Fire Performance of Full-Scale Building Subjected to Earthquake Motions: Fire Test Program and Outcomes

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ABSTRACT

A five-story reinforced concrete building was subjected to 13 different motion tests to investigate the influence of earthquakes on building's nonstructural components and systems (BNCS). After a series of motion tests, a total of six fire tests were conducted at four different locations in the third floor. Temperatures and video data were collected during fire tests to assess the performance of various BNCS including various fire safety measures. As the second paper of this project, following the first paper presenting details of motion tests in the same proceedings, the current paper presents an overview of the fire test program, fire test data, and observations with respect to the performance of fire safety measures such as fire door, sprinkler systems, various fire stop sealants and devices, and interior compartmentalization components.

KEYWORDS: post-earthquake fire, structural response, flame spread, compartmentalization

INTRODUCTION

Earthquakes can be extremely hazardous which may result in loss of life and property damage not only by intensive physical motions but also by fires following earthquakes. Generally speaking, fire incidents in buildings are typically caused by man-made fire hazards and limited to the individual buildings, but following earthquakes, they become extremely destructive as multiple ignitions or flame spread could lead to the involvement of numerous buildings over a large area. In 1923, urban conflagration following the Tokyo earthquakes resulted in 140,000 fatalities [1], and 1995 Kobe earthquake induced 148 separate fires destroying over 6500 buildings [2]. These significantly large damages are due to the characteristics of post-earthquake fires. Some of the characteristics from previous research are introduced below:

- The probability of fire occurrence in a building following an earthquake is greater than normal and there may be multiple simultaneous ignitions [3, 4].
- Effective and timely suppression and rescue activities of fire departments can be limited due to damaged roads, disconnected communication networks, lack of water resources due to ruptured or leaking water pipelines, and lack of personnel due to multiple fire locations [5].
- Occupant's moving speed is decreased in fire conditions due to the impact of earthquakes on the interior environment which generates obstacles in the path of movement [6].
- Structural and nonstructural building components including fire safety measures can be damaged by earthquakes and may not perform as intended in post-earthquake fire conditions [7-9].

With individual or a combination of these characteristics, building fire safety performance can be significantly decreased. Especially, the performance of in-house fire safety measures within the building is critical as suppression and rescue activities from fire department may not be available following earthquakes. In this context, the performance of building's nonstructural components and systems (BNCS) including fire safety measures were investigated in a five-story reinforced concrete building. The building was first subjected to 13 different earthquake motion tests on the high performance outdoor shake table and seismic performance of BNCS were investigated. Following the motion tests, six full-scale fire tests were conducted at four different compartments on the third floor where various fire safety measures were equipped such as a charged sprinkler system, a fire door, fire-rated walls and ceiling assemblies, and various fire stop sealants and devices. This paper, the second of the two papers dedicated to this project, presents fire test program and identified outcomes of fire tests. Details of building specification, ground motions, and seismic performance of fire safety measures before fire tests are included in the first paper which is presented in the same proceedings [10].

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FIRE TEST PROGRAM

The fire tests were conducted with two main objectives: to identify the performance of fire safety measures with the given damage from motion tests, and to assess the potential for fire and smoke spread from the collected data. The test outcomes can also serve as a base data set for seismic design of fire safety products and building components.

Several constraints were imposed upon designing and conducting fire tests. To identify the performance of sprinkler system, fire door, fire dampers, and fire stop sealants and devices, the gas temperature needed to be high enough to activate them. The building, however, which was already structurally damaged by earthquake motion tests, could not be further damaged by thermal impacts of fire. As such, it was required to design proper fire size for appropriate gas temperatures, but the final building damage state which can influence the heat release rate (HRR) via ventilation could be only informed after the final motion tests were completed. In addition, concerning that fire becomes uncontrolled within the building and / or spreads to nearby bush area of the test site which was possible due to the dry season in the area, the local fire department were required to attend the fire tests as safety observers and emergency responders. To minimize the influence of their commitment to the fire tests on the emergency responding capability of the fire department, only 4 hours per day over three days were provided to conduct the fire tests.

With this high level of uncertainty and a very tight time schedule for fire tests, a total of six fire tests were conducted in four different locations (one in small burn room (SBR), two in large burn room (LBR), one in around the elevator shaft (ES), and two in elevator lobby (EL)) in the third floor. The floor plan of the third floor and fire test locations are shown in Fig. 1.

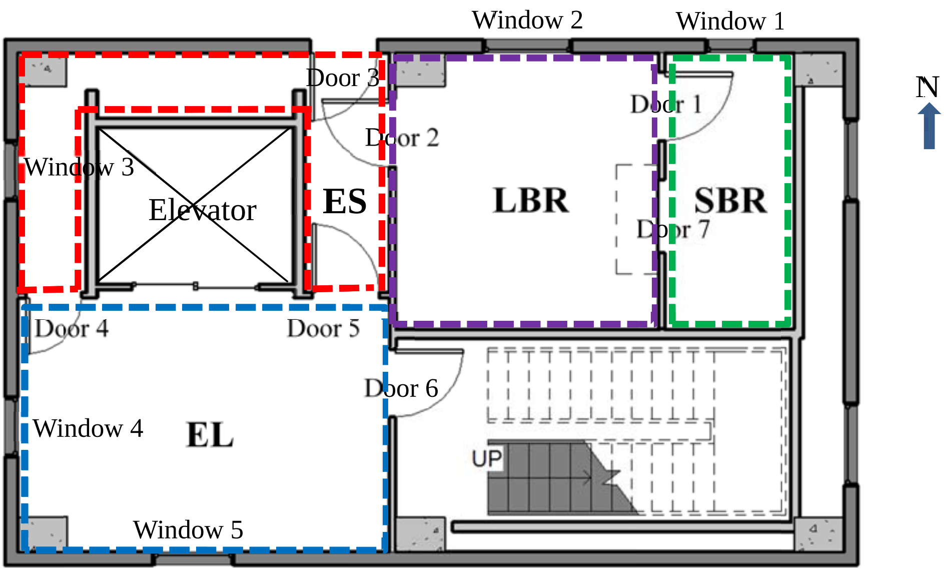
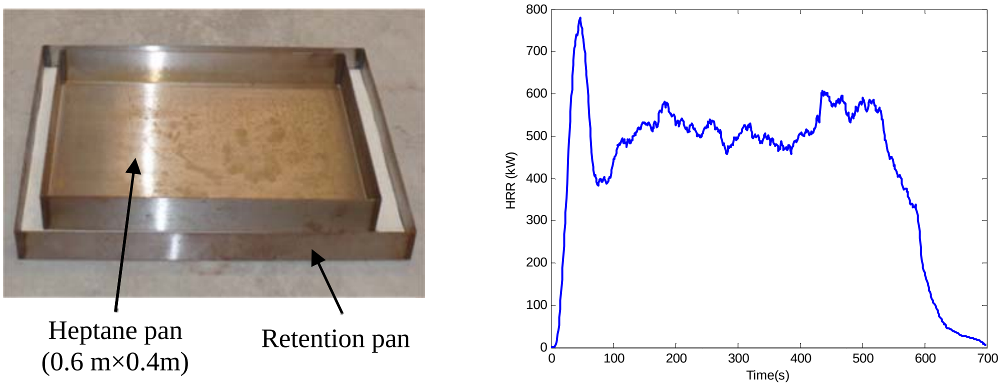


Fig. 1. Floor plan of the third floor

Fire design

Heptane in a steel pan was used as the fire source. Heptane has been widely used as pan fire fuel since it generates decent amount of smoke, is chemically stable in ambient temperatures and easy to ignite for fire tests. Considering spread of fuel items in post-earthquake fire conditions, using multiple small pans was deemed more reasonable than one large pan. The minimum gas temperature to activate fire stop sealants and devices was determined to be 250°C and depending on the compartment and ventilation characteristics, fire size ranged between 500kW to 2000kW, approximately. To obtain about 500kW fire size from one heptane pan, the heptane pan was sized with 0.6m by 0.4m based on steady-state mass burning rate correlation [11]. To prevent heptane spread on the floor by physical and thermal damage, the heptane pan was located in a retention pan. Ceramic fiber board as insulator and a proper amount of water as a heat sink were placed in the retention pan as shown in Fig. 2 (a) to prevent the heptane pan from warping. The fire size and duration of burning were determined by the number of pans in the compartment and the amount of heptane placed in the heptane pan, respectively. A preliminary test was conducted to validate the correlations used to calculate pan size and heptane amount under the large oxygen depletion calorimeter in the ISO room. The measured HRR is shown in Fig. 2 (b). The peak HRR was almost over 800 kW, but average HRR during the effective burning time of 9.5 minutes was about 510kW, which was in a good agreement with the design calculation. It should be noted that the actual HRR in the fire tests can be different from this value due to multiple pans used for fire tests which would provide more heat feedback to the fuel surface and the different test room size from the ISO room. In addition, the HRR could be decreased by the sprinkler activation although only a small amount of water was discharged.



(a) (b)

Fig. 2. Heptane pan design (a) and HRR of 9L of heptane (b)

Instrumentation and data collection

Two data types were mainly obtained: temperature and video clips to assess fire and smoke spread phenomena between compartments. A maximum of 96 thermocouples were used to measure gas and surface temperatures of various locations and building components depending on the objectives of each fire test including spaces below and above the ceilings and inside the elevator shaft, and on the surface of fire stop sealants and ceiling vents. Especially for the spaces below and above the ceilings, thermocouple trees in which thermocouples were placed vertically at 0.3m increments were fabricated to collect the data of thermal environment at various heights. A total of 21 video cameras were installed inside and outside the fire test compartments to obtain visual data of the actual fire, fire and smoke spread phenomena, and the activation of fire protection systems. Detailed locations of thermocouples and video cameras in each test can be found in a separate document [12].

Fire tests

A total of six fire tests were conducted in four different locations with different fuel amounts as shown in Fig. 3. Before each test, the sprinkler system in the building was charged at a pressure of 35kPa and the system in the third floor was disconnected from the rest of the floors to minimize the amount of water discharged. The primary purpose and test conditions of each of the fire tests are provided below:

- LBR-1fire test was conducted to examine the functionality of the sprinkler system and fire door after seismic motion tests. One heptane pan with 8L was used with windows 1 and 2 and supply / return vents sealed, door 1 and 7 open and door 2 closed.
- SBR fire test was conducted to examine the functionality of the sprinkler system and fire door after seismic motion tests and smoke spread to LBR. One pan with 3L heptane was used with windows 1 and 2 and supply / return vents sealed, door 2 open, and door 1 and 7 naturally closed.
- LBR-2 fire test was conducted to identify fire and smoke spread to SBR and space above ceiling, and fire spread to the building façade of balloon framing. Two pans of 8L heptane each were used with window 1 and 2 open, door 1 and 2 naturally closed and door 7 open.
- ES fire test was conducted to examine the performance of various fire stop sealants and devices. Two pans of 8L heptane each were used with window 3 open, door 2, 4, and 5 closed, and door 3 partially opened.

- EL-1 fire test was conducted to identify fire and smoke spread to remote floors through the elevator shaft with the elevator door being damaged as shown in Fig. 4 (a). Three pans of 8L heptane each were placed with supply / return vents closed, window 4 and 5 partially open, and door 4, 5, and 6 closed.
- EL-2 fire test was conducted to examine the effects of opening size on the fire development in comparison with EL-1 and the performance of vertical fire stop sealants. Three pans of 8L heptane each were placed with supply / return vents open, windows 4 and 5 fully open, and door 4, 5, and 6 closed. Additional opening by cutting a portion of ceiling was provided right underneath of vertical fire stop sealants.

LBR-1 .BR-2

l) ES EL-2

Fig. 3. Fuel locations in each test, a red box representing a heptane pan

FIRE TEST RESULTS

In this section, fire performance of various BNCS subsystems is addressed and possible fire and smoke spread issues identified from the fire tests are described.

The performance of sprinkler systems and fire door

The automatic sprinkler system and the roll-down fire door were not physically damaged during ground motion tests and also activated as intended during the fire tests. A total of seven sprinkler heads (four quick response pendent heads and three quick response upright heads with activation temperatures of 68°C and 79°C, respectively) were installed in the fire test floor. The roll-down fire door was activated by a fusible link with the activation temperature of 74°C in both LBR-1 and LBR-2 tests.

Elevator performance

The elevator was not operational after the largest ground motion test due to the distorted elevator doors, especially from the 2nd to 4th floor. The elevator door damage on the 3rd floor is shown in Fig. 4 (a). In EL-1 fire test, the elevator button panel melted and wires behind the panel were burned as shown in Fig. 4 (b). Even without the door damage, elevator could be malfunctioned due to the short circuit by the burned wire. Since elevators can be included as an acceptable means of egress during fire conditions with additional fire safety measures and communication systems, its operability is critical for safe and efficient evacuation. It may be necessary to provide thermal protection to the wires behind the panel or incombustible button board for better elevator performance in fire conditions.

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Fig. 4. Damaged elevator door after motion tests (a) and melted elevator button after EL-1 (b)

HVAC duct performance

Although powered fan unit was not attached to HVAC ductwork, various parts were assembled together to establish a comprehensive HVAC subsystem. One ends of ducts were connected to supply / return vents in the compartments and the other ends were open to air in the 4th floor allowing hot smoke to leave the compartment driven by buoyancy. In the LBR-2 test in which the upper gas temperature reached over 800°C as shown in Fig. 5 (a), the flexible duct connecting vents and metal duct was ruptured as shown in Fig. 5 (b). The legend in Fig. 5 (a) indicates the heights from the 3rd floor surface with solid and dotted lines for the spaces above and below the ceiling, respectively. Despite the fire-rated ceiling and lighting assemblies and their good performance during the LBR-2 fire test, the failure of the flexible duct allowed hot gases into the plenum space. This provides a good lesson for fire safety, which shows the entire system performance can be limited by the weakest link, in this case the flexible duct.

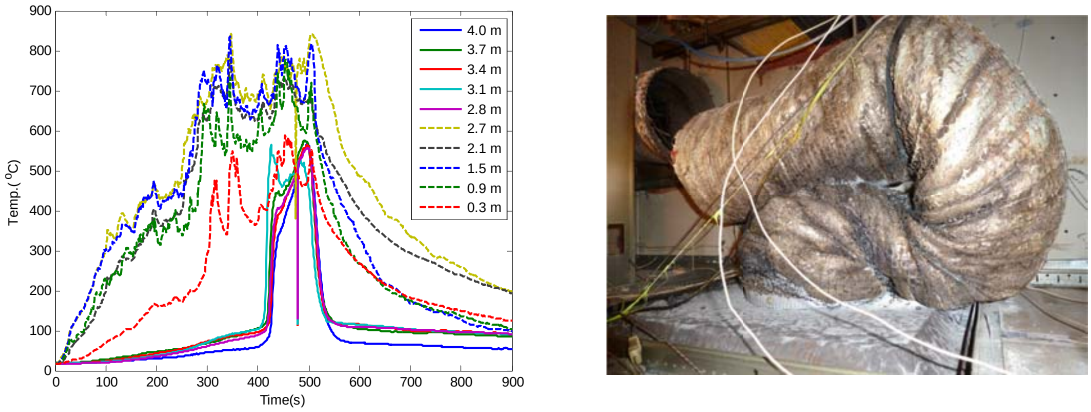

Fig. 5. Temperature increase in the space above LBR ceiling (b) and flexible duct rupture (b)

Fire damper performance

The functionality of fire dampers during fire tests were not able to be examined due to unexpected power loss during fire tests. After the seismic tests, however, one damper out of three malfunctioned. This was due to a screw used for the damper installation which prevented a full damper blade rotation. Once the screw was adjusted, the damper functioned well. The reason for the extrusion of the screw was not clear, but it was probable that the screw became loose and displaced from its original position by the ground motions. Considering its functionality after the adjustment, it was assumed that fire dampers were functional during fire tests.

Fire stop performance

Fire stop sealants and devices were installed in 42 different locations including vertical and horizontal penetrations for pipes, cables, HVAC ducts, and wall and floor assembly joints. Most applications of fire stop for joints were in accordance with tested and listed designs, but there were some joints just caulked by fire stop sealants since tested and listed design solutions do not exist for those. Most of the fire stop sealants and devices performed well preventing fire and smoke spread through the penetrations.

Depending on the configuration of joints and assembly materials, building joints can be largely divided into two: dynamic and static, and different fire stop sealants are used for each. All dynamic and truly static joints performed well in fire tests. However, it was found that in earthquake conditions, the differentiation between dynamic and static may not be critical as most joints tended to behave like dynamic joints. Therefore, it may be necessary to apply dynamic fire stop design solutions even to static joints for the buildings in seismic zones for better fire stop performance.

The fire stop applied to gypsum wall to column joint had minor damage with several holes which seemed to be created by different drift amount of the interior wall of the balloon framing and the column during motion tests. The fire stop, however, was found completely detached and fell to the floor after the ES fire tests as shown in Fig. 6 (a) and (b). This result revealed that fire stop can be deteriorated after earthquakes which may not be clearly identified by visual inspection, but may not perform as intended during fire conditions.

Fig. 6. Fire stop sealant before ES (a) and its fall-down after ES (b)

Another concern of fire stop performance was raised by thermal expansion of metal pipes. As shown in Fig. 7 (a) and (b), which were taken from the 4th floor, the black metal pipe was elongated during the ES test by thermal expansion which can be identified by the different locations of the letters on the pipe. Note that all other contents are located in the same position in the grids, but the red boxes which contains the same letters on the pipe is at different height in Fig. 7 (a) and (b). This lifted the fire stop sealants a few millimeters, although this did not seem to decrease its functionality. The temperature measurement between the fire stop sealant and the surface of the black metal pipe and video clips substantiated good performance of fire stop sealants. However, the exposed metal pipe length to the fire environment was only 4m which is the floor height. In conditions where long metal pipes are exposed to high heat environments such as in vertical shafts or near the ceiling over wide floor area, the thermal expansion would become significantly larger, which may influence the performance of fire stop sealants. American Standard Test Method subcommittee E06.21 is currently developing a test method for measuring relative movement capability of penetration fire stop systems.

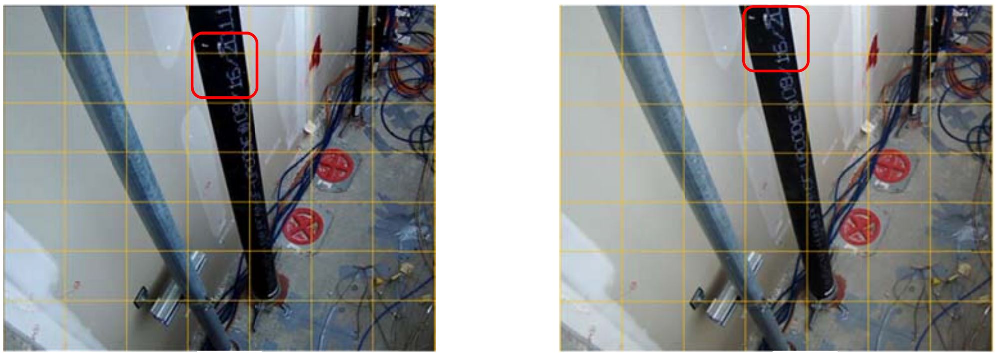

Fig. 7. Metal pipe's thermal extension: before ES (a) and during ES (b) from the 4th floor

Postulated structural component performance

After the largest motion test, serious structural damage occurred in several joint areas in the 2nd floor where the largest inter-story drift was recorded. The rebar was exposed with the loss of concrete cover due to repetitive hinge motion between the north center column and the northeast beam, and between northeast column and the 3rd floor slab as shown in Fig. 8 (a) and (b), respectively. Fire tests were not intended to examine the performance of structural building components, but based on the test results, their performance can be postulated.

Except for ES, ceilings were installed and separated one compartment into two: spaces below and above the ceilings. If this separation remains intact during earthquake conditions, the structural components may have less opportunity to be exposed to high heat environment. However, as shown in Fig. 5 (a), failures of ceiling assembly and connected components such as flexible ducts can significantly increase gas temperature in the space above the ceiling and the damaged structural components can be directly exposed to high heat. The gas temperature above the ceiling in LBR-2 test reached 550°C with approximately 2000kW fire burning for less than 15 minutes. As reliability of automatic fire sprinkler system is generally decreased, despite the perfect activation in this project, it may be necessary to provide passive structural protection which may include additional fire-rated insulation especially at joints of the structural components where most structural damages were observed.

(a) (b)

Fig. 8. Structural damage after the motion tests in the second floor: north center column and east beam connection (a) and northwest column and the 3rd floor slab connection (b)

Fire / smoke spread

Exterior Insulation and Finish System (EIFS) is widely used for façade of commercial buildings [13], and there have been several fire incidents in which EIFS are suspected to contribute to external flame spread. In the test specimen building, the EIFS as part of balloon framing façade was only exposed to high heat environment when flame extention through window openings occurred in LBR-2, EL-1 and EL-2. The insulating material were burned as shown in Fig. 9 (a), but no flame spread was observed.

(a) (b)

Fig. 9. Burnout of EIFS on window 4 opening (a) and smoke residue on damaged balloon framing (b)

Significant smoke spread, however, through the balloon framing was observed. Since the balloon framing covered with EIFS ran from the 1st to the 3rd floor being attached to the floors with vertically aligned steel brackets, the space surrounded by the interior gypsum wall board, EIFS, and steel brackets can be a channel for the smoke spread. For the ES fire test, smoke spread was observed through the gap on top of damaged balloon framing façade and the cracked corner near the first floor. The gap on top of the damaged balloon framing is shown in Fig. 9 (b). The latter case shows possibility of downward smoke spread to remote locations following the channel inside the balloon framing. As the fire tests were conducted on the third floor and the balloon framing ending at the 4th floor level (to the top of 3rd floor), smoke spread to other compartments inside the building could not be identified. However, based on the downward smoke movement to the first floor, it can be highly probable.

From the motion tests, about 0.025m wide gap was formed along the joint between the interior wall of balloon framing and the wall between the LBR and the SBR. In LBR-2 fire test, flame extended to SBR through this gap. The location of the gap is marked using the red circle in Fig. 10 which is taken from the northeast corner of the SBR. Although flame spread did not occur as no fuel item was located in SBR, flame extended several times to SBR with hot smoke. In conditions such as a fabric curtain being located near the gap, flame spread could have occurred as the gas temperature near the gap in SBR was over 350°C for more than 1 minute as shown in Fig. 11.

Fig. 10. View from the northeast corner of SBR to door 1

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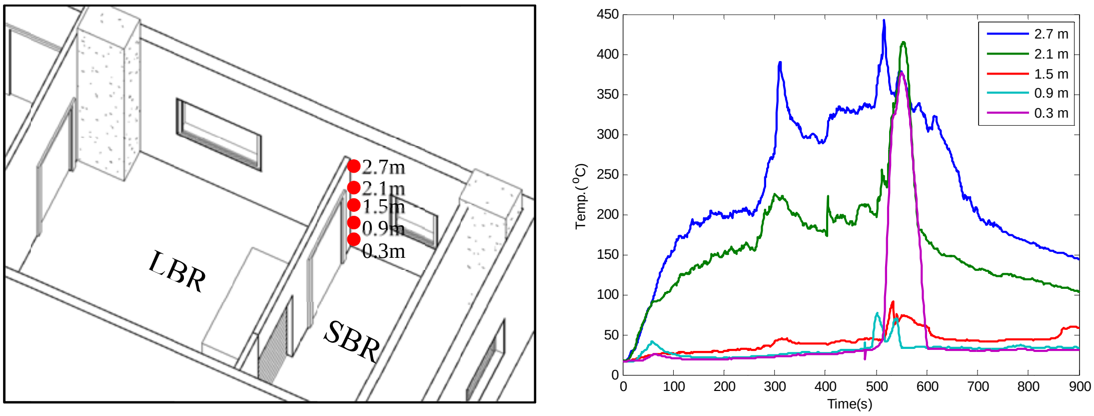
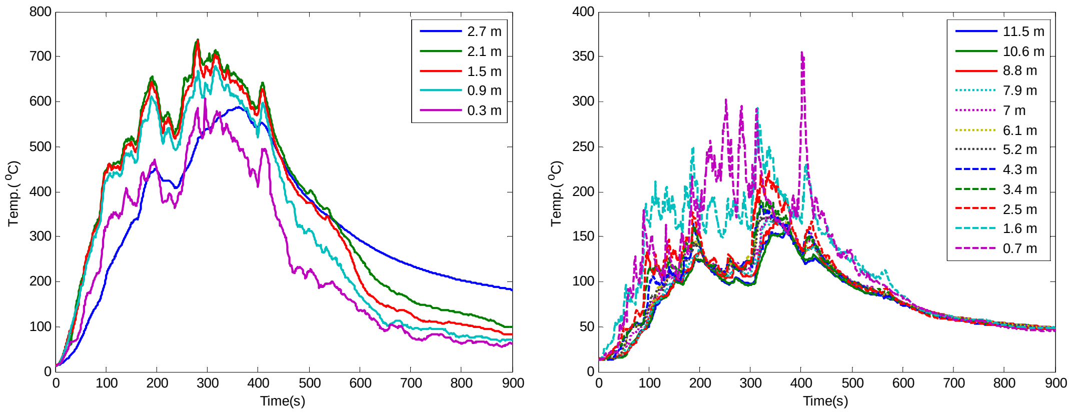


Fig. 11. Locations of thermocouples and temperature profile in LBR-2 fire test

Fire and smoke spread through the elevator shaft was examined with three heptane pans placed in the elevator lobby. From the largest motion test, the elevator door and its frame in the third floor were distorted with the opening as large as 0.24m as shown in Fig. 4 (a). With partially closed window openings, gas temperatures at various heights in the elevator lobby are shown in Fig. 12 (a). A total of 12 thermocouples were located within elevator shaft to assess smoke spread and possibility of additional ignition with the top thermocouple being located 11.5 m above the 3rd floor slab. The highest temperature was recorded near the fire source, 0.7m above the 3rd floor, but over the shaft heights corresponding to the 4th and 5th floors (from 5.2m to 11.5m), relatively uniform temperatures were observed. The peak gas temperatures in this region range between 150^{o}C and 200^{o}C which may not be high enough to cause ignition of materials in the shaft, but near the damaged door, the temperatures range between 250^{o}C and 300^{o}C. This temperature range may be high enough to cause ignition with a pilot flame ignition source and large enough burning time.



(b)

Fig. 12. Gas temperatures in elevator lobby (a) and gas temperature in elevator shaft (b)

A significant amount of smoke spread was observed to the fourth and fifth floor through the elevator shaft in the EL-1 fire test. Soot deposits on the concrete shaft wall and elevator door edges are shown in Fig. 13. As the opening size becomes bigger in upper floors, the neutral plane height becomes low, which contributes to smoke spread to upper floors and entrains more smoke into the elevator shaft [14]. This showed that smoke spread through the elevator shaft can be a critical problem for fire safety.

) (b)

Fig. 13. Smoke spread through the gap of elevator shaft joint (a) and the gap of elevator door (b)

DISCUSSION

The specimen building was subjected to multiple ground motions whose seismic intensity ranges 0.21 m/sec^2 to 0.77 m/sec^2 in the peak ground surface acceleration, i.e., shake table acceleration. According to previous research in Japan, the percentages of the damaged sprinkler system ranged from 34% (1993 Kushiro-oki earthquake) to 41% (Sanriku-haruka-oki earthquake) in about 0.25 m/sec^2 to 0.40 m/sec^2 in ground surface acceleration. The percentage of the damaged sprinkler system and fire door was about 41% and 31%, respectively in the Kobe earthquake whose ground surface acceleration is 0.25 m/sec^2 or more [7]. In the 1994 Northridge earthquake, various pipe joints damage and separations in the sprinkler system were reported in the intensity of 0.35 m/sec^2 to 0.90 m/sec^2 [9]. In addition, 50% effective reduction in fire resistance capability for partitions were expected when subjected to a drift ratio of 0.33% and fire spread could occur at a drift ratio of 0.85%.

Compared to these previous research, the current building was subjected to more severe earthquake conditions [10, 12]. However, the fire safety measures including the automatic sprinkler system and compartmentation were somewhat less damaged than the reported results. The reason for this may be better workmanship of constructors and installers as they already knew that the building would be subjected to earthquake tests and fire tests, which is inevitable situation in such an experimental environment as this. It should be noted that the practical value of the current fire tests and the outcomes, however, is not generating representative damage data, but improving holistic understanding of post-earthquake fire conditions, and based on this, developing a fire safety design framework for fire safety engineers.

CONCLUSION

A series of full scale experiments were conducted to investigate the performance of building nonstructural components and systems (BNCS) in earthquakes and post-earthquake fire conditions in a 5-story reinforced concrete building. As the second paper over a series of two papers, this paper is dedicated to investigating the performance of BNCS in post-earthquake fire conditions addressing fire test program and results. Various BNCS were subjected to fire tests and the performance of individual BNCS was described in addition to holistic aspects of their performance with respect to fire / smoke spread. The identified results are summarized as below:

1. Most mechanically undamaged fire protection systems from the earthquake motions such as automatic sprinkler system and fire door functioned well in fire tests.
2. Via damaged compartmentalization assemblies such as wall to wall joints and balloon framing and elevator shaft with openings of damaged elevator doors, smoke spread to adjacent and remote locations was observed and substantiated by TC data. Also, the potential of fire spread through the gap formed in wall to wall joint was identified.
3. Most fire stop sealants and devices were activated and prevented fire and even smoke spread. Several potential concerns, however, were raised such as the performance of fire stop sealants for pipe

penetration with the pipe being thermally expanded, detachment of fire stop applied joints of strong inter-story movement in fire conditions.

4. The differentiation of dynamic and static joints may not be valid in earthquake conditions. Therefore, it may be necessary to consider all joints as dynamic joints for buildings constructed in seismic zones.

5. Since structural damage by the motion tests were observed mainly in joints of structural components, additional thermal insulation on the joints may help the structural integrity in fire conditions. If the structural damage in the second floor had occurred in the third floor, the fire tests may not have been able to be conducted.

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