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Hybrid Fire Testing for Assessing Performance of Structures in Fire – Application

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Abstract. This paper presents the results for application and implementation of the hybrid fire testing (HFT) approach, developed previously for performance assessment of the structure in fire. The HFT carried out by means of both computer simulation and experimentation using the National Research Council Canada's (NRC) testing facilities in Ottawa. The test specimen was a full-scale 6-storey building structure with a fire compartment scenario on the main floor of the building. Using the HFT, 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, simultaneously. The methodology of the HFT and its numerical verifications were developed and described in a previous paper. This paper includes application of the HFT and some of results for fire structural performance of the whole 6-storey building. It also includes results of a separate, benchmark, column specimen with identical specifications, tested in fire using the traditional prescriptive fire resistance test method. The HFT was carried out successfully. The results indicated that the hybrid fire testing method would provide more realistic fire endurance evaluation than the prescriptive method due to including the effects from the rest of the building on the column specimen during the test.

Keywords: hybrid test, fire resistance, performance-based design, performance-based design, hybrid test, full-scale test, test and analysis/simulation, hybrid fire testing, HFT, standard fire resistance test.

Introduction

Traditionally, fire resistance of building structures is being determined using prescriptive methods. These methods evaluate the fire endurance of individual structural elements, as single elements, without considering the effects from the rest of the structure. A single element testing method would have limitations in providing a realistic estimation for performance of the whole building in fire, since the interactions between the single element specimen and the rest of the building are disregarded in the assessment. In the last few decades, building codes and standards, in different countries, have been undergoing a new revision to include a performance-based or objective-based philosophy in the design and assessment of building structures. For instance, the National Building Code of Canada (NRC 2005 and 2010), provides an objective-based method, as an alternative methodology option, for the design of buildings. However, there is still a lack of design and assessment tools and practical approaches for the implementation of such methods in practice. A performance-based fire resistance assessment of a building could be carried out by evaluating the performance of the whole building for the applied fire scenarios. The assessment could be implemented either by building and testing a full-scale building specimen in fire or performing a reliable analysis of the whole building. However, the full-scale testing methods are very expensive, and require significant efforts and time as well as large laboratory space and facilities. On the other hand, available numerical analysis tools are less reliable when structural elements experience large deformation/damage in fire.

An alternative performance-based method to the full-scale testing could be a hybrid fire testing (HFT) method, but with significantly less time, space and cost required. HFT would provide more flexibility and more test data compared to the full-scale testing method. As such, computer simulations could be revised simply, with almost no cost, and for any new

configuration, only building a small specimen would be required. While in the full-scale testing, for any new study scenario, a new full-scale specimen would be required.

Furthermore, the computer simulation could provide details of the building performance components, such as internal load, deformation, stress and strain, which would be impractical or very difficult to measure during the full-scale testing.

Compared to the tests, available fire structural analysis tools are less reliable when structural elements experience major damage/large deformation, at the post-peak response. The HFT would provide more reliable results since the structural part with the most damage is simulated by a physical test and the rest of the structure with smaller damage is simulated by the analysis software. This would not only reduce the structural response prediction errors but also enable engineers to estimate the structural response for a larger deformation, compared to when the entire structure is simulated by a numerical method.

Although hybrid fire testing (HFT) is a new method for assessing fire performance of structures (Mostafaei, 2011), the concept of hybrid testing is not a new methodology. The hybrid testing of structures has been widely studied and performed for response simulation of structures under seismic loads, since a few decades ago (Dermitzakis and Mahin 1985, and Chen et al. 2009). The same methodology and concept has been adopted here for hybrid testing of structures under fire loads.

The HFT methodology was previously presented (Mostafaei, 2011). This paper describes the implementation of the HFT for a full-scale building. A 6-storey reinforced concrete building with a fire compartment in the centre of the first floor was tested 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 for an identical column, tested previously 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. This was selected to demonstrate the application of the HFT and for the purpose of comparison with the results of a column tested previously, exposed to the same fire, but using the prescriptive test method. In case of a real fire test, the time-temperature curve of the real fire is employed both in the analysis and by the furnace. If the time-temperature curve changes during the test, the interactions in HFT must include the temperature component in addition to the load and deformation. This is to measure temperatures during the test and impose the rest of structures to the same temperatures in the analysis.

Full-Scale Test Specimen

The test specimen was a 6-storey reinforced concrete building prototype, designed and built based on the North American Standards (Mostafaei 2011, Part 1). Figure 1 shows the overall structural configuration of the building prototype.

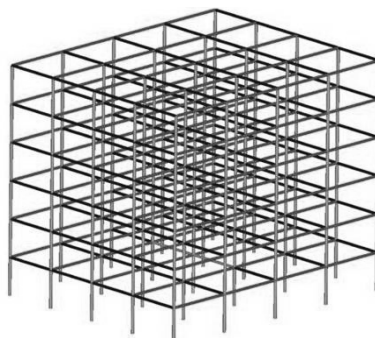


FIGURE 1. The Full-Scale Building Specimen.

Figure 2 shows both the floor plan of the building structure and the elevation of the main frame as well as the location of the fire compartment. 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.

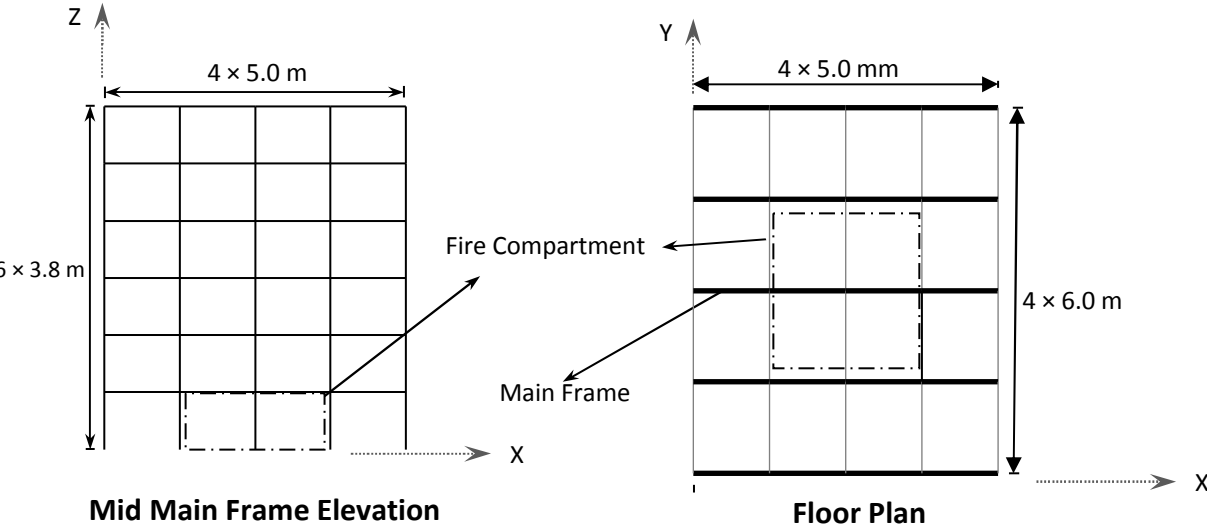


FIGURE 2. Elevation and Floor Plans of the Building Specimen.

The applied load for the main interior frames at the roof level was 43.7 kN/m and that for 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. The loads were determined based on the requirements specified by the National Building Code of Canada.

Cross section and details of the reinforcements for the column specimen are shown in Figure 3. The same details are employed for the rest of the columns.

The concrete was made of fine aggregates and siliceous coarse aggregates mixed with 168 kg steel fibre (based on 42 kg/m³). The internal relative humidity of concrete for the column specimen was measured before the test, which was 90.1% while the ambient relative humidity was 54%. Relative Humidity (RH) is the ratio of the vapor to the saturated vapor pressure of water at a specific temperature. RH is used to determine the moisture content of concrete.

Concrete compressive strength, for the column specimen, was 96 MPa obtained based on three cylinder compression tests, carried out before the fire test. Details of the concrete mix were provided in the initial test report (Mostafaei et al. 2011).

Figures 3 and 4 show the reinforcing details of the columns with the arrangement of the main reinforcing bars and ties. Figure 3 shows locations of the thermocouples on the column specimen's cross section, at the centre of the column. Thermocouples are made of Type K chromel-alumel 0.91 mm thick for measuring temperatures.

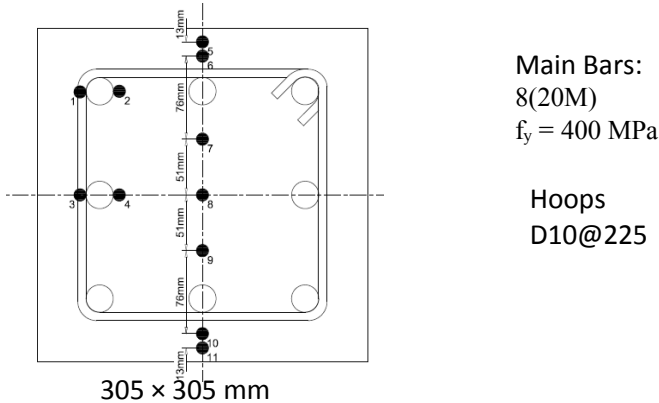


FIGURE 3. Cross Section of Columns and Location of the Thermocouples.

Figure 5 shows the cross section for the beams of the main frames with material properties for concrete and steel. Figure 6 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).

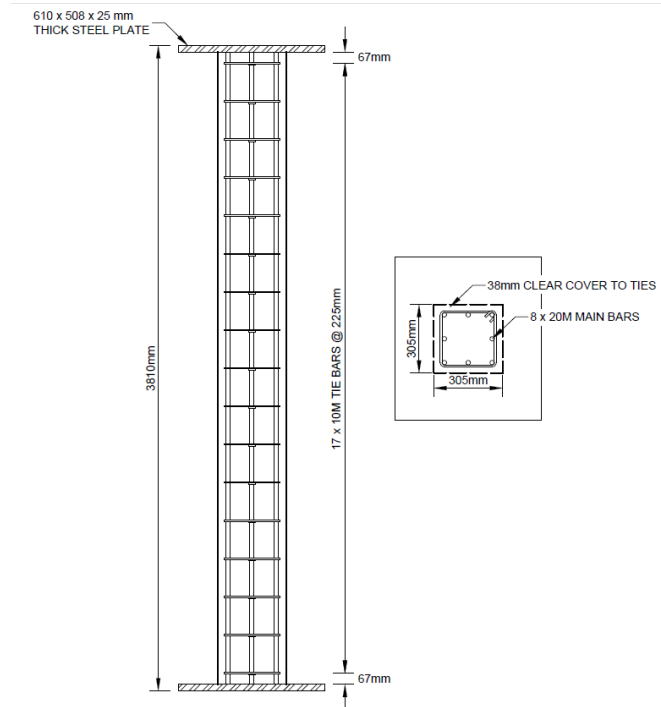


FIGURE 4. Details of the Reinforcement for the Column Specimen.

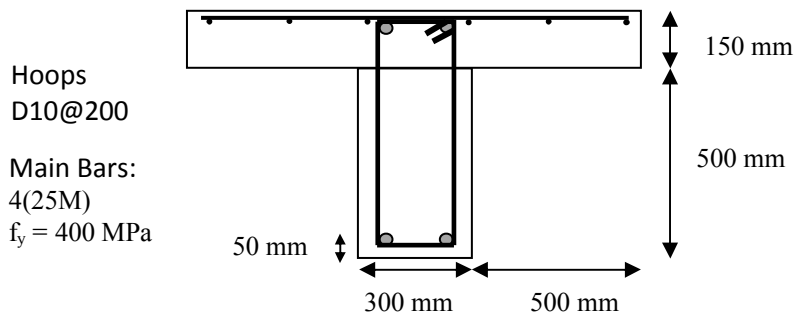


FIGURE 5. Beams Cross-Section of the Main Frames.

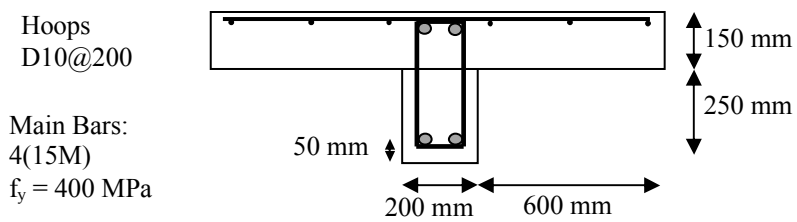


FIGURE 6. Beams Cross-Section of the Secondary Frames.

Testing Equipment

A column furnace with the required loading facility was used for the purpose of this study.

The furnace was designed to produce conditions that a structural element could be exposed to a fire, e.g. standard fire. Figure 7 shows the column furnace chamber.

The furnace chamber has a floor area of 2600 x 2600 mm and height of 4300 mm. Part of the column specimens are insulated at the top and bottom to keep the heat away from the test apparatus. Therefore, only 3200 mm of the column specimen is exposed to fire during the test.

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 7. The Column Test Facility.

Testing Approach

Figure 8 illustrates the HFT components for the 6-storey building specimen. The column specimen, the centre column on the first floor of the building, was placed in the furnace,

shown on the right of Figure 8. The rest of the building structure, including beams in the fire compartment, were simulated using the SAFIR software, the new released in 2011, shown on the left of the figure. For the numerical simulation part, beams and columns were simulated using fibre Bernoulli beam models and therefore shear responses of the elements were not considered. The fire compartment was located in the centre of the building; therefore, due to the symmetry reasons, lateral deformations, from thermal expansion, were not present (Mostafaei 2011). Therefore, the interaction components between the column specimen and the rest of the frame were the column end's axial load and axial deformation. In the analysis, all the beams in the fire compartment were exposed to the same fire as that for the column specimens. 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.

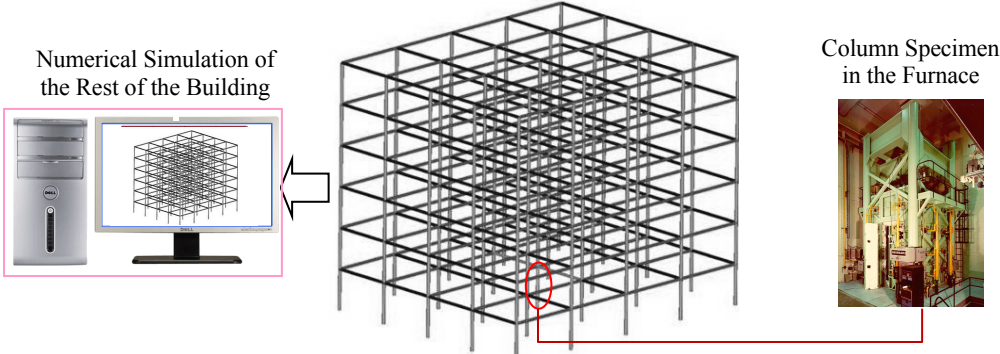


FIGURE 8. The HFT Components for the 6-Storey Building Specimen.

For the column in the furnace, rotations and lateral displacements were restrained 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. As such, this 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.

Simplified HFT Steps

The simplified HFT process (Mostafaei, 2011), for a 2D frame, was implemented for this experimentation. Here are the steps 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 to 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, and 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 a difference. 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. The test is now ready to start. Figure 9 shows the column specimen at this stage before the test.

Step 4: Start the fire in the furnace.

Step 5: Read the 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.

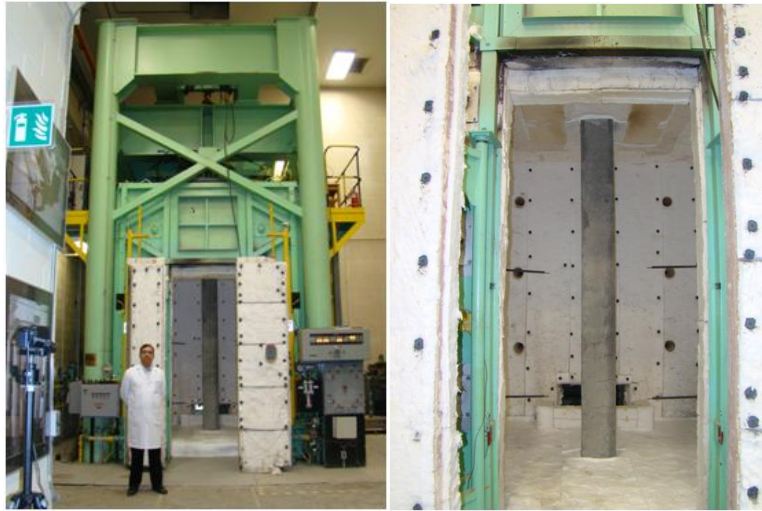


FIGURE 9. The Column Specimen Prior to the HFT Test.

Step 6: Adjust the axial load for the column specimen in the furnace with the load obtained from the 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 and of the velocity of the computer and/or software.

For the purpose of this test, Δt was approximately 5 minutes, which provided a reasonable accuracy. The analysis of the structure, each time, took approximately 2 minutes to complete. The remaining time, up to 5 minutes, was to manually transfer the interaction data from the analysis to the furnace control system and vice versa. For each attempt, the analysis started from the beginning, from time zero, however, with three to four time intervals, from time zero to the current time. Before the test, an attempt was made to ensure that the selected number of time intervals for each analysis would provide a reasonable accuracy up to the end of the test.

HFT TEST RESULTS AND VALIDATION

Figures 10 and 11 illustrate the column specimen 4 hours and 20 hours after the fire exposure was stopped, respectively.



FIGURE 10. Column Specimen just after 4 Hours Fire Exposure.



FIGURE 11. Column Specimen 20 Hours the Fire was Stopped.

Figure 12 shows the average temperature in the furnace and the E119 standard curve for the 4 hour duration of the test, which illustrates a consistent correlation. The same temperature curve was used in the numerical analysis to simulate fire on the beams, in the fire compartment.

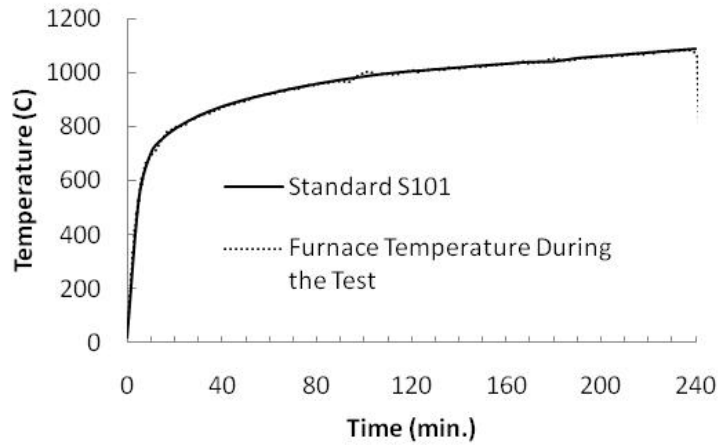


FIGURE 12. Comparison between Measured Time-Temperature and the E119/S101 Standard Time-Temperature Curve.

During the test, temperatures were measured in concrete and steel bars. Figure 13 illustrates temperatures in cover concrete, thermocouple no. 5 in Figure 3, and temperatures in the centre of the concrete, thermocouple no. 8 in Figure 3, compared with the average temperatures in the furnace, during the fire and the cooling phase. It also indicates the temperature in the centre of the concrete cross section increased even up to 1 hour after the fire exposure stopped. The results show that the temperature in the cross of the concrete reaches the ambient temperature after almost 4 days. More test data can be found in Mostafaei et al. (2011).

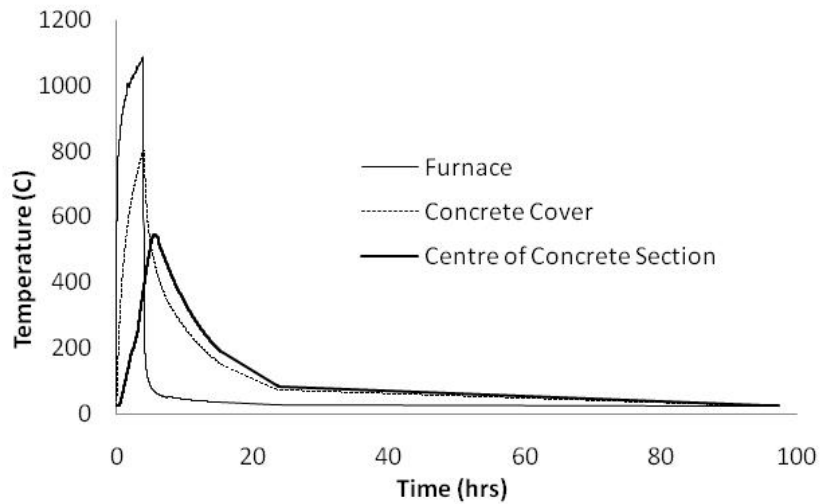


FIGURE 13. Temperatures in Furnace, Cover Concrete and Centre of The Concrete Section of the Column Specimen.

The axial deformation of the column specimen was measured during the first 8 hours of the test and was then imposed to the rest of the building being simulated by the computer. Figure 14 illustrates the axial deformation of the column during the fire test and the cooling phase for up to 6 days. The 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 approximately -26 mm. This is in agreement with the significant temperature reduction in concrete, as shown in Figure 13, 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.

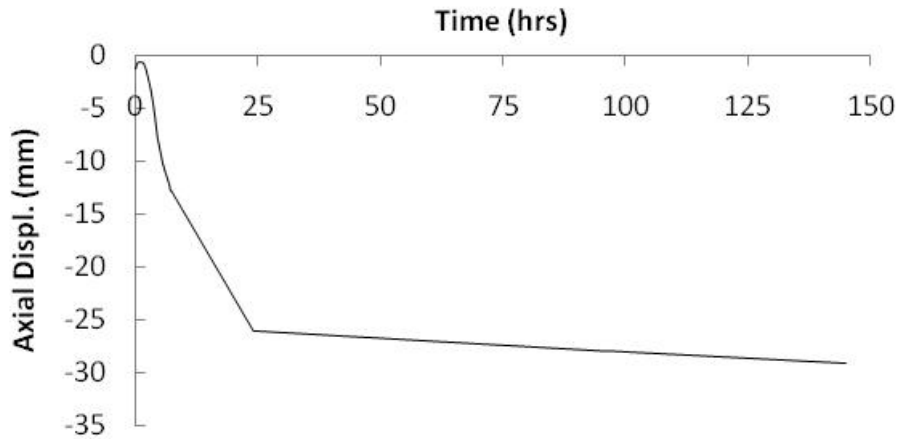


FIGURE 14. Axial Displacement, Expansion/Contraction, of the Column Specimen.

The 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 the axial load of the column specimen for the next step. Figure 15 shows the axial load of the column specimen during the fire exposure and the cooling phase. Initially, the axial load was increased slightly, from its initial value of 2000kN up to 2130kN, due to the thermal expansion of the column and its interaction with the frame; frame was resisting to expansion of the column specimen. However, the axial load was later reduced due to start of the column specimen's contraction. In other words, the rest of the building structure started to carry part of the load that was carried by the column specimen. In fact, after 8 hours, the column contraction increased significantly so that the axial load in the column specimen reached about zero. No numerical simulation was carried out after the 8 hours. However, a minimum axial load (172kN) was applied each day for 1 hour, up to 6 days, to measure the column contraction and its cross-section temperatures. After 6 days, the column was loaded axially first up to its initial applied load 2000kN and then to its failure load, ~2200kN.

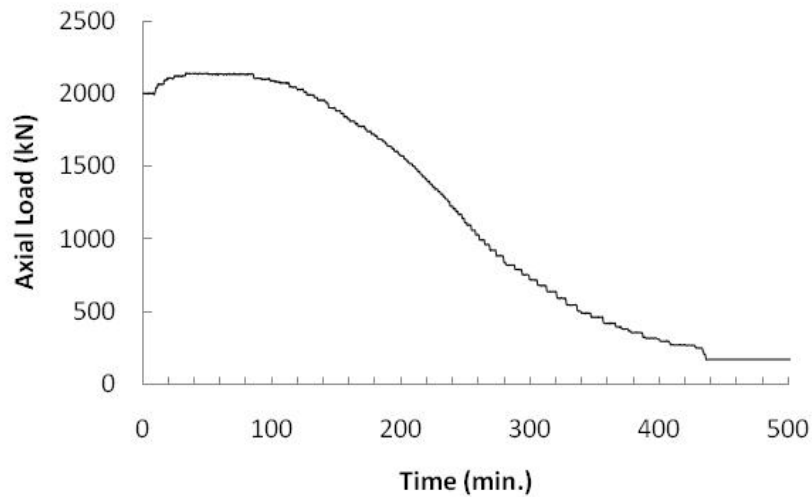


FIGURE 15. Axial Load Response of the Column Specimen.

The main purpose of this study was to show that the HFT is practically achievable. Therefore, only overall results of structural performance of the building are provided in this paper. More information is usually available from the analysis which is not presented here. Figure 16 illustrates the deformation of the building at the time when the fire exposure stopped, 4 hours.

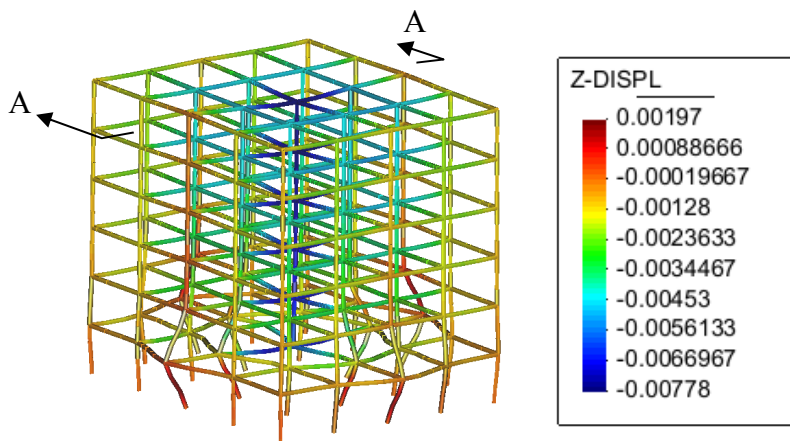


FIGURE 16. Contours of Vertical Displacements for the 6-Storey Building after 4 Hours Fire Exposure shown on the Deformed Frame (Displacements were Amplified).

Figure 17 shows only half of the building shown in Figure 16. The colors in both figures illustrate the intensity of the vertical deformation of the building which ranges from red with a

maximum of about 2 mm (expansion/upward) vertical displacement to blue with a minimum of 7 mm (contraction/downward) vertical displacement in the fire compartment. A maximum horizontal displacement of 35 mm, due to thermal expansion of the beams and floors in the fire compartment, was obtained at the first floor level, node no. 505, shown in Figure 17. Labels in Figure 17 provide numbers assigned to a few elements/nodes of the building, those near the fire compartment.

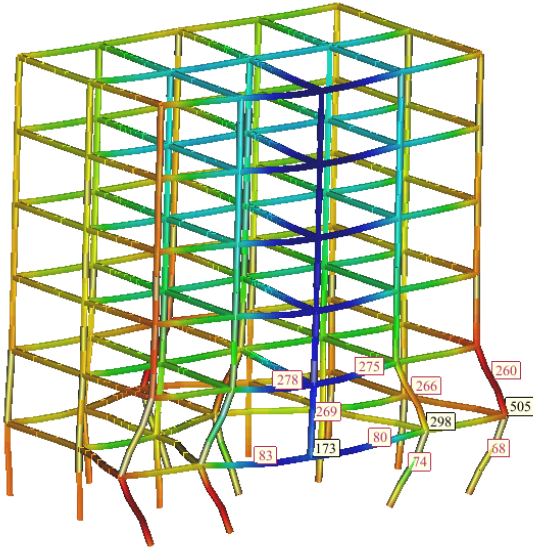
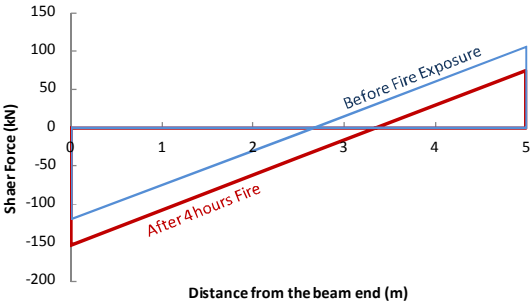


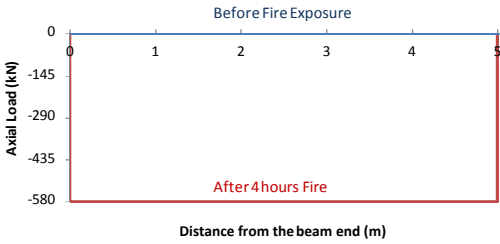
FIGURE 17. Section A-A of building in Figure 16.

A tension axial load of 270 kN was determined for beams at the upper level on the fire compartment, beam no. 275. On the other hand, a compressive axial load of -580 kN was obtained for the beam right underneath, element no. 80, which was about zero before the start of the fire. The high compressive load in element no. 80 was due to the thermal expansion of the beam at the high temperatures. The tensile axial load in element no. 275 is due to its resistance from the expansion induced by element no. 80. Maximum shear force imposed in the external columns, columns no. 260 and no. 68, were about 100kN. The axial load in the right column to the column specimen, column no. 269, reduced from about 1600 kN to 980 kN after 4 hours of fire exposure. The 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

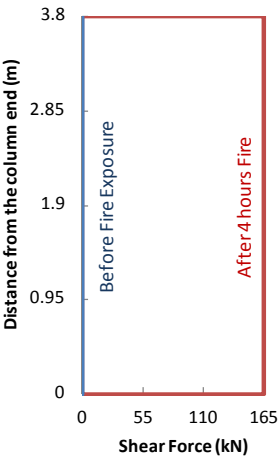
load redistribution. Shear and axial load diagrams for a beam and a column just next to the fire compartment are provided in Figure 18. The figure includes the results for the time of zero, just before the fire started, and after 4 hours of fire exposure.



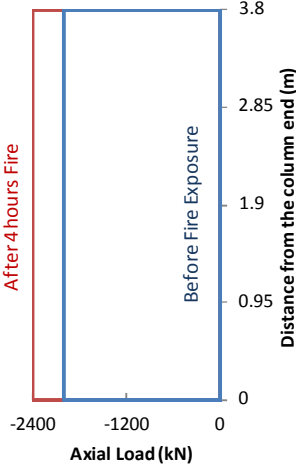
V-diagram for the beam including No. 80



N-diagram for the beam including No. 80



V-diagram for the column including No. 74



N-diagram for the column including No. 74

FIGURE 18. Shear (V) and axial load (N) diagrams for the beam and column just next to the fire compartment

Verification of Interactions between Simulation and Test

For verification, the two interaction components, load and deformation, of the column specimen and that of the rest of the building must show reasonably close values, for the duration of the HFT (Mostafaei, 2001).

Axial deformation interaction

Axial deformation of the top end of the column specimen, no. 173 in Figure 17, was measured every 10 seconds during the test. However, just about every 5 minutes, the rest of the building was imposed to the measured deformation. Figure 19 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 correlation. This indicates that the selected time intervals for the HFT provided a reasonable correlation and accuracy.

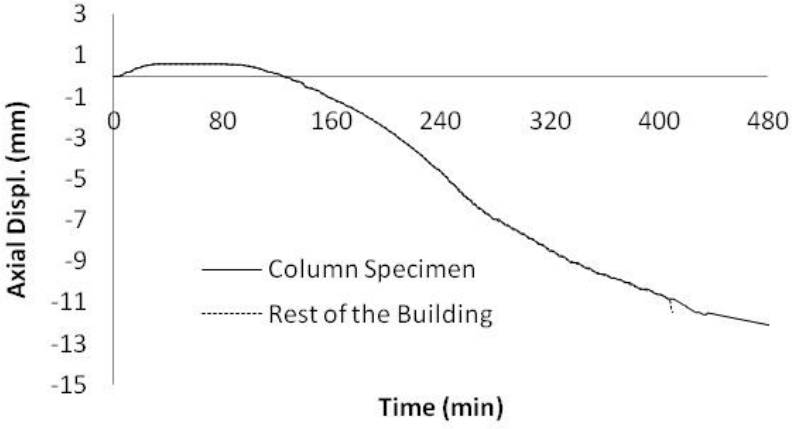


FIGURE 19. Axial Deformation for the Column Specimen and That in the Computer Simulation for the Rest of the Building.

Axial load interaction

The axial load of the column was controlled during the test based on the result obtained from the numerical analysis. Comparison of the imposed axial load on the column specimen and the corresponding vertical load on the building obtained from the analysis were shown in Figure 20, indicating again a good correlation.

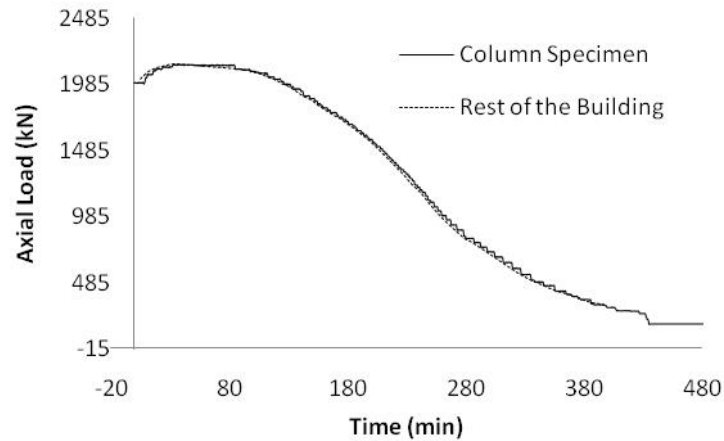


FIGURE 20. Axial Load for the Column Specimen and That in the Computer Simulation for the Rest of the Building.

A Comparison between the HFT and the Standard Test

For a comparison between the HFT and the prescriptive/standard test, results of the column specimen were compared here with the results of a column previously tested using the E119 standard. Note that in the prescriptive method, the axial load of 2000 kN was applied on the column without any change during the test.

Figure 21 shows temperatures for both column specimens at the centre of the concrete cross section, thermocouple no. 8 in Figure 5. 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). Figure 22 compares axial loads of the two column specimens during the tests.

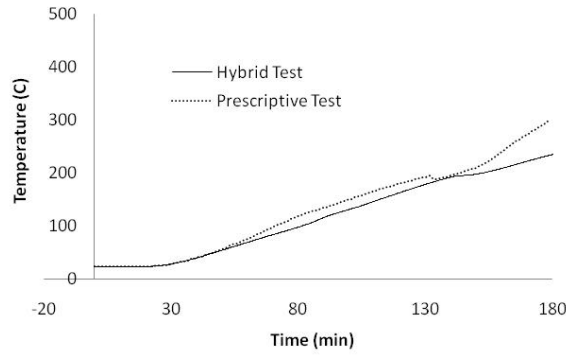


FIGURE 21. Temperatures in the Centre of the Column Section for Hybrid Test and the Prescriptive Test.

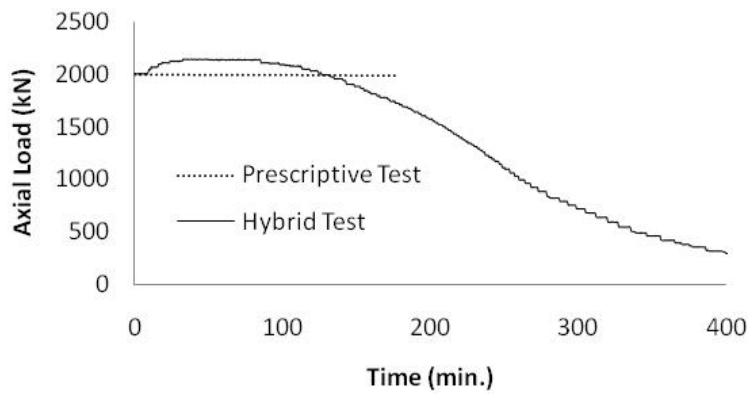


FIGURE 22. Axial Load Response for Hybrid Test and the Prescriptive Test.

Figure 23 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. The column under constant axial load showed significant increase in axial contraction after the first hour and half. However, the HFT column responded with much lower contraction which is due to axial load reduction resulting from its interaction with the rest of the building. Although one may conclude that a higher fire resistance was determined by the HFT for the column specimen than that determined by the

standard test. Further studies needed to investigate other scenarios, e.g. test of corner columns.

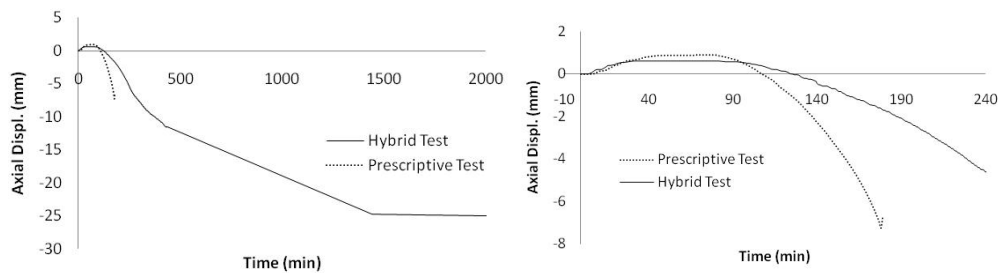


FIGURE 23. Axial Deformation Response of the Column Specimens for HFT and the Prescriptive Test; Diagram on the Right Shows the Same Results but for the First 4 Hours.

Conclusion

The new hybrid fire test (HFT) was carried out for the performance evaluation of a full-scale 6-storey building with a fire compartment located on the main floor. The following conclusions can be extended based on the results of the HFT test:

1. The HFT was carried out successfully. The application was verified by achieving a consistent correlation between the interaction components of the column specimen and that of the rest of the building.
2. The column specimen experienced a much larger contraction, column shortening, during the cooling phase than that during the fire exposure. The column shortening resulted in the redistribution of the load within the building frame; that is, reduction of the load in the column specimen and increase of the loads of the adjacent columns. Such effects could not be evaluated using the prescription/standard fire testing.
3. The column tested using the HFT showed more fire endurance than that tested using the prescriptive/standard method. Further studies needed to study HFT in other scenarios, e.g. corner columns, upper floor columns, etc.

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