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17 Vulnerability assessment of RC structures in fire and earthquake

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Abstract:

This chapter provides an overview on the performance and vulnerability of structures in fire and earthquake. Two main scenarios of fire and earthquake were explored: 1) when a structure is damaged first by an earthquake and then exposed to a fire (fire following an earthquake) and 2) when a structure is damaged by a fire and therefore its residual seismic capacity needs to be assessed and inspected. Three case studies were presented: one for the fire following an earthquake scenario and two case studies for the second scenario. A large-scale six storey reinforced concrete building, previously tested on a shaking table, was selected and numerically evaluated for the scenario of the fire following an earthquake. The results of the analysis show that damage to the structural elements, during an earthquake, could result in degradation of the concrete mechanical properties and could increase heat transfer to the structural elements and therefore lower its residual fire resistance. Two reinforced concrete columns tested previously in fire were chosen and numerically assessed for their residual seismic resistance. Furthermore, a reinforced concrete column was experimentally tested in a fire and then tested under both axial and lateral load to evaluate and inspect its residual lateral load capacity. The results from these

two studies indicate that a fire could considerably reduce lateral and axial load capacity as well as ductility of the structures. Finally, some of the research gaps in this area were identified and future studies were recommended.

17.1 Introduction

Various design codes, standards and guidelines for fire or seismic design of structures have been developed in different countries around the world to ensure the safety of occupants in buildings in the event of a fire or an earthquake. Seismic design codes provide tools for design and recommendations for analysis of structures against earthquake, while fire design codes provide requirements for the fire protection and fire resistance of building elements to reduce the risk of structural damage and loss of life in the case of a fire.

However, there is a lack of guidelines and tools for assessment, design and protection of structures for scenarios when a combination of both fire and earthquake are considered as potential threats to the structures. For instance, buildings are not designed explicitly for a fire following an earthquake. There are few reliable post-fire inspection tools to evaluate residual seismic resistance of a structure after a fire incidence (Mostafaei, et al. 2009).

Previous major seismic events have caused devastating damage to structures. The 1755 Lisbon, Portugal earthquake of a magnitude of 8.5–9.0 triggered both fire and tsunami, and caused ~100,000 deaths; the 1906 San Francisco, United States earthquake of a magnitude of 7.9 also resulted in widespread fire damage and produced 3000 deaths; the 1995 Kobe, Japan earthquake with a magnitude of 7.2, followed by fire, caused ~6500 deaths; the 2004 Sumatra, Indian Ocean earthquake with a magnitude of 9.2 led to catastrophic tsunami damage (more than 300,000 casualties); and the 2011 Tōhoku, Japan earthquake of a magnitude of 9.0, was accompanied by both fire and tsunami, causing ~20,000 deaths and large economic loss. All of these events signify the importance of considering the impact of the consequent events on the structural performance of buildings.

On the other hand, in the United States, the average annual fire occurrence in moderate and high-rise buildings exceeds 10,000 incidents (Hall, 2001). More than 50,000 fire incidents in Canada have been reported annually (CCFMFC, 2002); approximately 3,500 of which were fire incidents that occurred in apartments, hotels and dormitories. These mid- to high-rise structures experienced minor to major damage due to fire exposure, such as column and floor damage due to thermal expansion and degradation of mechanical properties of the material. Therefore, there is also a need to develop reliable tools to assess structural damage after a fire, to measure whether or not the residual seismic load capacities, after the fire damage, are sufficient and if they can satisfy the required seismic load capacity (i.e. original seismic design load).

This chapter provides information about recent studies on the performance evaluation of structures in fire following an earthquake and methodologies for analysis and testing of structures to assess their residual seismic load capacity after they are damaged by a fire. It will focus on providing a summary of research carried out at the National Research Council Canada on vulnerability assessment of structures in fire and earthquake. The main purpose of this research was not to develop design tools or solutions for such threats to structures, but to explore the needs for further research and to develop an understanding of how vulnerable structures could be to scenarios of fire and earthquakes. Two case studies were carried out by considering scenarios of structural columns in fire and earthquake. One study simulates a scenario of fire following an earthquake while the other investigates a scenario of an earthquake after fire-damage. In the second scenario, the earthquake does not occur right after a fire, as it is less likely; an exception is in aftershocks when a fire has been ignited already due to the main shock. The case study is for a post-fire seismic evaluation scenario to perform a post-fire structural damage evaluation and to assess the residual seismic load capacity of the structures after fire.

Although the information provided here would be useful for developing an understanding of the performance of different structural systems in fire and earthquake, the scope of this chapter is limited to reinforced concrete building structures, constructed with normal strength concrete.

17.2 Structural Response to Fire

Response of structures to fire is typically evaluated using a fire resistance approach. A common approach for fire endurance assessment of structures is to implement a full-scale fire resistance test. One of the first fire resistance/endurance tests was carried out using an experimental method in Denver, Colorado in 1890 (Harmathy, 1993). There are now standards, such as E119 "standard test methods for fire tests of building construction and materials," that describe how a fire resistance test can be performed. Although, application of the new performance-based approach is permitted by some of the design codes, due to little assessment tools being available and accessible to the practitioners, it is not widely being used for evaluation of fire resistance. A large number of fire resistance tests have been carried out, since development of the E119 standard. The purpose of these tests was to better understand how structural elements and assemblies, such as columns, beams, floors, and walls, perform during a fire. The results of these tests led to the development of requirements for fire resistance design of structures.

There are many factors that contribute to the fire resistance of a building structure; the higher the fire load, the lower the fire resistance. Increase of temperatures normally results in the reduction of mechanical properties of the materials, such as compression/tensile strength and modulus of elasticity. Thermal expansion of structural elements is another major effect from fire. It results in inducing large deformation to the structural elements and could cause considerable damage to the structural members even far from the fire compartment. When the structure cools down after a fire, it suffers more damage due to shrinkage of the elements from the rapid temperature drop after the fire. Various studies and research have been carried out to assess structural response and damage due to fire. However, there are still gaps in the availability of appropriate tools for performance evaluation and design of the whole structural systems in fire.

A new emerging performance-based fire resistance evaluation of structures emphasizes the consideration of response and behaviour of the whole building in the fire endurance assessment (Mostafaei, et al. 2011). For instance, current fire resistance standards require only a constant axial load applied during the column fire test. However, effects from lateral deformation due to thermal expansion of floors and change in axial load of the column due to its interaction with the rest of the building are ignored.

Figure 1 shows an example of the column's lateral deformation due to the thermal expansion in fire. Figure 1a illustrates shear failure of a column on the 6th floor of the US

Military Personnel Records Centre building due to the fire that occurred in 1973 (Beitel 2002), and Figure 1b demonstrates how the thermal expansion induces lateral deformation to the columns. Although the response of reinforced concrete columns under lateral loads has been studied for many years, a remaining challenge has been the development of a reliable methodology for evaluating effects of such lateral deformation in performance of the structure in fire.

17.3 Seismic response of structures

Various standards and guidelines have been developed, worldwide, for seismic design of structures. Based on the seismicity and site condition of structures, methodologies have been developed for evaluating response of the structures to the seismic loads and for designing and retrofitting the structures against such a hazard. The different approaches include equivalent static seismic load and analyses, design based on the mode shapes, dynamic and time history analyses.

The main effect from a seismic load on structures is the lateral load induced by the earthquake; except for structures subjected to near field earthquakes. This is normally the main design load required by the codes/standards, since building structures are more vulnerable to the effects from the horizontal wave of the earthquake. This would perhaps be the main reason that most of the research and studies have been focused on protection of structures against structural loads induced by the lateral component of the seismic waves. For instance, for reinforced concrete columns, significant amount of efforts have been made by researchers to develop models for estimating damage and the ultimate load capacity of the columns due to lateral loads, e.g. Park et al. (1982), Vecchio and Collins (1986), Lynn et al. (1996), Elwood and Moehle (2005), and Mostafaei and Kabeyasawa (2007).

There is still a lack of information on how structures would respond to a scenario when there are consequent events after an earthquake, such as a tsunami or fire. Although, including consequent events may complicate the problem to solve in order to achieve a reliable and realistic assessment, structures need to be evaluated, designed and protected considering all practical loads and consequences.

17.4 Fire performance of a reinforced concrete building following an earthquake

This is a scenario when a fire started in a building due to e.g. movement of a fire source, such as a stove, furnace, etc., induced by a tremor. In such a scenario, typically the building may suffer initial damage from the earthquake and then undergo further damage as the result of exposure to the fire, following the earthquake. Depending on the amount of available fuel, such a fire could last anywhere from a few minutes to several hours. Usually, the number of available first responders or fire-fighters is not as many as is required due to their need to respond to a large number of incidents at the same time, as is normally the case after a natural disaster. Therefore, full burn-out fires would be expected in many of these post-earthquake fires. In other words, structures engulfed in a fire following an earthquake would experience considerable fire damage, for a long duration, depending on the fire loads present in the structures.

This section explores a case study to provide a better understanding of how structures would perform in such a full burning scenario, following an earthquake. The case study investigates the vulnerability of a six-storey building to a fire following an earthquake using a numerical analysis tool. The building was in fact tested in January 2006 under a seismic load representing the 1995 Kobe Earthquake ground motion, using the large scale shaking table facility in Miki (or Hyogo), Japan. Since detailed information and experimental results of the test were available, this is a suitable example to be investigated for the scenario of fire after an earthquake. For this purpose, it was assumed that the building structure has undergone a fire following the tested earthquake. Performance of the building in the hypothetical fire was simulated by carrying out a numerical analysis. The six-storey building was made of reinforced concrete. Figure 2 shows the building on the shaking table after the earthquake test.

Damage to the reinforced concrete structures due to an earthquake may include concrete spalling, shear/flexure cracks, or failure of the structural elements. If the structural elements are protected by a means of fire protection, e.g. insulations, there is also a possibility of damage to the protection systems due to large deformation as the result of the seismic vibration.
The induced damage on the concrete elements could change the heat transfer mechanism and temperature distributions, and degrade load bearing capacity of the structural elements. This is because heat could penetrate faster to the core of the concrete elements through the cracks and the concrete loses its strength at high temperatures. Therefore, in the structural response assessment effects of the damage need to be included in both heat transfer and structural analysis.

In this case study, observations of the concrete cracks and damage, recorded during the shaking table tests, were closely studied to determine potential heat/flame penetration through the damaged elements. An analytical model was then utilized to determine the change in the concrete strength capacity due to the induced seismic deformation.

Fire load after an earthquake will be dependent on amount of combustible materials in the buildings, e.g. furniture, plastic produces, etc., at the time of the earthquake. A design fire could be developed based on the available fire load and ventilations. However, considering a worst case scenario and for simplicity, a standard fire was considered in this study for fire resistance evaluation of the building. A standard fire curve is a time-temperature curve, e.g. ASTM E119 (2007), which is used for fire resistance tests of structural elements.

The results presented in the following section could not be applied for any building under a fire following earthquake. Types of structural materials, combustible contents in the building, location of fire, building geometry, and fire compartmentations are among the many other major factors that could change the outcomes.

19.4.1 Building Structure Specifications

The six-storey nearly full-scale reinforced concrete building has a total height of 15 meters, (Kabeyasawa et al. 2005). The building was previously tested on a shaking table under the 1995 Kobe ground motion at the E-Defense Miki (or Hyogo), Japan. Details of the structural system, dimensions, and material properties can be found in Kabeyasawa et al. (2005). Figure 2 shows a picture from the building specimen on the shaking table.

19.4.2 Structural Performance of Building in Fire with and without Seismic Damage

To better understand the effects from the earthquake damage on the fire resistance of structure, the building was numerically analyzed for two scenarios; 1) for a fire without any prior earthquake or damage, and 2) for a fire following an earthquake with seismic damage. A finite element modeling technique using a structural analysis program called SAFIR (Franssen, 2007) was employed to model the building specimen. First, analysis was carried out for scenario (1) to assess fire resistance of the building before having any seismic damage to the structure. It was assumed that the fire started on the first floor but was confined in the same floor and had not spread to other levels of the building. As a worst case scenario, the analysis was carried out for an eight hour fire exposure. A typical fire in such buildings may last less than this time. The eight hours fire exposure was selected to induce failure of the building in the first scenario.

In the second scenario, fire resistance of the building was evaluated after it was damaged by the earthquake, which was the input seismic excitation used during the shaking table test. For the sake of comparison, the same fire load and location, ASTM E-119, as that used in the first analysis, was assumed for the purpose of this assessment.

An analytical method was utilized to evaluate degradation in mechanical properties of concrete due to the seismic damage and a numerical analysis was then employed to assess the effects of heat and flame penetration, into the damaged and cracked concrete elements, on the building fire resistance. Another effect to include, in a post-earthquake fire resistance evaluation, is the effects of residual lateral deformation of the structures. However, no residual lateral deformation was observed during the shaking table test of this building; therefore this was considered in this study. Note that two middle columns in Axis X1 at the first floor (see Figure 3), were not included in the analysis, since both columns collapsed during the earthquake test.

19.4.3 Degradation of Mechanical Properties of Materials

Typically, mechanical properties of materials degrade when they undergo large deformation. When a building structure is subjected to an earthquake, large lateral deformation may result in significant damage to the structural elements and degrade their material mechanical properties.

In reinforced concrete structures, large flexure, shear and tensile/compression deformation may lead to the post-peak response of the material, where the materials incurred permanent strength degradations. Therefore, if the deformation caused by the earthquake to the structural elements is larger than the peak-strength deformation capacity, those elements are likely to have a permanent change in their mechanical properties. For a post-earthquake fire performance assessment of structures, such permanent changes in mechanical properties, due to the earthquake, need to be taken into account. Although there are various models available that could estimate degradation of the material properties for structural elements of a building, there is still a challenge due to the lack of reliable analytical tools to precisely estimate such permanent damage. One of the reasons is the irregularity of the damage distributions in the elements and their cross sections. In other words, even in a single cross section of an element, concrete degrades differently across the section depending on the induced deformation distributions. For simplicity, in this study, an analytical approach was used to estimate average values that quantify overall damage of the elements' material properties due to the earthquake.

For the purpose of heat transfer analysis, location of cracks and crashed concrete is very important, as it affects the level of heat penetration into the elements. Since, experimental results were available, locations of cracks and damage to the concrete in different structural elements were identified and evaluated based on observations, taken place, after the shaking table test. Only columns in the first floor suffered permanent damage and major cracks during the test. Therefore, the effects of heat penetration and degrading material properties were determined only for these elements. The rest of the elements, columns in upper floors, walls and beams were considered to have no damage. Figure 3 shows prevalent damage to various first floor columns. The pictures placed on the figure were taken right after the shaking table test.

The main mechanical property of the concrete that were mostly affected by the earthquake was its compressive strength. Concrete may experience large non-linear deformation during the earthquake resulting in partial but permanent loss of concrete compression strength. However, the main challenge for that is to quantify the compression strength of degraded concrete for different structural elements that would experience variable deformation at different locations on the cross section. One may suggest running a time-history analysis where first the effects of the earthquake on structural elements and material properties are determined and then the response of the damaged structure is simulated for the fire effects. However, this would require a reliable analytical/numerical tool for both seismic simulation and fire analysis. Currently, there are more reliable numerical programs available for seismic response simulation and for fire resistance calculation, independently, than that for the combined simulation of fire and earthquake effects. Hence, in this study, the independent simulations were performed.

A pushover analysis, using the Axial-Shear-Flexure Interaction (ASFI) approach developed by Mostafaei and Kabeyasawa (2007), was implemented to determine the degradation of concrete compressive strength for the seismic damaged elements. The ASFI method is a displacement-based evaluation approach, developed based on coupling the traditional section analysis method, which is an axial-flexure model, with an axial-shear model, e.g. modified compression field theory (MCFT) (Vecchio and Collins 1986).

To estimate the degradation in the concrete strength, first for each structural element, a pushover analysis was performed, by the ASFI method, to determine lateral load degradation of the element at the maximum lateral deformation, experienced by the column during an earthquake. Then, the same degradation ratio was assumed, as an approximate degradation ratio for the concrete compression strength of the column. Figure 4 shows an example of the analysis for a corner column, which indicates an 80% loss of lateral load capacity or 20% residual capacity giving an 80% degradation in the concrete strength. This simulation was performed for each of the columns in the first floor with recorded seismic damage.

Estimating degradation of concrete strength based on the loss of lateral load capacity might not be considered an accurate estimation method since distribution of compression stress, and therefore the concrete strength degradation, on the cross section of the column, under both axial and lateral load, is not uniform. Furthermore, for columns that fail in flexure, yielding the main steel bars would govern the column response and therefore concrete would degrade less than that of the lateral load capacity. However, this method may be considered as a conservative method, based on a worst case scenario, and for the sake of safety its application would be reasonable. Further research is needed to develop a more reasonable and accurate estimation methodology.

The fire resistance analysis of the whole building was then carried out when the above compressive strength degradation was included for the structural elements that were damaged during the earthquake.

It is noted that in this study, experimental results were available for the seismic response of the building and its structural elements. In general, when such data are not accessible, a time history nonlinear analysis of the entire building subjected to the earthquake input motion can be performed to estimate the building seismic response.

19.4.4 Heat Penetration

Openings, such as crack and spalling, could accelerate heat penetration into the structural elements and, therefore, increase the heat transfer through the elements. For instance in the case of concrete or masonary structures such cracks or spalling could occur as the results of large deformation due to an earthquake. When the cracks are large enough, these openings would let the heat and flames penetrate deep into the structural elements and elevate the temperatures rapidly in the elements. This will in turn result in degradation of material properties and reduction of building load bearing capacity. Figure 5 shows the temperature distribution of the damaged and the undamaged cross-sections due to fire, for a column in the first floor of the building. The results indicate considerable effects of concrete damage due to the temperature distribution.

19.4.5 Residual Drift and P-Δ Effects

After an earthquake, a building could experience large deformation which could lead to a nonlinear stage that could result in some deformation off-set or residual lateral deformation. In other word, the building could not recover its original position after the ground shaking. Such residual deformation will cause eccentric loading on the structural columns (i.e. P-Δ effects). Typically, performance of the building would degrade, when P-Δ effects are present.

In this study, since the residual lateral displacement of the building, measured during the test, was nearly zero, P-Δ effects are not included in the analysis. For a worst case scenario, this building would result in less fire resistance after the earthquake, should the structure have experienced such a residual drift. More detailed information on the results of the analysis of the six-storey building in fire following the earthquake can be found in Mostafaei and Kabeyasawa (2010).

19.4.6 Main Analysis Results and Observations

Figures 6 and 7 show the results of the fire resistance response for the short corner columns in the first floor, Axis X1, of the building before and after they were damaged by the earthquake. Based on the results of this case study, following remarks can be made:

- Fire resistance of the six-storey building after seismic damage was considerably less than that before the earthquake.
- Factors contributed in determining fire resistance of the building after the earthquake were mechanical properties degradation of concrete and the extent of crack and spalling of the concrete.
- Relatively high fire resistance was available for the building when only effects of concrete cracks and spalling in the heat transfer analysis were included in comparison with the case when only degradation of material mechanical property was considered. In other words, preventing concrete from spalling or limiting the spread of cracks results in an effective post-earthquake fire protection, for such buildings.
- Due to partial/complete failure of some of the structural elements, loads were redistributed to the adjacent elements. For instance in this case, the loss of the two middle columns in Axis X1, caused increase of axial load for the corner columns in the same axis. Therefore, higher applied load may be imposed on certain structural elements during a post-earthquake fire. The increased load would in turn reduce the fire resistance of these elements.

17.5 – Residual seismic resistance of fire-damaged building columns

This case study explores the second scenario in which residual seismic load capacity of fire-damaged structural elements is investigated. For the purpose of this case study, two reinforced concrete columns, Column A and Column B, made with siliceous aggregate, previously tested at the National Research council Canada (Lie et al., 1986), were selected. The clear height of both column specimens was 3760 mm. Column A was exposed to a standard fire ASTM E-119 for one hour and Column B was exposed to the same fire for two hours. A constant axial load was applied during the test. After terminating the fire, the two columns were kept intact until they reached ambient temperature. Then, they were then loaded until they reached their axial load failure. Figure 8 shows axial deformation response of the two columns during the fire test, the cooling phase, and the final loading.

A numerical analysis was carried out using VecTor3 (2008), a nonlinear finite element analysis program for three-dimensional reinforced concrete solid structures subjected to quasi-static load conditions developed at the University of Toronto. The analysis was first done for these two column specimens for the purpose of model validation under the axial load. Then, the same numerical analysis was carried out using the software to estimate the residual seismic capacity of the two columns.

17.5.1 Axial load response analysis (verification)

Maximum temperatures reached at various depths, in the cross section of the two columns, during the heating and cooling period were obtained and averaged from the test results (Lie and Woollerton, 1988) as illustrated in Figure 9. Then, the numerical simulation was carried out to evaluate the axial response of the two columns under axial loads. The analysis was done considering degradation of the concrete material properties due to its exposure to the elevated temperatures.

Load-deformation results from the numerical analysis were then compared with the load–deformation ratio measured during the test. Figure 10 illustrates the comparison between the test and the numerical results for the two columns. The figure shows a reasonable agreement between the results, indicating a successful verification of the numerical analysis employed for the axial load response estimation. Furthermore, for comparison, the axial response of the two columns with no fire exposure, using the original properties, was also estimated and provided in the same figure. The results show that residual axial capacity was reduced to 73% for Column A; and 52% for Column B.

17.5.2 Lateral load resistance

VecTor3 was utilized to investigate the residual lateral load response of the two column specimens after the fire damage. One may be concerned that validation of the numerical model for axial behaviour would not apply for lateral response simulation. This is true since lateral response of the columns involves shear and flexure mechanisms in addition to the axial mechanism. It is noted that VecTor3 has been validated for such columns under lateral load in ambient temperature. Since the two column specimens in this case study are relatively long, their governing behaviour would be axial and flexure when subjected to the lateral loads. In the analysis, each column section is divided into small fiber elements, hence the main impact on these elements will be either axial compression or tension response. Furthermore, the VecTor3 model was validated for axial response of the two columns in the previous section. Therefore, it is anticipated that VecTor3 would produce relatively reasonable results for the two columns under the lateral loads.

For the analysis, half of the column was modeled based on the symmetric conditions, e.g. loads and supports. Lateral load was applied horizontally at the top of the columns, in a deformation controlled mode, and incremented from zero up to the column failure deformation. Figure 11 shows numerical results for the columns before and after fire exposure. The results indicate that the residual lateral load capacity is reduced to 73% and 58% of the original lateral load capacity for Column A and Column B, respectively. With respect to the column ductility, the ultimate lateral deformation is reduced to 48% and 61% of its original value with no fire damage for Column A and Column B, respectively. Therefore, both ductility and lateral/seismic load capacity of the columns were substantially reduced as a result of the fire exposure.

17.5.3 Strength recovery

The loss of concrete strength due to fire exposure is largely recoverable in the long-term using a proper curing method (Weigier and Fisher, 1968; Poon et al. 2001). For instance, concrete that is exposed to an elevated temperature of 500°C, recovers 90% of its original strength in about a year (Lie et al., 1992). Therefore, if time permits, by employing a proper inspection and assessment approach after a fire, and applying an efficient curing/retrofitting method, concrete structures may almost regain their minimum axial and seismic resistance capacities that were required for the original seismic design. Further studies would be required to develop more efficient inspection techniques and proper curing/retrofitting methodologies for structures damaged after a fire.

17.6 – Lateral load resistance of a fire damaged column using a hybrid method

Recently, a hybrid test procedure has been developed and implemented at the National Research Council of Canada, for evaluating lateral load resistance of reinforced concrete columns after experiencing fire damage. Through this study, a column was tested as part of the six-storey concrete building using a hybrid testing technique. The test included a fire on the first floor of a six storey building. Figure 12 shows the setup of the hybrid testing technique for the fire test. In the hybrid method, the whole building is divided into two substructures; the test specimen and the model component. Then the fire performance of the whole structure is evaluated based on coupling the performance of the two substructures and by including their interactions in real time during the simulation. In this study, the hybrid method was performed for estimating fire resistance of the building. Six days later, after the entire structure had cooled down to the ambient temperature, the building was subjected to lateral loads, determined based on a design seismic load, for estimating its residual lateral load capacity. The column's residual lateral load-deformation results obtained from this hybrid test were then compared with the results previously obtained for a column but with no fire damage. Considerable reductions were reported in both stiffness and deformation capacity of the column and the building due to the fire damage. More information on the hybrid test can be found in Mostafaei et al. (2011). Figure 13 shows an example of a lateral deformation response of the building after fire damage.

17.7 Conclusions and Future Trends

The overall results of three case studies on the vulnerability of reinforced concrete structures in fire and earthquake were provided in this chapter. The two main scenarios investigated included the effects of a fire following an earthquake on performance of the structures and the residual seismic capacity of the fire-damaged structures. The results from these cases studies highlighted that:

- Seismic damage to structural elements and the fire protection systems would considerably reduce the fire resistance of the structure after an earthquake;
- Fire damage to structures could reduce lateral load and deformation capacity of structures, and;
- Enhancing seismic resistance of fire protection systems and structural elements would enhance fire resistance of the structures in the event of a fire following an earthquake.

There is still a need for research and studies on the assessment, design and protection of structures in fire and earthquake. For a fire following an earthquake, new methods should be studied to reduce damage to fire protection systems of buildings, e.g. sprinklers systems and structural elements of fire compartments. More efficient methods need to be developed to assess the fire damage of the building structure, and for the evaluation of their residual seismic resistance. Solutions are also required to conduct seismic retrofitting of fire-damaged buildings.

17.8 References

ASTM E119 (2007). "Standard Test Methods for Fire Tests of Building Construction and Materials", *American Society for Testing and Materials*.

Beitel, J., Iwankiw, N. (2002). "Analysis of Needs and Existing Capabilities for Full-Scale Fire Resistance Testing", *National Institute of Standards and Technology*, NIST GCR 02-843.

CCFMFC (2002). "Fire Losses in Canada", Annual Report 2002, *Council of Canadian Fire Marshals and Fire Commissioners*, pp. 42.

Elwood, K.J. and Moehle, J.P. (2005). "Drift Capacity of Reinforced Concrete Columns with Light Transverse Reinforcement." *Earthquake Spectra*, Earthquake Engineering Research Institute, 21, 71-89

Franssen, J.M. (2007). "User's Manual For SAFIR 2007a Computer Program For Analysis of Structures Subjected to Fire", *University of Liege*, Belgium.

Hall, J.R. (2001). "High-rise building fires." *NFPA*, Quincy, MA.

Harmathy, T.Z., Fire Safety Design & Concrete, Longman Group UK Limited, 1993

Kabeyasawa, T., Matsumori, T., Katsumata, H., and Shirai, K. (2005). "Design of the Full-Scale Six-Story Reinforced Concrete Wall-Frame Building for Testing at E-Defense", *Proceedings of the First NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structures*, PEER-2005/10, California, Berkeley.

Lie, T.T. (editor) (1992). "Structural fire protection." *ASCE Committee on Fire Protection*, Structural Division, 78.

Lie, T.T., Rowe, T.J., and Lin, T.D. (1986). "Residual strength of fire-exposed reinforced concrete columns." *American Concrete Institute*, ACI SP92-9,153-174.

Lie, T.T., and Woollerton, J.L. (1988). "Fire resistance of reinforced concrete columns – Test results." *National Research Council Canada*, Internal Report No. 569.

Lynn, A.C., Moehle, J.P., Mahin, S.A., and Holmes, W.T. (1996). "Seismic evaluation of existing reinforced concrete building columns." *Earthquake Spectra*, 12(4), 715–739.

Mostafaei, H. and Kabeyasawa, T. (2007). "Axial-Shear-Flexure Interaction Approach for Reinforced Concrete Columns." *ACI Structural Journal*, 104(2), 218-226.

Mostafaei, H., Kabeyasawa, T. (2010). "Performance of a Six-Story Reinforced Concrete Structures in Post-Earthquake Fire", *The 9th US National and 10th Canadian Conference on Earthquake Engineering*, July 25-29 2010, Toronto, Canada.

Mostafaei, H., Leroux, P., Lafrance, P.S. (2011). "Hybrid Fire Testing for Performance Evaluation of Structures in Fire - Part 1 Application," Research Report No. 317, *National Research Council Canada*, pp.1-34.

Mostafaei, H., Vecchio F.J., and Bénichou N., (2009), "Seismic Resistance of Fire-Damaged Reinforced Concrete Columns", American Society of Civil Engineers, Proceedings of the 2009 ATC & SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures

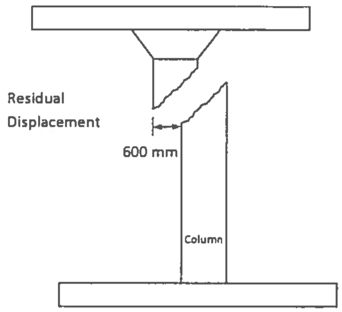
Park, R., Priestley, M.J.N., Gill, W.D. (1982). "Ductility of square confined concrete columns." *Journal of Structural Division ASCE*, 108(4), 929–950.

Poon, C.S., Azhar, S., Anson, M. and Wong, Y.L. (2001). "Strength and durability recovery of fire-damaged concrete after post-fire-curing," *Cement and Concrete Research*, 31(9), 1307–1318.

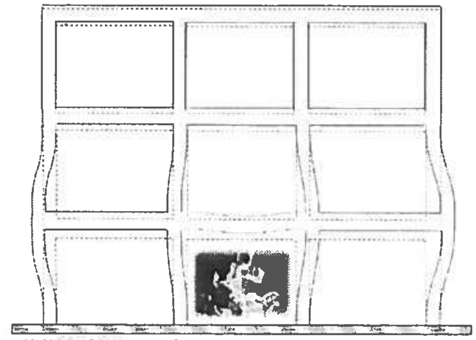
Vecchio, F.J., and Collins, M.P. (1986). "The Modified Compression Field Theory for Reinforced Concrete Elements Subjected to Shear." ACI Journal, 83(2), 219-231.

VecTor3 (2008). "VecTor3 software." VecTor Analysis Group, Civil Engineering Department, *University of Toronto*, http://www.civ.utoronto.ca/vector/ (accessed Aug. 2009).

Weigier, H., and Fisher, R. (1968). "Beton bei temperaturen vo 100 C bis 750 C." *Beton Herstellung*, Verwendung, 18(2).



a) Resembling the column failure during the fire at the Military Personnel Records Centre (USA)



b) Building frame deformation due to thermal expansion

Figure 1. Lateral deformation of columns due to the thermal expansions of structures in fire

Figure 2. The reinforced concrete wall-frame building specimen.

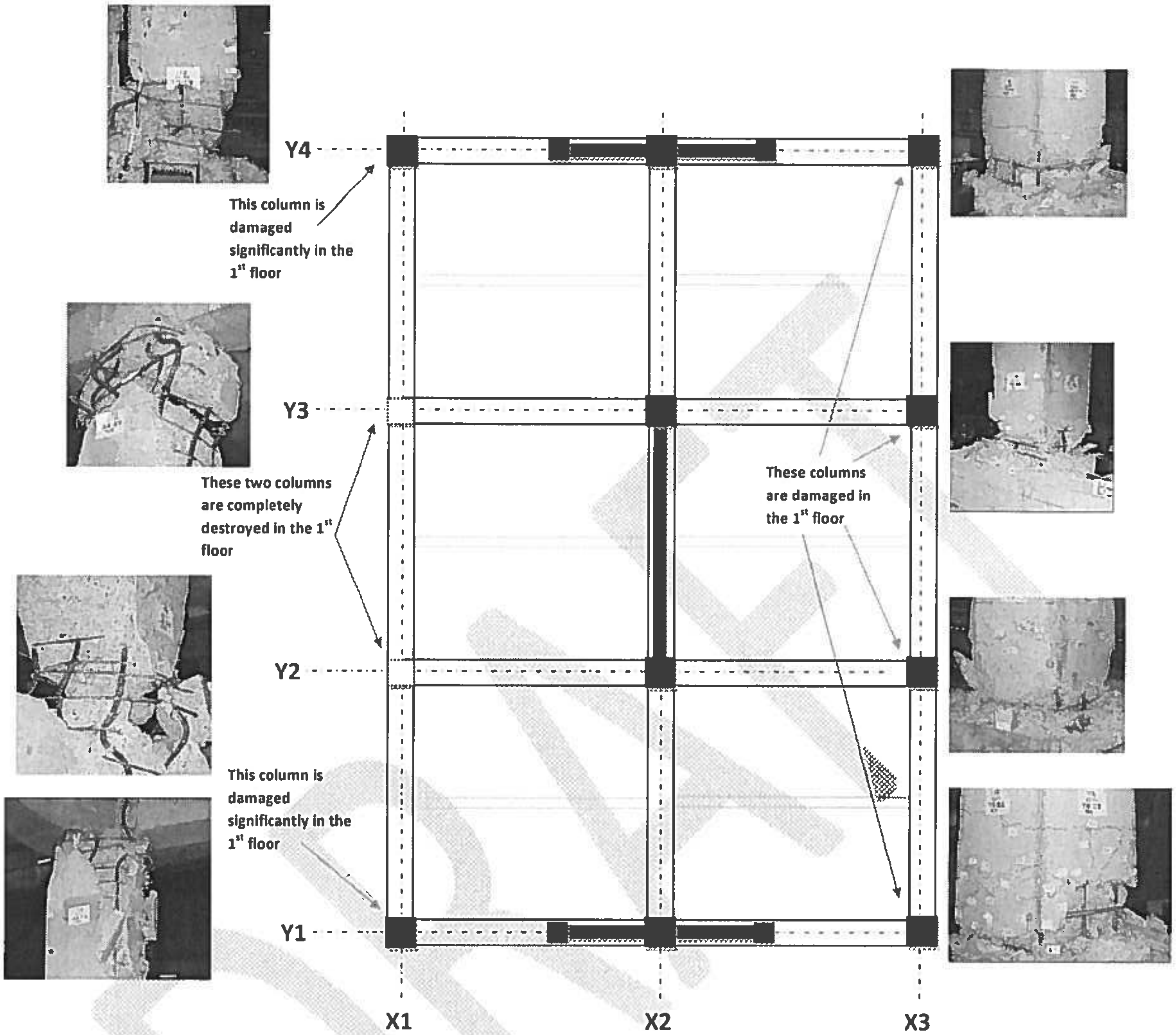


Figure 3. Photos taken after the shaking table test showing damage to the columns on the main floor. (Mostafaei and Kabeyasawa, 2010).

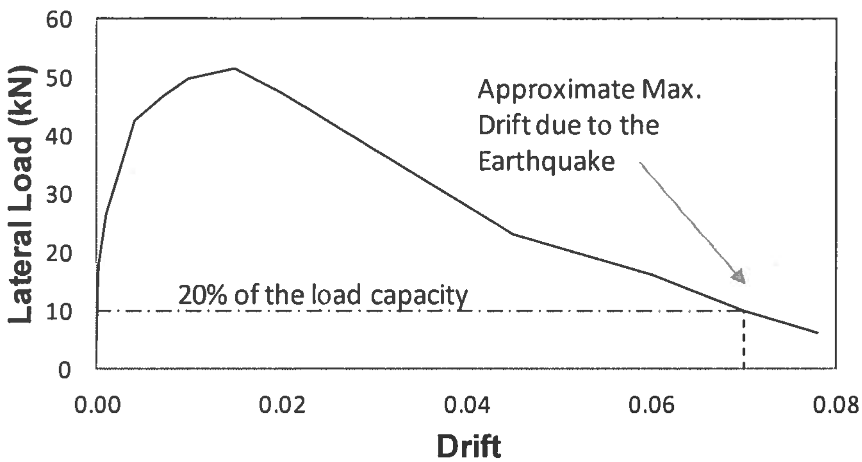
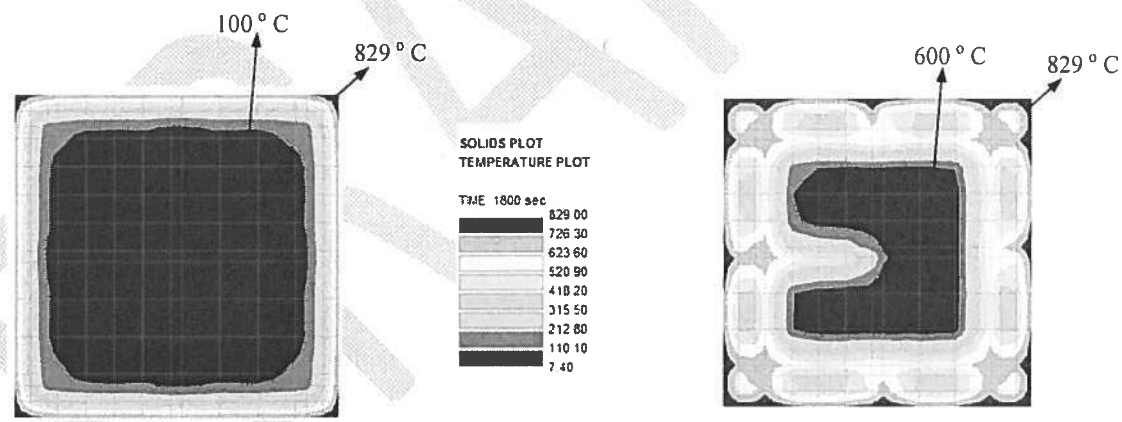


Figure 4 Lateral load-drift response of the two columns, X1-Y1 and X1-Y4, in the ground floor, obtained by the ASFI method, and the residual load capacity



a) Section with no seismic damage

b) Section with seismic damage

Figure 5. Temperature distributions on a cross-section of a column 30 minutes after the fire started

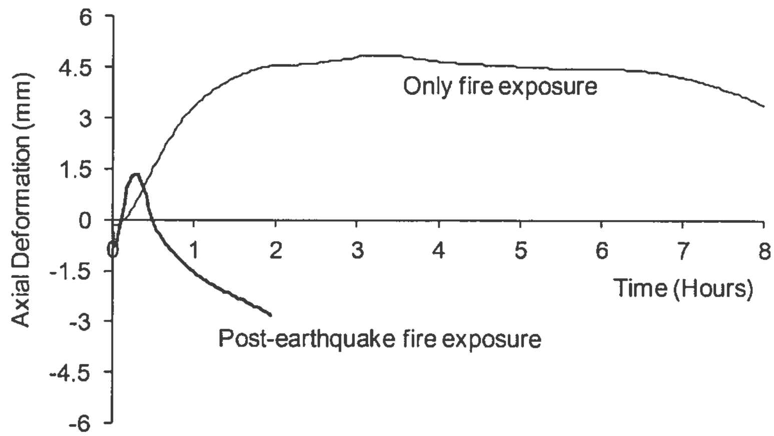


Figure 6. Axial deformation capacity response of a short column in the ground floor

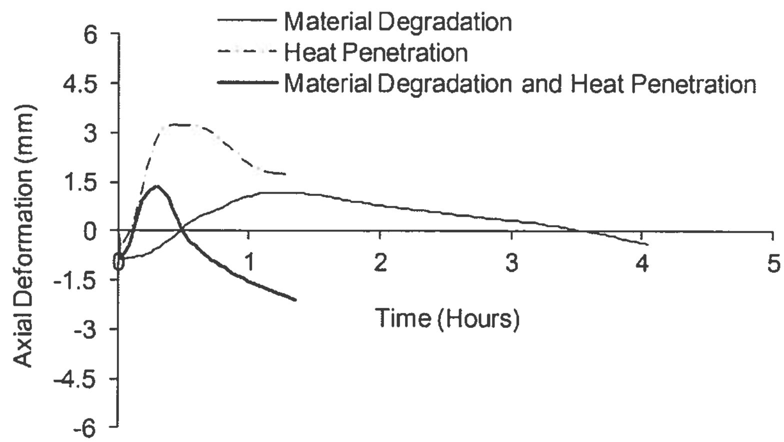


Figure 7. Axial load capacity response of a short column in the ground floor subjected to post-earthquake fire showing effects of material degradation/heat penetration on the response

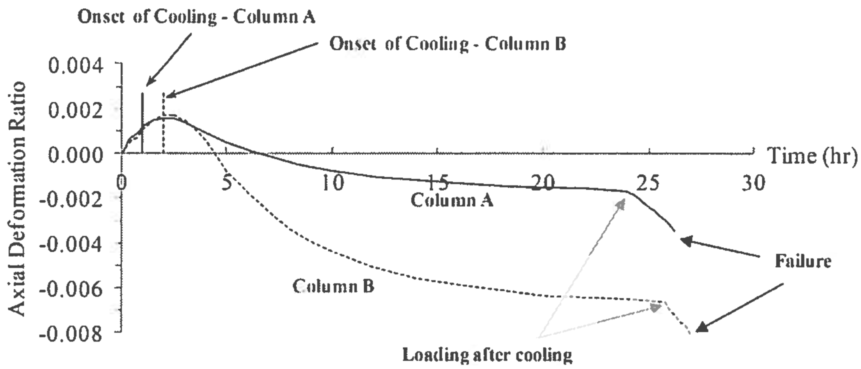


Figure 87. Time history of the axial deformation ratio response for Column A and Column B (Test Data)

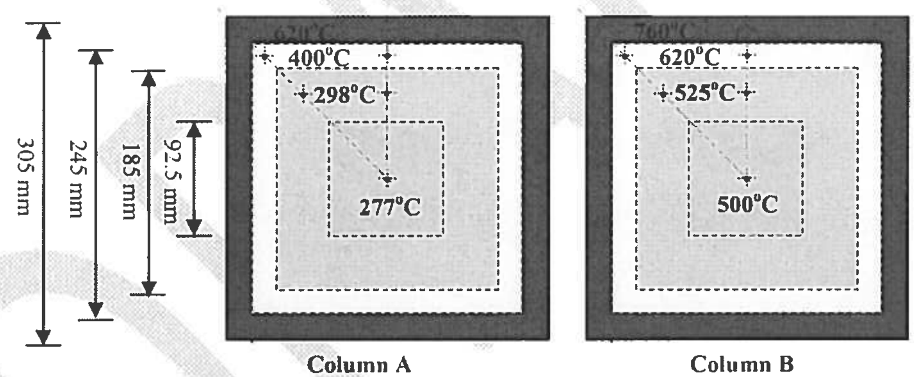
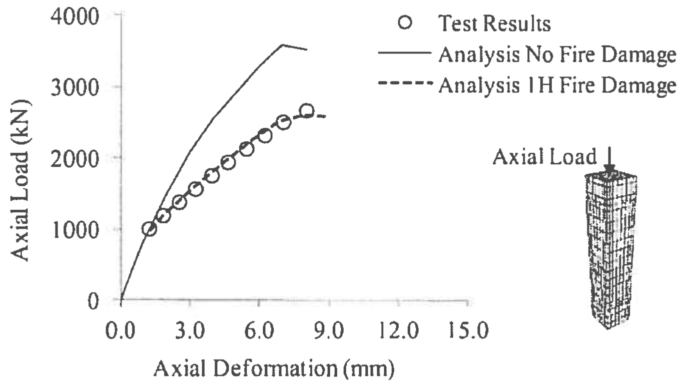
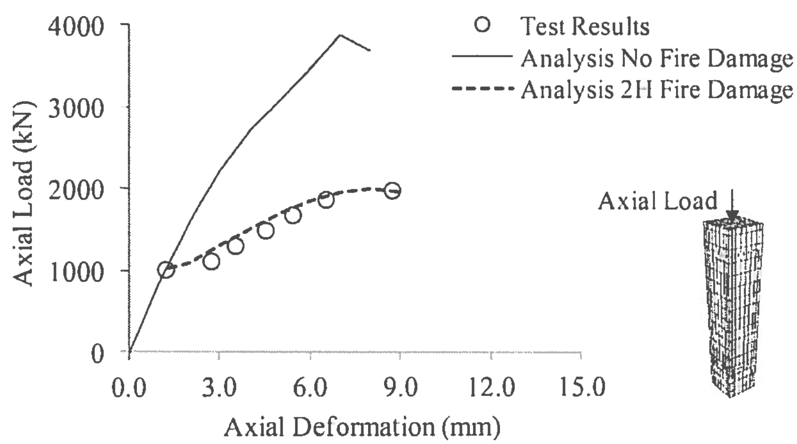


Figure 9. Temperature distributions assumed for the analysis, obtained from test data by averaging maximum temperatures that each part of the sections reached during the fire exposure.

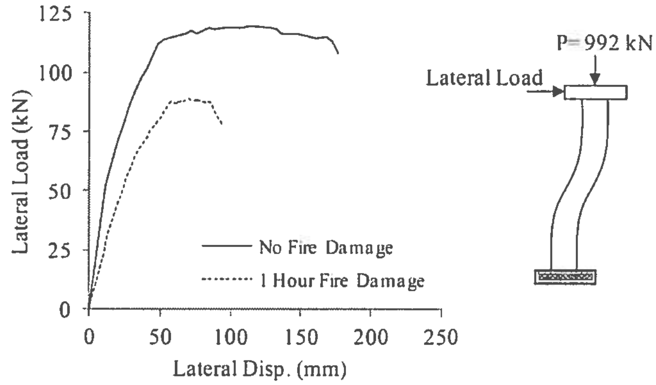


(a) Column A

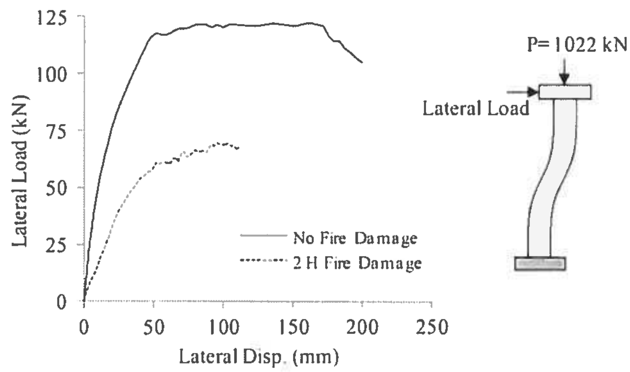


(b) Column B

Figure 10. Axial load and deformation ratio relations: numerical and test results.



(a) Column A: 1 hour fire damage



(b) Column B: 2 hour fire exposure

Figure 11. Lateral load and lateral deformation ratio response analysis.

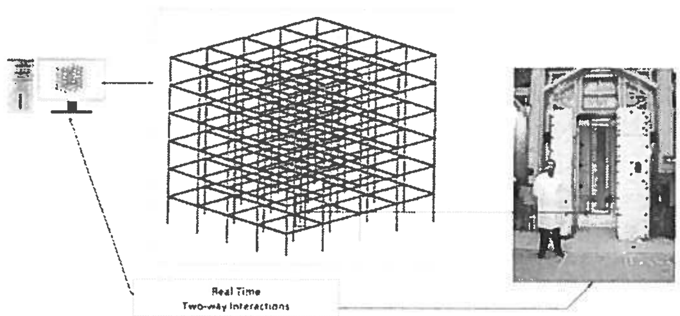


Figure 12. Hybrid Fire Testing (HFT) method employed for a six-storey building, which involved two-way interactions between the computer simulation, on the left, and the physical test, on the right (Mostafaei et al., 2011).

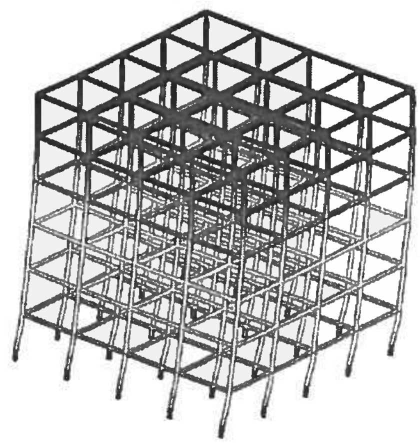


Figure 13. An example of displacement response of a six-storey building after fire exposure, the darker the colour the larger the deformation