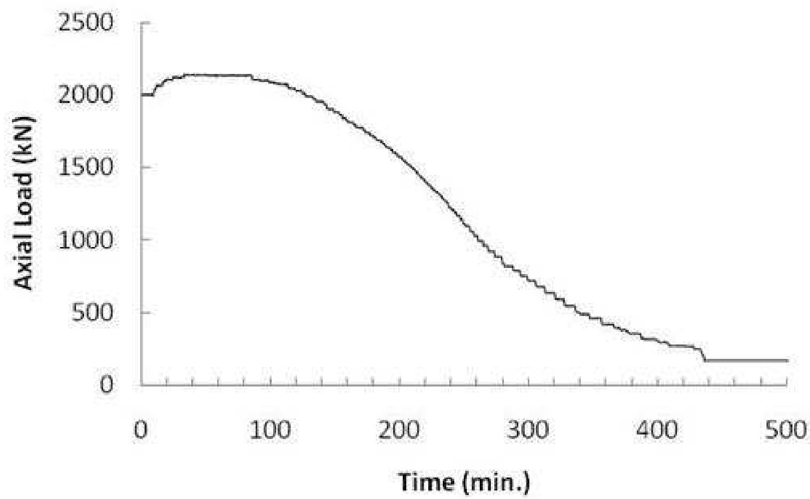

FIGURE 18. Axial Load Response of the Column Specimen.

Displacement response of the whole building

The numerical simulation of the whole building, except the column specimen which was tested in the furnace, was carried out using computer software called SAFIR (2005), the new version released in 2011. More information on the numerical analysis is provided in Mostafaei (2011). During the test, approximately every 5 minutes the analysis was carried out for the 6-storey building. The results of the analysis include shear and axial load, moment, deformations and rotations for all the building elements and nodes as well as temperature distributions of the beams in the fire compartment. The main purpose of this study is to show that the HFT is achievable. Although, all the performance components for the building structure were calculated during the test, this study focuses more on the application of the HFT. Therefore, only overall results of structural performance of the building are provided in this report. Figure 19 illustrates deformation of the building at the time when the fire exposure stopped, 4 hours. Figure 20 shows only half of the building in Figure 19, the rest of the building was hidden, to better observe the structural response at the fire compartment location. The colors in both figures illustrate intensity of the vertical deformation of the building which ranges from red with maximum of about 2 mm (upward) vertical displacement to blue with minimum of 7mm (downward) vertical displacement in the fire compartment. Maximum horizontal displacement of the building, due to thermal expansion of the beams and floors in the fire compartment, occurred at the first floor level, node no. 505, shown in Figure 20, which was 35 mm. That is about 1% lateral deformation ratio for the external columns. Compressive axial load of 580 kN was obtained for the beam in the fire compartment, beam no. 80. At the ambient temperature this beam carried almost a zero axial load. Number labels in Fig 20 shows numbers assigned to elements/nodes, those near the fire compartment, in the analysis.

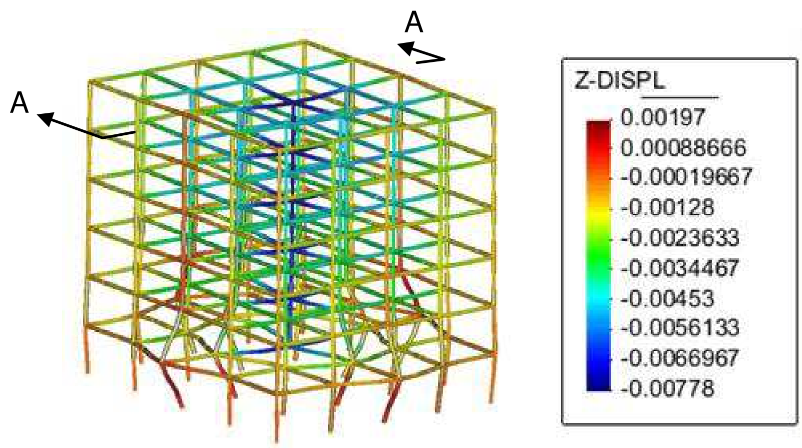

FIGURE 19. Vertical Displacement Response of the 6-Storey Building after 4 Hours Fire Exposure.

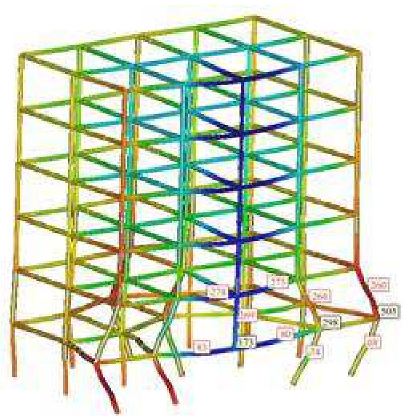

FIGURE 20. Section A-A of building in Figure 20.

A tension axial load of 270 kN was determined for beams at the upper level on the fire compartment, beam no. 275, see element numbers shown in Figure 20. Maximum shear force imposed in the external columns, column no. 260 and no. 68, were about 100kN. Axial load in the column right to the column specimen, column no. 269, reduced from about 1600 kN to 980 kN after 4 hours fire exposure. Axial load in the column next to the fire compartment, column no. 74, increased from 2000 kN at the start of the test to 2330 kN after 4 hours, due to load redistribution.

VERIFICATION OF INTERACTIONS BETWEEN SIMULATION AND TEST

In a previous report on the HFT methodology, Mostafaei (2001), it was verified that for the HFT implemented for this building, with the two interaction components of axial load and deformation, performance of the whole building can be simulated and evaluated with a reasonable accuracy. In order to validate that this interaction was adequately performed, the two interaction components of load and deformation must have the same values, during the test and analysis, for the column specimen and for the rest of the building.

Axial deformation interaction

Axial deformation of the column specimen was measured during the test and at the exposed designated time interval, about every 5 minutes; the rest of the building was imposed to this deformation. Figure 21 shows the axial deformation measured from the column specimen and the corresponding vertical displacement for the rest of the building, which illustrates a very consistent relationship.

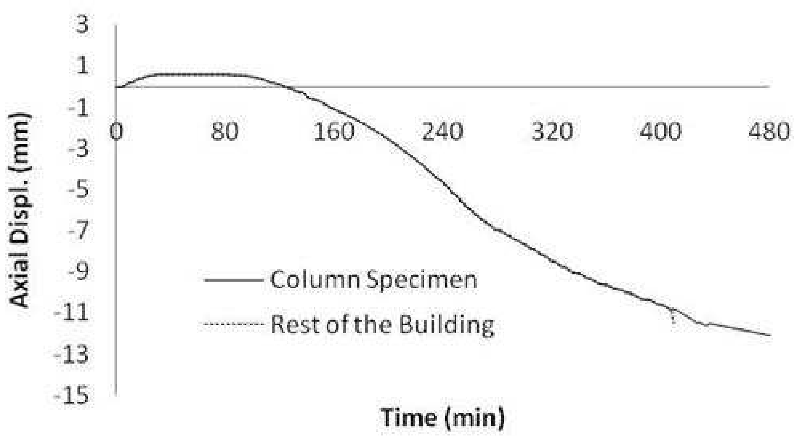

FIGURE 21. Axial Deformation for the Column Specimen and That in the Computer Simulation for the Rest of the Building.

Axial load interaction

Axial load of the column was controlled during the test based on the result obtained from the numerical analysis of the rest of the building. Comparison of the imposed axial load on the column specimen and the corresponding vertical load on the building obtained from analysis were shown in Figure 22, indicating a good interaction between the column specimen and the analysis.

COMPARISON BETWEEN THE HFT AND THE PRESCRIPTIVE TEST

Results of the column specimen, previously tested using a prescriptive method under a constant load, were compared with the results of the column tested for this study, using the HFT method. The difference between the two tests for the column was value of the applied axial load. In the prescriptive method, the axial load of 2000 kN was constantly applied during the test. However, in the HFT the axial load was varied according to the results obtained from analysis of the rest of the building. Furthermore, the prescriptive test was carried out three years after the concrete was cast and the HFT was carried out 15 years after casting the concrete. The column specimen for the HFT was stored indoor since the humidity of the concrete of the column after 12 years was still high, 90%. The time is considered to have a minimum impact on the column response.

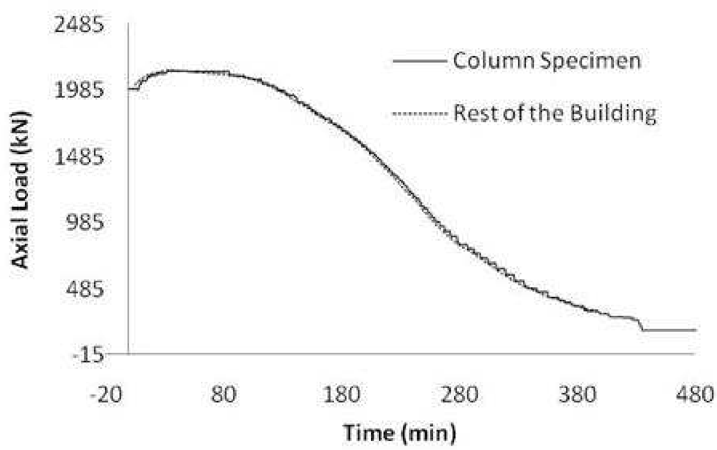

FIGURE 22. Axial Load for the Column Specimen and That in the Computer Simulation for the Rest of the Building.

Comparison of temperature, axial load and deformation of the column specimens are provided here.

Temperature In Column Specimens

Figure 23 shows temperatures for both column specimens at the centre of the concrete cross section, thermocouple no. 8 in Figure 6. The results indicate that both columns experienced almost the same temperatures for the first three hours. The column specimen tested using the prescriptive method failed after three hours. The diagram in Figure 23 was set for this time period only, for the purpose of comparison. In both column specimens, locations of thermocouples were the same.

Axial load of the column specimens

Both columns were initially subjected to the same axial loads of 2000 kN. The axial load of the column during the hybrid test increased (upward) slightly during the first hour of the test. This was due to the thermal expansion of the column and its interaction with the rest of the building. After the first hour, the axial load was reduced due to the column shortening, the transient strain of concrete at high temperatures. Figure 24 shows axial loads for both column specimens during the tests. The axial load from the HFT is considered to be a more realistic load response of the column than that of the prescriptive test, since response of the whole building is included.

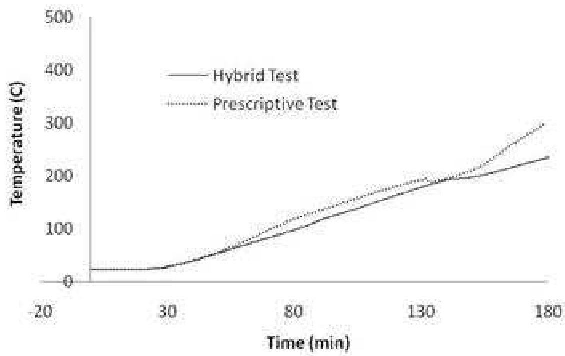

FIGURE 23. Temperatures in the Centre of the Column Section for Hybrid Test and the Perspective Test.

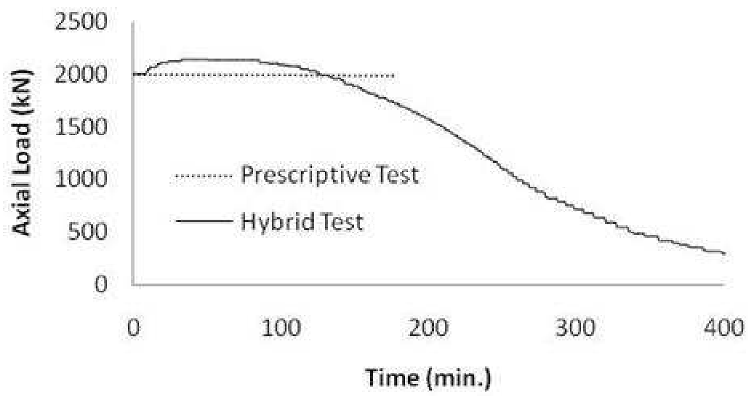

FIGURE 24. Axial Load Response for Hybrid Test and the Perspective Test.

Figure 25 shows the axial deformation of the column specimen for the two tests. The results indicate that the axial deformation of the HFT column was, in the first hour, slightly smaller than that of the column under constant load. This was due to a higher axial load for the HFT column specimen, resulting from its interaction with the rest of the building; when the column expands, it pushes the building frame up, which results in higher frame reaction and therefore a higher axial load in the column specimen. The column under constant axial load showed significant increase in axial deformation (downward) after the first hour and half. However, the HFT column responded with much lower deformation which is due to axial load reduction resulting from its interaction with the rest of the building.

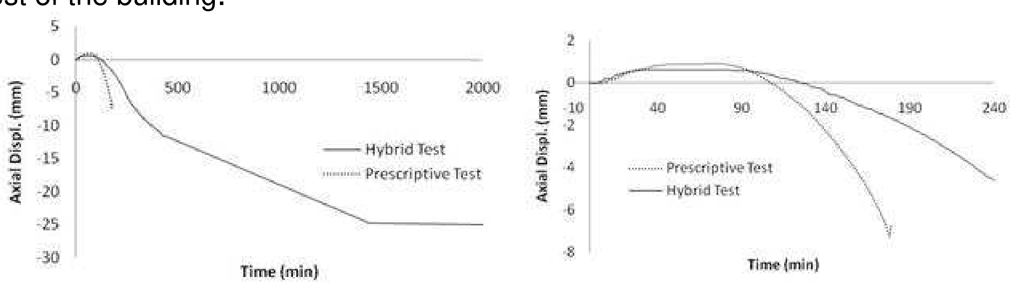

FIGURE 25. Axial Deformation Response of the Column Specimens for HFT and the Perspective Test; Diagram on the Right Shows the Same Results But for the First 4 Hours.

CONCLUSION

The new hybrid fire test (HFT) was implemented for the performance evaluation of a 6-storey reinforced concrete building with a fire compartment in the centre part of the building's main floor. Using the HFT, the column in the fire compartment was tested in a column furnace and the rest of the building was simulated using structural analysis software.

The following conclusions can be made based on the results of the HFT test:

1. The HFT was implemented successfully; verifying that the hybrid fire test is achievable and can be implemented using a column furnace facility.

2. HFT would simulate a more realistic response for both fire endurance evaluations of the building and performance-based fire resistance assessment of column specimens, since the interaction of the whole building is included.

3. Consistent correlation was obtained between the interaction components of the column specimens and that of the rest of the building, verifying the applicability of the HFT.

4. The column tested using the HFT showed more endurance to fire than that tested using the prescriptive method. However, this was archived for the fire compartment in the centre column location and with a relatively strong building frame that could carry the lost load without the column specimen. Future HFT tests are recommended to assess other fire compartment scenarios, e.g., corner columns, and weaker frame structure, where failure of the frame could be feasible as the result of the failure of the column specimen.

5. Considerably higher deformation, in the form of column shortening, was measured for the column specimen during the cooling phase. Such deformation resulted in load redistribution and consequently carrying more loads by the frame of the building. Therefore, it is important to make sure that the building has adequate capacity to carry the rest of the load. On the other hand, due to the large creep, there would be no further interaction between the exposed column and rest of the frame after such fire. This will result in larger deflection of the beams connected to this column. Hence, such effects need to be considered in post-fire evaluations of buildings.

The HFT was implemented for a centre column on the first floor. However, as described in report, Part 1, the HFT can be employed for columns in other floors as well as an external column, where lateral load and deformation is interacted between the column specimen and the rest of the building.

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Table 2. CAN/ULC-S101 Standard and Measured Furnace Temperature.

Time (min)	Standard Temperature (°C)	Furnace Temperature (°C)
0	20	48
5	538	519
10	704	692
15	759	755
20	794	795
25	821	812
30	843	840
35	862	852
40	878	870
45	892	886
50	905	898
55	916	915
60	927	922
65	937	939
70	946	940
75	954	954
80	963	957
85	971	965
90	978	971
95	984	971
100	991	1005
105	997	998
110	1002	998
115	1006	1002
120	1010	1008
130	1017	1016
140	1024	1018
150	1031	1024
160	1038	1036
170	1044	1039
180	1046	1055
190	1059	1053
200	1066	1064
210	1072	1066
220	1079	1078
230	1087	1081
240	1093	1077
250	20	223
260	20	153
270	20	124
280	20	106
290	20	95
300	20	87
310	20	79
320	20	74
330	20	70
340	20	67
350	20	64
360	20	61

Table 2. Continued.

Time (min)	Standard Temperature (^oC)	Furnace Temperature (^oC)
370	20	59
380	20	58
390	20	56
400	20	55
410	20	54
420	20	52
430	20	51
440	20	50
450	20	50
460	20	51
470	20	51
480	20	51
490	20	50
500	20	49
510	20	49
520	20	48
530	20	47
540	20	47
550	20	46
560	20	46
570	20	45
580	20	45
590	20	45
600	20	44
610	20	44
620	20	43
630	20	43
640	20	42
650	20	42
660	20	42
670	20	41
680	20	41
690	20	40
700	20	40
710	20	40
720	20	39
730	20	39
740	20	39
750	20	39
760	20	38
770	20	38
780	20	38
790	20	38
800	20	37
810	20	37
820	20	37
830	20	36
840	20	36
850	20	36

Table 2. Continued.

Time (min)	Standard Temperature (^oC)	Furnace Temperature (^oC)
860	20	36
870	20	35
880	20	35
890	20	35
900	20	35
910	20	34
920	20	34
1420	20	29
1430	20	28
1440	20	28
1450	20	29
5750	20	23
5760	20	23
5770	20	23
5780	20	23
5790	20	23
5800	20	23
5810	20	23
5820	20	23
5830	20	23

Table 3. Measured Temperatures in Reinforcement Steel.

Time (min)	Standard Temp. (°C)	Furnace Temp. (°C)	Temperature (°C) Measured at Thermocouple # SP-1 (°C)	SP-2 (°C)	SP-3 (°C)	SP-4 (°C)
0	20	48	23	23	23	23
5	538	519	25	24	26	24
10	704	692	40	33	41	32
15	759	755	79	65	66	47
20	794	795	98	91	81	62
25	821	812	102	98	87	73
30	843	840	103	103	95	81
35	862	852	118	112	103	89
40	878	870	138	127	114	100
45	892	886	159	145	126	112
50	905	898	180	163	140	114
55	916	915	202	182	154	122
60	927	922	224	202	169	133
65	937	939	246	222	185	144
70	946	940	267	243	203	157
75	954	954	288	263	221	171
80	963	957	309	282	239	185
85	971	965	329	301	256	199
90	978	971	349	320	273	213
95	984	971	368	338	290	227
100	991	1005	386	355	307	241
105	997	998	405	373	323	255
110	1002	998	423	391	340	270
115	1006	1002	441	408	355	284
120	1010	1008	459	425	370	297
130	1017	1016	493	459	400	326
140	1024	1018	528	491	431	356
150	1031	1024	549	516	460	385
160	1038	1036	571	538	489	415
170	1044	1039	594	561	517	443
180	1046	1055	617	584	543	471
190	1059	1053	640	607	569	498
200	1066	1064	663	629	595	523
210	1072	1066	683	650	618	547
220	1079	1078	700	670	638	570
230	1087	1081	714	688	657	592
240	1093	1077	728	703	675	613
250	20	223	739	717	687	633
260	20	153	730	717	678	642
270	20	124	710	706	659	638
280	20	106	686	686	638	628
290	20	95	665	668	618	616
300	20	87	632	638	595	603
310	20	79	603	611	575	590
320	20	74	578	586	560	578
330	20	70	554	563	547	566
340	20	67	533	543	534	554
350	20	64	514	524	522	542

Table 3. Continued.

Time (min)	Standard Temp. (°C)	Furnace Temp. (°C)	Temperature (°C) Measured at Thermocouple # SP-1 (°C)	SP-2 (°C)	SP-3 (°C)	SP-4 (°C)
360	20	61	496	507	512	531
370	20	59	480	490	501	520
380	20	58	465	475	491	509
390	20	56	450	461	481	498
400	20	55	437	448	471	487
410	20	54	425	435	461	477
420	20	52	413	424	452	467
430	20	51	402	412	443	457
440	20	50	391	402	434	447
450	20	50	381	392	426	438
460	20	51	372	382	418	429
470	20	51	363	373	410	420
480	20	51	354	365	402	411
490	20	50	347	357	395	403
500	20	49	339	350	387	395
510	20	49	332	343	380	387
520	20	48	325	336	373	380
530	20	47	319	329	366	372
540	20	47	313	323	359	365
550	20	46	306	317	353	358
560	20	46	301	311	346	351
570	20	45	295	305	340	344
580	20	45	289	299	333	338
590	20	45	284	293	327	331
600	20	44	278	288	321	325
610	20	44	273	283	316	319
620	20	43	268	278	310	313
630	20	43	263	273	304	307
640	20	42	259	268	299	301
650	20	42	254	263	293	296
660	20	42	249	258	288	290
670	20	41	245	254	283	285
680	20	41	241	249	278	280
690	20	40	236	245	273	275
700	20	40	232	241	268	270
710	20	40	228	236	263	265
720	20	39	224	232	259	260
730	20	39	220	228	254	255
740	20	39	216	224	250	251
750	20	39	213	221	245	246
760	20	38	209	217	241	242
770	20	38	205	213	237	237
780	20	38	202	209	232	233
790	20	38	199	206	228	229
800	20	37	195	202	224	225
810	20	37	192	199	221	221
820	20	37	189	196	217	217
830	20	36	186	192	213	213

Table 3 Continued.

Time (min)	Standard Temp. (°C)	Furnace Temp. (°C)	Temperature (°C) Measured at Thermocouple # SP-1 (°C)	SP-2 (°C)	SP-3 (°C)	SP-4 (°C)
840	20	36	183	189	209	210
850	20	36	179	186	206	206
860	20	36	176	183	202	202
870	20	35	174	180	199	199
880	20	35	171	177	195	195
890	20	35	168	174	192	192
900	20	35	165	171	189	189
910	20	34	162	168	186	185
920	20	34	160	165	183	182
1420	20	29	76	78	85	83
1430	20	28	76	77	84	82
1440	20	28	75	76	83	81
1450	20	29	74	75	82	80
5750	20	23	24	24	24	24
5760	20	23	24	24	24	24
5770	20	23	24	24	24	24
5780	20	23	24	24	24	24
5790	20	23	24	24	24	24
5800	20	23	24	24	24	24
5810	20	23	24	24	24	24
5820	20	23	24	24	24	24
5830	20	23	24	24	24	24

Table 4. Measured Temperatures in Concrete.

Time (min)	Standard Temp. (°C)	Furnace Temp. (°C)	Temperature (°C) Measured at Thermocouple #						
			SP-5 (°C)	SP-6 (°C)	SP-7 (°C)	SP-8 (°C)	SP-9 (°C)	SP-10 (°C)	SP-11 (°C)
0	20	48	23	23	23	23	23	23	23
5	538	519	48	24	23	23	23	23	39
10	704	692	106	27	23	23	23	26	83
15	759	755	158	36	21	23	25	35	124
20	794	795	197	50	18	24	28	47	160
25	821	812	242	69	11	25	35	62	189
30	843	840	281	85	3	29	43	79	223
35	862	852	312	98	-7	34	53	95	255
40	878	870	341	102	-16	40	62	104	284
45	892	886	370	106	----	47	71	109	311
50	905	898	397	113	----	55	78	116	335
55	916	915	421	123	----	62	85	124	358
60	927	922	443	134	----	70	92	133	379
65	937	939	463	145	----	77	101	144	399
70	946	940	482	155	----	84	110	153	418
75	954	954	499	166	----	91	122	164	436
80	963	957	515	178	----	98	124	176	453
85	971	965	531	191	----	106	132	188	469
90	978	971	545	203	----	116	140	201	484
95	984	971	559	216	----	124	148	213	499
100	991	1005	572	228	----	132	156	226	512
105	997	998	587	241	----	139	164	239	527
110	1002	998	599	253	----	147	173	251	541
115	1006	1002	610	266	----	155	183	264	553
120	1010	1008	620	278	----	163	192	277	565
130	1017	1016	640	302	----	179	213	301	587
140	1024	1018	662	324	----	193	234	326	609
150	1031	1024	679	342	----	198	252	348	630
160	1038	1036	695	365	----	209	271	370	649
170	1044	1039	710	388	----	223	292	392	667
180	1046	1055	725	410	----	235	314	414	683
190	1059	1053	740	431	----	253	334	436	699
200	1066	1064	754	453	----	280	356	457	713
210	1072	1066	767	475	----	307	378	479	728
220	1079	1078	780	496	----	332	401	500	741
230	1087	1081	791	518	----	356	423	521	754
240	1093	1077	801	538	----	379	445	541	766
250	20	223	753	558	----	402	467	562	744
260	20	153	674	574	----	424	489	578	684
270	20	124	619	582	----	446	508	586	636
280	20	106	579	583	----	467	524	588	600
290	20	95	549	581	----	486	537	586	572
300	20	87	524	577	----	503	546	582	549
310	20	79	504	572	----	526	552	577	529
320	20	74	486	566	----	539	557	567	514
330	20	70	470	559	----	544	559	557	500
340	20	67	456	552	----	544	559	546	487
350	20	64	443	544	----	542	557	536	475
360	20	61	430	535	----	539	554	526	463

Table 4. Continued.

Time (min)	Standard Temp. (°C)	Furnace Temp. (°C)	Temperature (°C) Measured at Thermocouple #						
			SP-5 (°C)	SP-6 (°C)	SP-7 (°C)	SP-8 (°C)	SP-9 (°C)	SP-10 (°C)	SP-11 (°C)
370	20	59	419	527	----	534	550	516	452
380	20	58	408	519	----	516	544	503	447
390	20	56	398	510	----	507	538	493	437
400	20	55	388	501	----	498	532	484	427
410	20	54	379	493	----	489	525	474	418
420	20	52	370	484	----	480	517	465	409
430	20	51	361	475	----	471	510	456	400
440	20	50	353	466	----	463	502	447	392
450	20	50	345	458	----	454	494	439	384
460	20	51	339	449	----	445	486	430	376
470	20	51	333	441	----	437	477	422	369
480	20	51	328	432	----	428	469	414	362
490	20	50	322	424	----	420	460	406	355
500	20	49	316	417	----	412	452	398	348
510	20	49	311	409	----	404	444	391	341
520	20	48	305	401	----	396	435	383	335
530	20	47	300	394	----	389	427	376	328
540	20	47	294	386	----	381	419	369	322
550	20	46	289	379	----	375	411	362	316
560	20	46	284	372	----	369	403	355	309
570	20	45	279	365	----	363	396	348	303
580	20	45	274	358	----	356	388	342	297
590	20	45	269	352	----	349	381	336	292
600	20	44	264	345	----	342	373	329	287
610	20	44	260	338	----	336	366	323	282
620	20	43	255	332	----	330	359	317	276
630	20	43	251	326	----	323	352	312	272
640	20	42	246	320	----	317	346	307	267
650	20	42	242	314	----	311	339	301	262
660	20	42	238	308	----	306	333	296	257
670	20	41	233	302	----	300	326	290	253
680	20	41	229	297	----	294	320	285	248
690	20	40	225	291	----	289	314	280	244
700	20	40	222	286	----	283	308	275	239
710	20	40	218	281	----	278	302	270	235
720	20	39	214	275	----	273	297	266	231
730	20	39	210	270	----	267	291	262	227
740	20	39	207	265	----	263	285	257	223
750	20	39	203	261	----	258	280	252	219
760	20	38	200	256	----	253	275	248	215
770	20	38	196	251	----	249	270	244	211
780	20	38	193	247	----	244	265	240	208
790	20	38	190	242	----	240	259	235	204
800	20	37	186	238	----	235	255	231	201
810	20	37	183	233	----	231	250	227	197
820	20	37	180	229	----	227	245	223	194
830	20	36	177	225	----	223	240	219	190
840	20	36	174	221	----	219	236	215	187
850	20	36	171	217	----	215	232	211	184

Table 4. Continued.

Time (min)	Standard Temp. (°C)	Furnace Temp. (°C)	Temperature (°C) Measured at Thermocouple #						
			SP-5 (°C)	SP-6 (°C)	SP-7 (°C)	SP-8 (°C)	SP-9 (°C)	SP-10 (°C)	SP-11 (°C)
860	20	36	168	213	----	211	227	207	181
870	20	35	166	209	----	207	223	204	178
880	20	35	163	205	----	204	219	200	175
890	20	35	160	202	----	200	215	197	172
900	20	35	158	198	----	196	211	193	169
910	20	34	155	195	----	193	207	190	166
920	20	34	152	191	----	190	203	187	163
1420	20	29	73	86	----	86	89	85	77
1430	20	28	72	85	----	84	88	83	76
1440	20	28	72	83	----	83	87	82	75
1450	20	29	71	82	----	82	85	81	74
5750	20	23	24	24	24	24	24	24	24
5760	20	23	24	24	24	24	24	24	24
5770	20	23	24	24	24	24	24	24	24
5780	20	23	24	24	24	24	24	24	24
5790	20	23	24	24	24	24	24	24	24
5800	20	23	24	24	24	24	24	24	24
5810	20	23	24	24	24	24	24	24	24
5820	20	23	24	24	24	24	24	24	24
5830	20	23	24	24	24	24	24	24	24

Table 5. Measured Axial Deformation and Axial Load.

Time (min)	Axial Deformation (mm)	Axial Load (kN)
0	0.000	1999
5	0.014	1998
10	0.210	2041
15	0.340	2059
20	0.438	2100
25	0.544	2118
30	0.596	2120
35	0.616	2136
40	0.616	2133
45	0.615	2135
50	0.616	2133
55	0.616	2132
60	0.616	2131
65	0.616	2131
70	0.616	2128
75	0.616	2131
80	0.615	2128
85	0.582	2133
90	0.574	2102
95	0.561	2094
100	0.503	2089
105	0.423	2078
110	0.322	2071
115	0.216	2042
120	0.137	2028
130	-0.096	1991
140	-0.422	1949
150	-0.684	1877
160	-1.067	1807
170	-1.372	1773
180	-1.701	1702
190	-2.070	1637
200	-2.500	1571
210	-3.011	1498
220	-3.507	1396
230	-4.080	1313
240	-4.607	1212
250	-5.228	1107
260	-5.959	1026
270	-6.436	922
280	-6.936	835
290	-7.231	795
300	-7.638	721
310	-8.014	679
320	-8.476	626
330	-8.746	547
340	-9.050	491
350	-9.317	466
360	-9.605	419

Table 5. Continued.

Time (min)	Axial Deformation (mm)	Axial Load (kN)
370	-9.851	394
380	-10.045	358
390	-10.327	322
400	-10.593	307
410	-10.806	273
420	-11.145	270
430	-11.461	252
440	-11.489	172
1445	-24.723	173
1447	-24.723	174
1450	-24.723	173
5750	-26.626	173
5760	-26.626	172
5770	-26.626	173
5780	-26.626	172
5790	-26.626	171
5800	-26.626	170
5810	-26.626	174
5820	-26.626	172
5830	-26.625	172
8711	-27.78	172