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PERFORMANCE OF A SIX-STORY REINFORCED CONCRETE STRUCTURES IN POST-EARTHQUAKE FIRE

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ABSTRACT

This paper presents results of a 3D performance simulation of a six-story reinforced concrete structure exposed to a fire after the shaking table test for the Kobe Earthquake 1995. The structural analysis software, SAFIR, capable of 3D simulation of building structures in fire, was employed to evaluate performance of the building under fire. The ASTM E119 standard fire was selected as the fire load for this study. In order to consider the effects of damages to the structural elements during the earthquake, material mechanical properties degradation and heat penetration, due to cracks, were considered for the post-earthquake fire analysis. The fire was assumed to occur in the ground floor next to the short columns that experienced considerable damages during the earthquake. A comparison study was implemented to investigate the level of effects by material degradation/heat penetration on the fire resistance of the building after the earthquake.

Introduction

Fire has always been a major hazard and risk to buildings and infrastructures after major earthquakes. Results from post-earthquake damage reconnaissance and investigation show that fire following the earthquake could significantly increase the level of lost and damage. In such events, post-earthquake fires are rapidly growing and becoming out of control. This is mainly due to the occurrence of a large number of fire incidents in a short period of time and damages to the communication, water supply and transportation systems, which limits access of fire fighters to the fire scenes (Mousavi and et al. 2008). Furthermore, deformation of the structures due to earthquake could damage fire protection systems in the structures. In reinforced concrete and masonry structures, cracks and crash of cover concrete could results in penetration of the flame and elevating the temperatures within the element more rapidity. Most of buildings and structures in post-earthquake fire could experience a full fire load while their fire-resistance has diminished significantly due to the earthquake damages. This is perhaps one of the main reasons that a large number of post-earthquake building fires result in the collapse of the buildings. Studies on post-earthquake fires, such as the 1906 San Francisco earthquake and the 1923 Tokyo earthquake (Scawthorn et al. 2006), referring as the largest urban fire in history in peacetime, indicate that 80% of the building damages (28,000 buildings destroyed only in San Francisco) were due to the post-earthquake fire rather than the shaking. Therefore, there is a need to better understand the performance and response of structures in the events of post-earthquake fire for disaster mitigation.

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To this direction, the goal of this study is to evaluate collapse simulation of a six-story reinforced concrete building structure exposed to a fire senior after it was subjected to the Kobe 1995 earthquake ground motion. The building was tested previously at the E-Defense full-scale shaking test facility in Kobe Japan. This study will only explore the building response to a fire based on the damages observed after the shaking table test.

Building Structural Specifications

A six-story nearly full-scale reinforced concrete building was designed by Kabeyasawa et al. (2005), for the shaking table testing under Kobe 1995 ground motion at the E-Defense Kobe, Japan. The same building has been selected for the purpose of this study. The structural configuration and material properties of the building specimen were obtained based on the design specifications provided by Kabeyasawa et al. (2005). Figure 1 shows the overall configuration of the building structure. Plan of the building is shown in Fig. 2. Total high of the building is 15m. Cross section of the main columns is 500mm×500mm and of the columns next to the shear wall, SW2, in axes Y1 and Y4 is 300mm×300mm. The girders were designed with cross section of 300mm×500mm. The specimen has also floor beams in Y direction with cross section of 200mm×400mm. Shear walls are in both X and Y directions, SW1 and SW2, with thickness of 150mm. There are also Wing walls in axis X1 with height of 1000mm and thickness of 120mm.Slabs in all the floors are 150mm in thickness expect the roof the thickness of which is 190 mm. For simplicity in this study, all floors are considered with 150mm thickness.

Structural Modeling

For structural modeling of the building specimen a structural analysis software called SAFIR (Franssen 2007) was employed. SAFIR is a computer software developed at the University of Liege for response simulation of building structures in fire. Girders, beams and columns of the building were modeled using the fiber models and shear walls were simulated using the shell elements. In order to reduce the computation time and enhance convergence, slabs of the building were modeled as part of the girders and beams cross sections, instead of using shell elements. In other words beams and girders are simulated as T-sections. Since the building was designed according to the Japanese code, the effective flange widths of the T-sections were determined based on the AIJ design guideline (AIJ 1994). Fig. 3 shows the mesh for the fiber elements and the effective flange width of the middle girders for axes X2, Y2, and Y3.

The building entirely was built using normal concrete with compressive strength of 24MPa. There are mainly two types of reinforcing bars used for the elements: D19 as the main bars with yield stress of 380MPa and D10 for hoops, walls and slabs with yield stress of 365MPa. The ASTM E119 standard fire load was selected for the fire scenarios in the analysis. Each floor of the building specimen has a weight of 1225 kN; this includes the 1.0 m surrounding balcony in each floor. This load is transferred by the floor beams to the main girders in Y directions. Therefore, only girders in Y directions are considered to carry the loads. The girders in Y1 and Y3 axes were subjected to a uniformed distributed load of 23.80 kN/m and those in Y2 axis to 34.028kN/m.

In this study, the goal is to investigate the effects of earthquake on the fire-resistance of reinforced concrete columns, damaged due to an earthquake. This is because mainly columns are the elements playing the major role in stability of the structure after an earthquake. In case of the building specimen, examined in this study, short columns of the ground floor experienced the most damage during the test compared to other elements of the building. Therefore, the short columns of Y1 axis in the ground floor were selected to be exposed to the standard fire after the earthquake. It is important to note that there are many possible post-earthquake fire scenarios that could be considered for this study. However, the above fire scenario is assumed to be one the worse case fire scenarios. The analysis was simulated for the building in two fire scenarios: first exposing the short columns to fire and simulate the performance of the building before any earthquake damage and then exposing the same columns to fire but by considering the damages caused to the building columns due to the Kobe Earthquake 1995. Fig. 1 shows the 3D analytical model of the building simulated for this study.

Performance of the Building Structure in Fire before any Damage

The two typical steps for structural fire performance analysis are heat transfer analysis and structural analysis. Using the same analytical steps, first a 2D mesh was assigned to the short column's cross section. Then the four edges of the cross section were exposed to the standard fire. The concrete moisture content was assumed to be 10 kg/m^3. The analysis was implemented for eight hours and the temperature distribution was obtained for the cross sections. Fig. 7 (a) shows the results of the temperature distribution of the cross section after one hour fire exposure. Cross sections of the other elements, walls, beams and columns, were also discretized in 2D mesh, however with no elevated temperature applied. The second step of analysis was to implement structural analysis for different time steps considering results of the heat transfer analysis. For this purpose, the entire building structure was modeled in 3D. For the short columns of axis X1 in the ground floor, the heated cross sections were employed and for the rest of the elements the cold cross sections were used. Axial deformation and axial load of the short columns exposed to fire are plotted at different time steps in Fig. 9 along with the result of analysis described in the next section.

Performance of the Building Structure in Fire after the Kobe Earthquake 1995

Effects of earthquake damage on the post-earthquake fire performance of the building structure are considered in three aspects: material strength degradation, heat and flame penetration into the damaged and cracked elements and effect of residual lateral deformation.

Material mechanical degradation

When a building structure is subjected to earthquake, large lateral deformations may result in damage to mechanical properties of the material. In reinforced concrete structures, flexure, shear and shear-compression failures could cause significant damage, crack and degradation to the concrete mechanical properties. A realistic method of post-earthquake fire performance assessment of structure is to run the analysis by subjecting the building first to the earthquake and then to the fire. However, currently, available analytical modeling tools can hardly estimate realistic values for the residual mechanical properties and damage to the building due to the earthquake to be used along with the following fire performance analysis. Therefore, simplified approaches need to be developed to determine and include the residual mechanical properties of the concrete after the earthquake. In this study, a simple analytical approach was used to estimate damage to the material properties of the columns in the ground floor. Damaged columns were identified based on observations after the shaking table test. Columns that damaged significantly during the test of the building structure are shown in Fig. 4. The figure shows that the two of the short columns in the X1 direction, ground floor, were completely collapsed, and therefore eliminated in the simulation, and the other two corner columns were damaged significantly.

Columns along axis X3 in the ground floor were also damaged considerably. The figure includes photos of the damaged columns taken after the test.

Concrete compression strength was the main mechanical property that its degradation was calculated for the damaged columns. For this purpose, a pushover analysis using the Axial-Shear-Flexure Interaction (ASFI) approach developed by Mostafaei and Kabeyasawa (2007) was implemented to determine the lateral load degradation of the columns when the elements were subjected to a maximum drift experienced during the test. Then the same degradation ratio was assumed approximately to be the concrete compression strength degradation of the damaged columns for use in the fire response analysis. Fig. 5 shows the results of analysis for lateral loading of the short columns and the load capacity degradation ratio. The result shows 20% residual lateral load capacity for the damaged columns after the test. Hence, for fire response of the building structure, concrete compressive strength for the damaged short columns is degraded to 20% of the original compressive strength or 4.8MPa. The same analysis was implemented for the long columns in the ground floor axis X3 also damaged during the earthquake. The result showed 50% residual lateral load capacity after the earthquake. Therefore, for these columns 50% of the original concrete compressive strength or 12MPa was assigned as the residual concrete compressive strength in the fire response analysis.

Heat penetration

Cracks and crash of cover concrete changes the heat transfer conditions of the elements after the damage due to the earthquake. Therefore, a new heat transfer analysis needs to be implemented for the damaged columns. Fig. 6 shows the crack pattern assumed for the damaged columns in the ground floor of the building. Hence, the fire frontiers were defined according to the damage part of the sections and heat transfer analysis was implemented considering the new condition. Fig. 7 illustrates temperature distribution of the cracked cross section and its comparison with that of the original cross section without any crack. The result indicates that temperature distribution changes considerably after the crack or damage of the cross section.

Residual drift and P-Δ effects

For the building structure of this study, based on the test result, residual lateral deformation of the building after the applied ground motion was very small and therefore this effect was ignored in the analysis of this building. However, for design purpose the effect of lateral deformation and P-Δ are considerable and need to be included in the analysis.

Comparison Study and Discussion

Fire resistance analysis was implemented by the SAFIR program for the building structure specimen before any damage and after the test, considering the structural damages due to the applied ground motion. In case of post-earthquake fire, for the comparison study three different analyses were implemented:

A. Post-earthquake fir performance of the building structure when both material mechanical degradation and heat penetration are employed for the short columns exposed in fire in the ground floor.
B. Post-earthquake fir performance of the building structure when only material mechanical degradation is employed for the short columns in fire.
C. Post-earthquake fir performance of the building structure when only heat penetration effect is considered for the short columns exposed in fire.

Figures 8 shows the deformed building structure when both heat penetration and material degradation are considered in the response evaluation. Figures 9 and 10 provide the axial deformation and load response of the short columns exposed to the post-earthquake fire and fire without any building damage. Figures 9-a and 10-a indicate that the short columns and therefore the building structure before the earthquake with no pre-damaged condition could survive the fire for about seven hours. However, after the earthquake it fails in less than an hour in fire. It is important to note that in this study the floor is not exposed to fire for the sake of comparison study on the column performance. It is likely that including the floor in fire could result in less fire resistance of the building.

Figures 9-b and 10-b illustrate the result of the analysis for the building performance in the post-earthquake fire for three above mentioned conditions of A, B and C. These analyses were done to evaluate the effects of material mechanical properties degradation and heat penetration on the post-earthquake fire resistance of the building. The results in these figures show that the structure, with only material degradation included, fails in one hour after start of the fire. In case of the analysis when the heat penetration is only included, the result shows about three hours fire resistance. Therefore, both material degradation and heat penetration had considerable effect in reduction of fire resistance of the structure after it is damaged by the earthquake. However, the consequence of heat penetration shows relatively higher effect on the response.

In this study failure is define as the post-peak point on the axial load capacity curve (Figures 9-b and 10-b) where the load reduces to 80% of the maxim load, provided that it is not less than the initial gravity load of the column.

Conclusions

A study was carried on to investigate fire resistance of a nearly full-scale six-story reinforced concrete building structure, tested previously on the E-Defense shaking table facility subjected to Kobe 1995 earthquake. As a result, the following remarks can be made:

1- Fire resistance of the building structure reduced considerably due to the earthquake damages to the structural elements such as columns.
2- Material mechanical properties degradation was identified as a major factor determining the post-earthquake fire resistance of the structure
3- Damages to the concrete elements change the temperature distribution of the cross sections which is due to penetration of flame and heat into the elements through the cracks and the damaged parts. The result of the analysis shows relative higher load capacity reduction due to the heat penetration compared to the material degradation effect.

Further studies need to be implemented on the lateral load deformation and P-Δ to investigate their effects on the performance of structure subjected to the post-earthquake fire.

Acknowledgments

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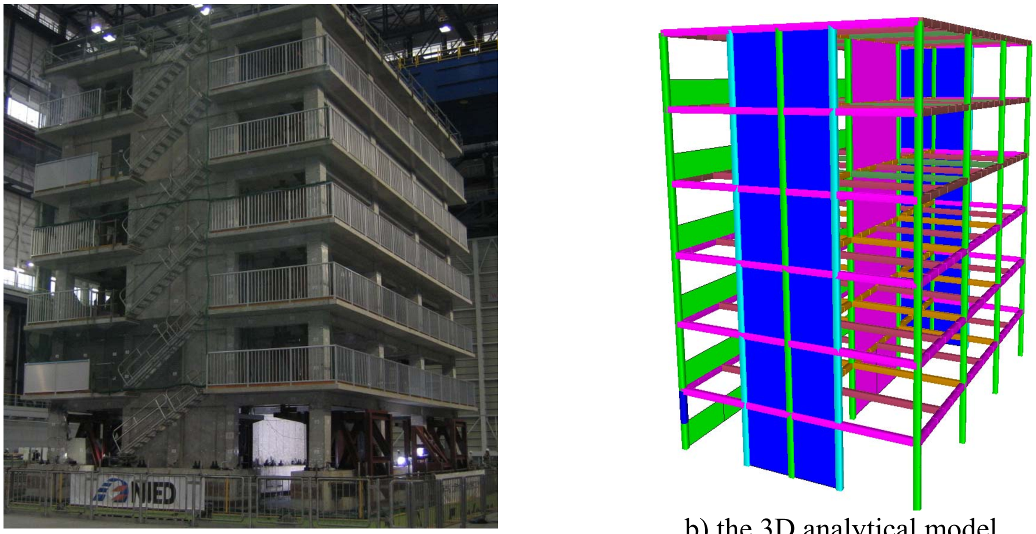


a) the building specimen

b) the 3D analytical model

Figure 1. The six-story reinforced concrete wall-frame building

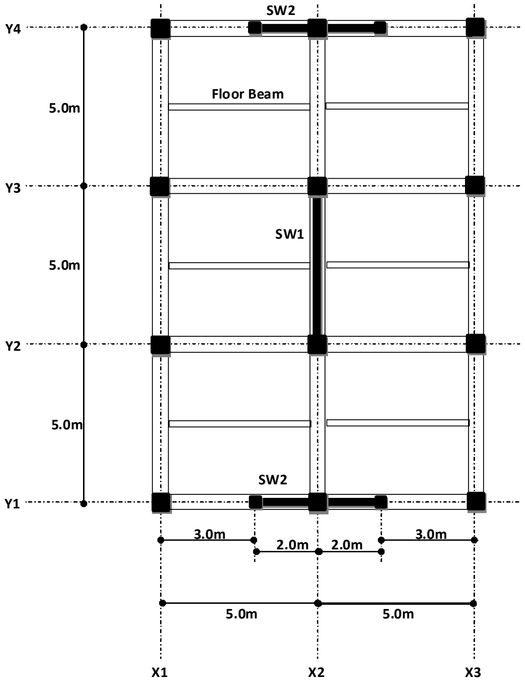


Figure 2. Plan of the full-scale building specimen

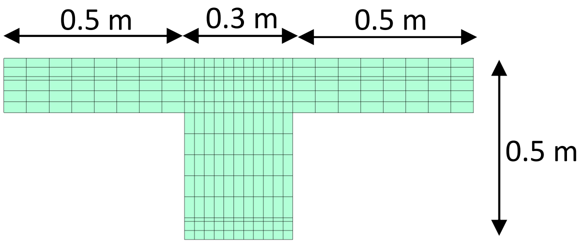


Figure 3. Middle girder cross sections (Axes X2, Y2, and Y3)

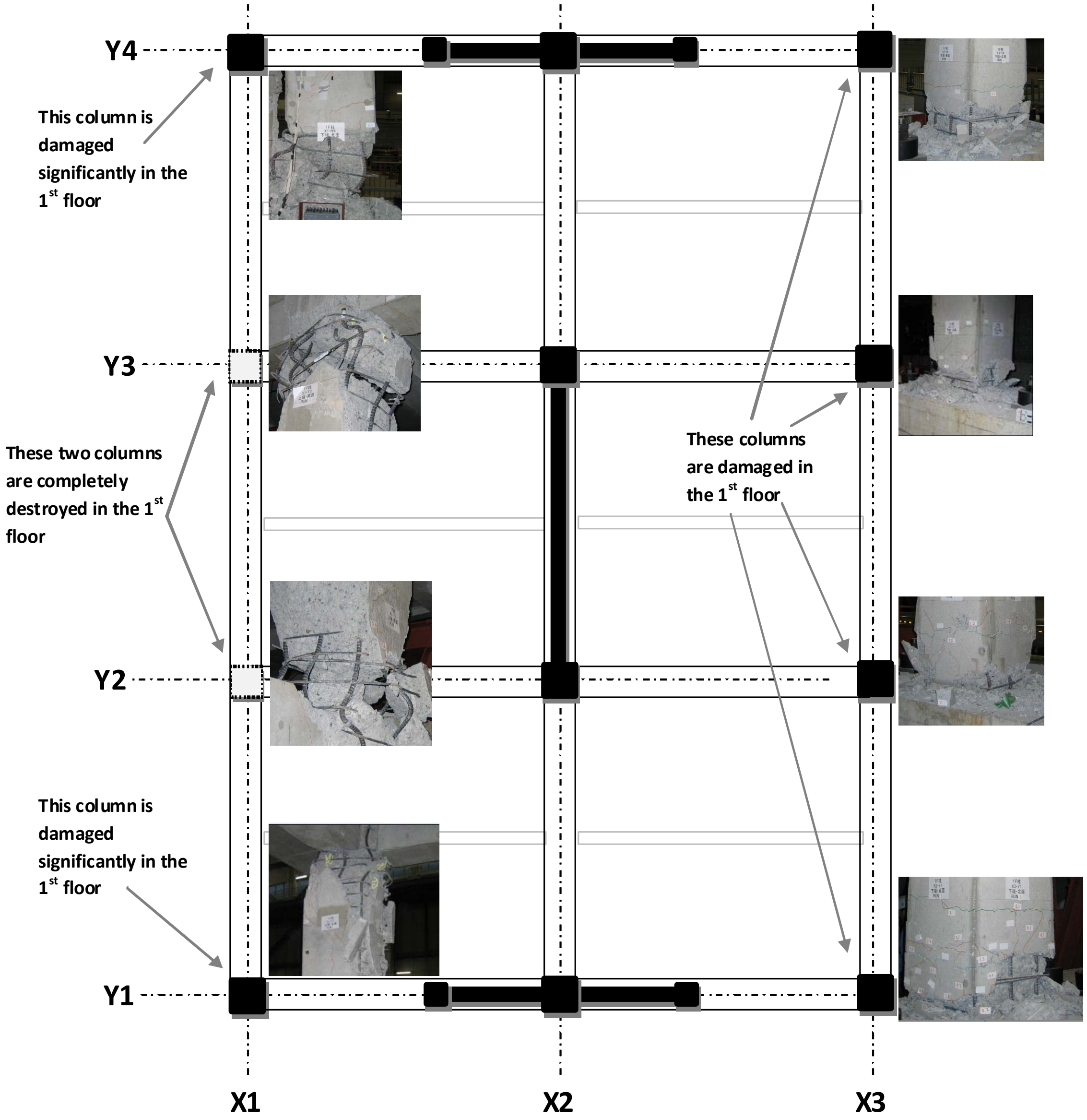


Figure 4 Columns mainly damaged in the ground floor due to the earthquake load

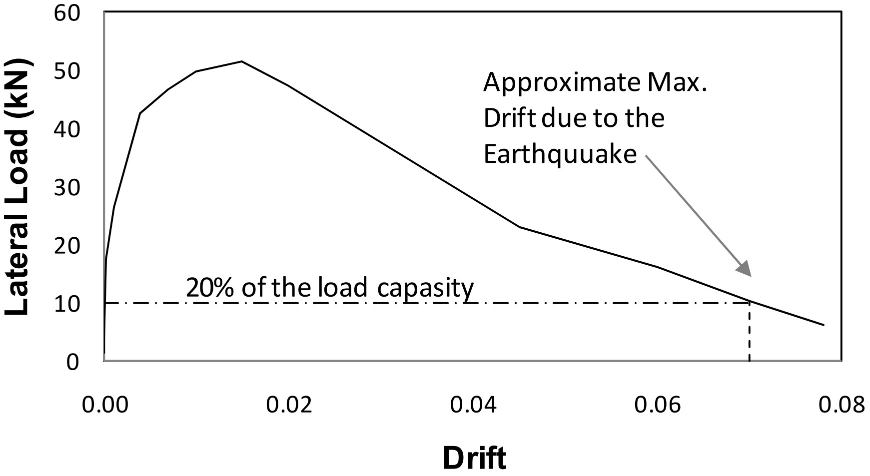
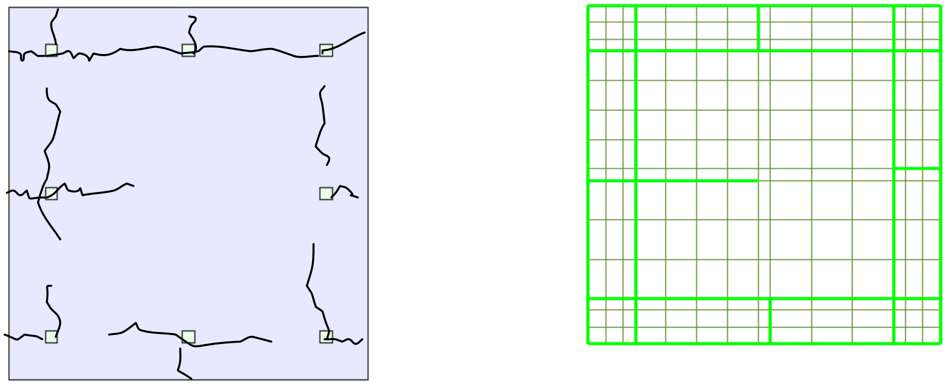


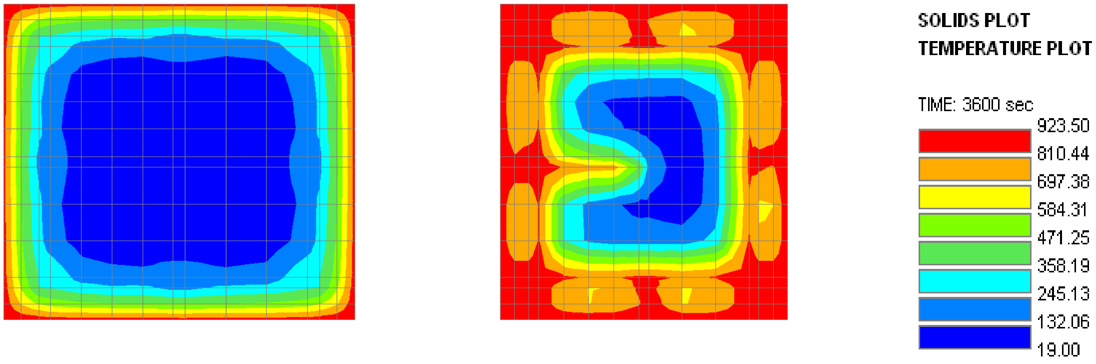
Figure 5 Lateral load-drift response of the two columns, X1-Y1 and X1-Y4, in the ground floor, obtained by the ASFI method, and the residual load capacity



a) Assumed crack patterns

b) Frontiers exposed to the fire

Figure 6. Cracks pattern and the fire frontiers assumed on the section of the X1-Y1 and X4-Y4 columns of the ground floor, after it is damaged due to the earthquake



a) Section with no damage b) Cracked section

Figure 7. Temperature distribution after one hour fire exposure on the section of the X1-Y1 and X4-Y4 columns of the ground floor, before and after it is damaged due to the earthquake

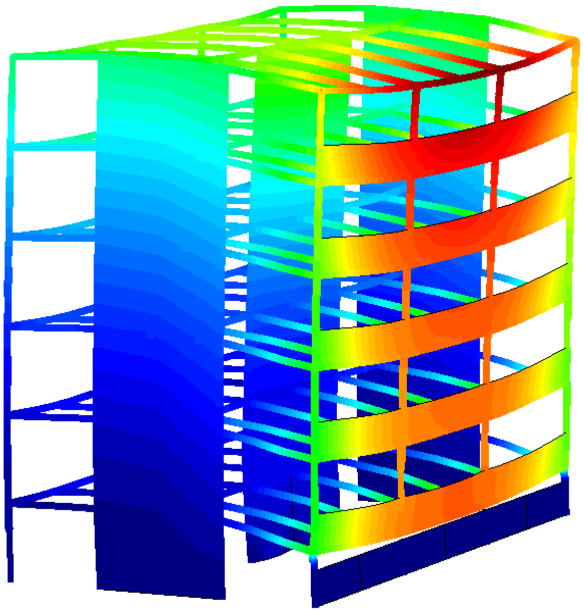
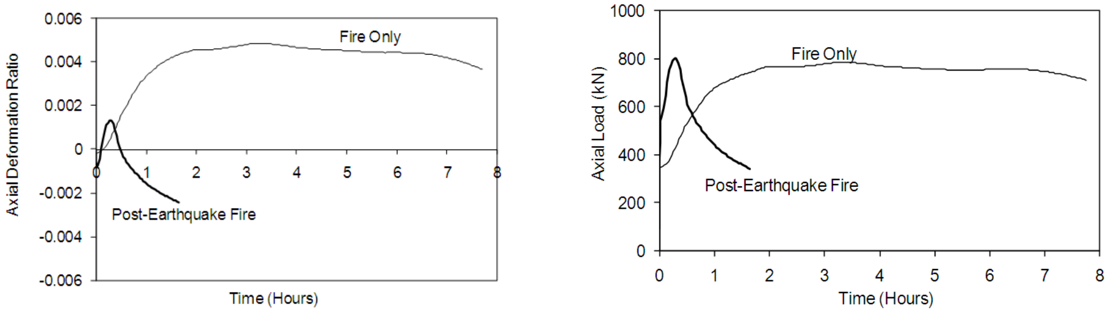
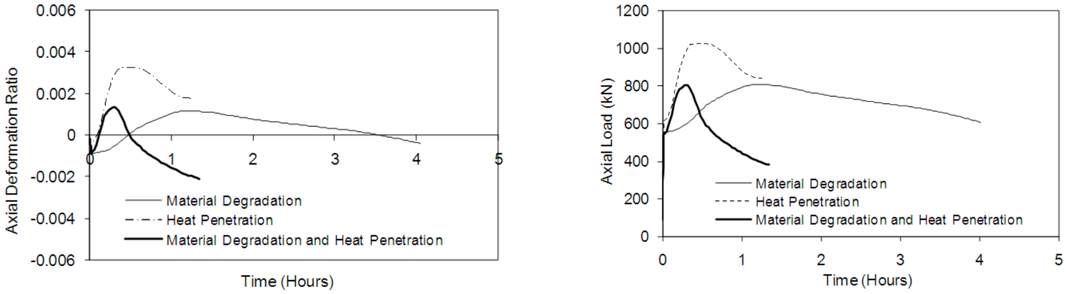


Figure 8 Deformed Building Structure in Post-Earthquake Fire



a) Axial deformation response b) Axial load capacity response

Figure 9 Performance of the short columns in the ground floor: a) Exposed to fire only and b) Exposed to post-earthquake fire



a) Axial deformation response b) Axial load capacity response

Figure 10 Performance of the short columns in the ground floor subjected to post-earthquake fire with Material degradation/Heat penetration effects