Structural and Nonstructural Building System Performance During Earthquake and Post-Earthquake Fire

Fire Test Program – Executive Summary

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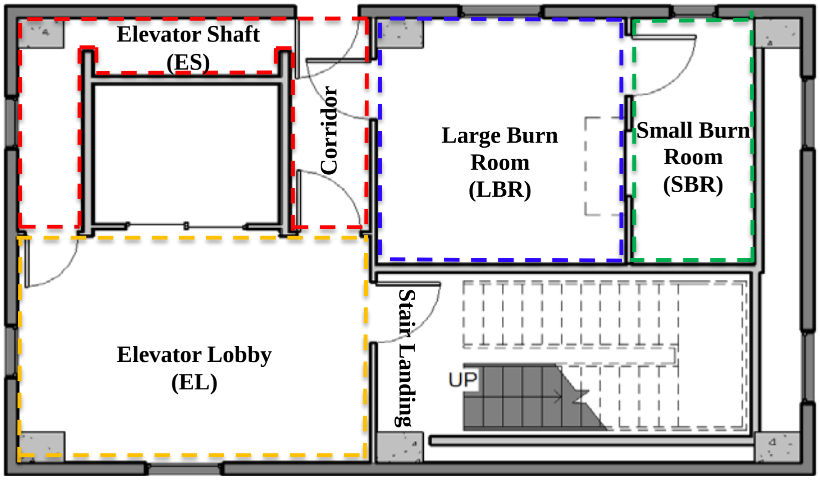
BNCS Test Specimen

In April and May 2012, a series of landmark full-scale experiments were conducted on and within a 5-story reinforced concrete frame test specimen, with floor plates measuring 6.6 meters by 11 meters (21.5 feet by 36 feet), which was erected on the nation's largest outdoor shake table at the Englekirk Structural Engineering Center at the University of California, San Diego. Referred to as the building nonstructural components and systems (BNCS) project (http://bncs.ucsd.edu/index.html), the goal of this $5 Million academe-industry-government collaborative was to investigate earthquake performance of nonstructural building systems and post-earthquake fire performance.

First, the test specimen was subjected to a total of 13 motion tests, seven with base isolation (BI) and six with a fixed base (FB) configuration. Seismic motions were selected from earthquake events occurring off the coast of California, in the central area of Alaska and the subduction zone of South America. These motions provided excitations with different frequency content distributions as well as varied strong motion durations and amplitudes. Seismic motions were designed and applied to the building to progressively increase the seismic demand on the structure and NCSs in both the BI and FB conditions. In addition, to compare the response and behavior of the structure and NCSs, the early (target) motions in the sequence of the BI and FB testing phases were similar. One maximum considered earthquake (MCE) motion and two serviceability level motions were obtained by spectrally matching to the ASCE 7-05 design spectrum achieved for a high seismic zone in Southern California (site class D). In addition a long duration motion from the 2007 Peru earthquake was selected and amplitude scaled (50, 100, and 140%, the later applied only during the BI testing phase). It was desirable to minimize the peak inter-story drift ratio (PIDR) to less than approximately 0.5% while the test specimen was isolated at its base, to preserve the structure for the FB testing phase. The design event imposed during the FB testing phase was intended to achieve approximately 2-2.5% PIDR and 0.8g peak floor acceleration in the test structure. The achieved peak input acceleration range for the FB earthquake motions ranged from about 0.2 to 0.8g, while the pseudo-spectral acceleration at a period of 1 sec ranged from about 0.3 to 1.3g (Ebrahimian et al., 2013).

To collect data on the earthquake performance of the structure, nonstructural components and systems, sensors were installed to collect drift and acceleration data. Cameras were used to record visual data relative to movement, cracking and related effects. Following each motion test, damage to structural and nonstructural components and systems were photographed and documented. Details on the seismic design of the test specimen, overall building layout, installed systems and contents, the seismic test program, including earthquake motions, sensors and instrumentation, and data from the motion tests, including for fire protection systems, are available in Chen et al. (2013) and Pantoli et al. (2013).

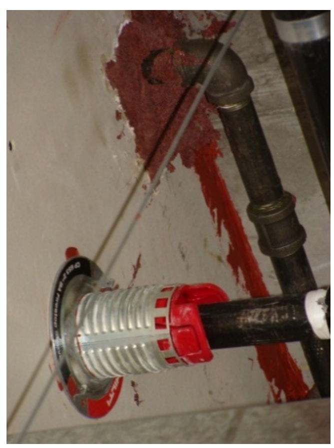
Following the motion tests, blower door fan tests were conducted in compartments on the third floor, specifically to measure the effective leakage area which developed as a result of the various ground motion tests. The aim was to collect data on compartment integrity and motion-induced ventilation openings: factors which can have significant impacts on building fire conditions. Then, following the last motion test, six live fire tests were conducted within the earthquake-damaged specimen to evaluate various aspects of the fire performance of earthquake-damaged buildings. This report details the fire-related tests, including the blower door fan tests, live fire tests, instrumentation plan, test plan, data collected and preliminary findings.



The primary focus of fire-related tests was the third floor, on which four compartments were configured for testing: the Large Burn Room (LBR), the Small Burn Room (SBR), the area around the Elevator Shaft (ES), and the Elevator Lobby (EL). The LBR and SBR construction was Type-X gypsum board on steel studs with doors and frames indicative of nominal 20-minute fire rated construction. Door closers and magnetic door holders were installed. The ceiling consisted of Type-X gypsum board on an Armstrong ceiling system, which could be configured for a nominal 60-minute fire resistance rating. Floor/ceiling slabs were of unprotected reinforced concrete construction.

A balloon framing system was used for the exterior walls. The third floor was served by an elevator and a full-size steel stair system, and was equipped with various nonstructural components, including heating, ventilation and air-conditioning (HVAC) system ductwork with fire dampers, a charged wet sprinkler system and smoke detectors. Various fire stop materials were installed within vertical and horizontal partitions, including around pipe penetration openings, floor, wall and ceiling joints. In addition, a roll-down steel fire door was installed within the partition wall between the LBR and SBR.


Sprinkler Components


Fire Stop Components


Fire Door

During the period 23-25 May 2012, two fire tests per day were conducted on the third floor: two in LBR, two in EL, and one each in SBR and ES. To control the fire size and duration, liquid heptane was burned in steel pans. The fire tests ranged in size from approximately 500kW to 2000kW, dependent on the compartment and ventilation characteristics, number of pans and amount of heptane used. A primary consideration was to limit the potential for fire-induced structural failure. To collect temperature data inside and outside of the fire test compartments, thermocouples were placed in various locations depending on the objectives of each fire test. The primary focus areas were to obtain data on the thermal environment within the fire compartment and adjacent spaces, to assess fire and smoke spread between compartments as a result of seismic-induced compartment integrity failure, and to assess the performance of the fire protection systems (fire stop material, dampers, sprinklers). Multiple video cameras were also installed throughout the building to collect visual data on smoke or fire spread and activation of the fire protection systems.

Test Fire in Elevator Lobby

Flame Out Window

Door After Test

Although most of the data on the fire performance of the test specimen was limited to systems and configurations on the third floor, and the live fire tests were limited in number and scope, important data were collected and the following initial observations are made. Please refer to the full fire test program report for details.

General observations regarding earthquake performance of the specimen, which could have an impact on fire performance of a building, include the following:

While the ceiling system on Floor 3 performed well, the ceiling systems on Floor 1 showed progressive damage with increased ground motion intensity. The potential fire performance concern is loss of compartment integrity and spread of fire and smoke. (See Chen et al., 2013 and Pantoli et al., 2013 for more details on these items.)

Contents indicative of residential and laboratory spaces on Floor 2, ranging from small items such as books, vases and a television set, to larger items such as bookshelves, storage shelves, and refrigeration units were displaced if not anchored. The potential fire performance concern is that most of the unanchored items were distributed on the floor, which would represent a distributed fuel load that is different that might be anticipated for a non-earthquake-damaged building. Also, following the largest ground motion test, a rigid steel pipe, representative of a fuel gas line, failed on Floor 1. The risk, without other mitigation measures (e.g., shutoff valve), is the supply of fuel to any post-earthquake fire. (See Chen et al., 2013 and Pantoli et al., 2013 for more details on these items.)

Some of the doors installed on Floor 3 were not functioning properly after the motion tests. In some cases doors were not able to close completely because door frames were distorted and locks were damaged. The potential fire performance concern here is that smoke and fire could spread through a door, which was designed to be closed during fire, hindering occupant egress and safety. In another instance, a door on Floor 3 was jammed closed during a ground motion test, requiring tools to be used to pry the door open. The potential fire performance concerns here are that occupants can be hindered when trying to escape, placing them at risk, and the fire service can be hindered when undertaking rescue and firefighting operations.

In various locations within the test specimen, including around the elevator shaft on Floor 3 and within the stairwell on various levels, gypsum wallboard sections became detached during motion tests. The potential fire concerns are loss of compartment integrity and spread of fire and smoke, hindering occupants when trying to escape and placing them at risk, and hindering the fire service when undertaking rescue and firefighting operations. (See Chen et al., 2013 and Pantoli et al., 2013 for more details on these items.)

Following the largest ground motions, the stair became detached from the stair landing and handrails were broken at locations between Floors 2 and 4. The potential fire performance concerns here are that occupants can be hindered when trying to escape, placing them at risk, and the fire service can be hindered when undertaking rescue and firefighting operations. (See Chen et al., 2013 and Pantoli et al., 2013 for more details on these items.)

Following the largest ground motions, significant spalling occurred on various concrete beam-column connections on the lower floor, resulting in exposed steel rebars, degrading the structural load-bearing capacity and fire performance of the connection and structural system. The potential fire performance concerns here are that occupants can be hindered when trying to escape, placing them at risk, the fire service can be hindered when undertaking rescue and firefighting operations, and the building could be at risk of localized collapse or worse. (See Chen et al., 2013 and Pantoli et al., 2013 for more details on these items.)

Following the largest ground motions, one intensive care unit breakout door was detached from the door frame on Floor 4. Since the door provides a smoke barrier, the potential fire performance concern here is that smoke could spread through the opening, and occupants, who may be required to be protected in place, might be put at risk. (See Chen et al., 2013 and Pantoli et al., 2013 for more details on these items.)

Following the largest ground motion test, the elevator was non-operable because the elevator doors and frames became distorted on several floors, with openings as large as 24 cm (9.4 inches) on the third floor. The potential fire concern is vertical spread of fire and smoke.

Some of the magnetic door holders installed on Floor 3 experienced damage during the motion tests. In one case, the magnetic bond was stronger than the fasteners used to connect the strike plate to the door, ripping the strike plate off the door. The potential fire performance concern here is that improperly operating doors might impede occupant egress and firefighter access.

General observations regarding fire performance of the specimen, following the live fire tests, which could have an impact on fire performance of a building, include:

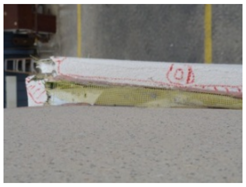
The automatic sprinkler system functioned well during ground motion tests and activated as expected during the fire tests on Floor 3. Smoke detectors activated as expected during the fire tests.

All dynamic and truly static firestop systems installed on Floor 3 performed generally well during the motion tests and to the fire tests except, in earthquake conditions, some joints that would be static in normal operation were not static anymore and joint seals applied on such joints became separated by the ground motion. The potential fire performance concern is loss of compartment integrity and spread of fire and smoke.

The roll-down steel fire door was intentionally not subjected to significant in-plane drifts during the motion tests and resisted shaking perpendicular to the plane of the door effectively (no damage, see Chen et al., 2013 and Pantoli et al., 2013 for more details) and activated as expected during fire tests.

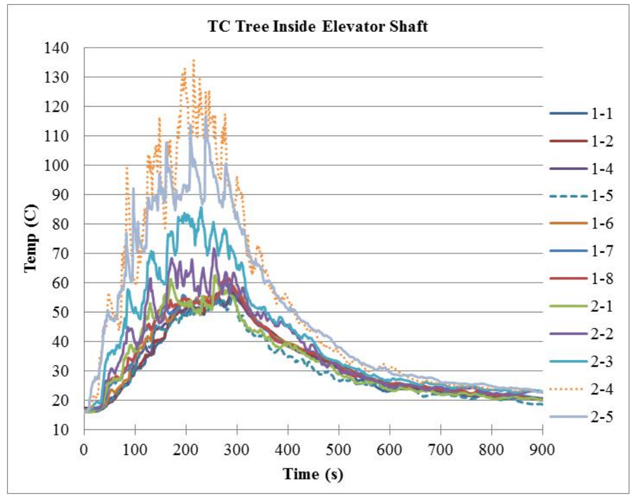
The fire dampers on Floor 3 performed generally well during the motion tests and fire tests. Two fire dampers closed completely following each motion test. The third damper's blade rotation was prevented by a screw used for damper installation which, once adjusted, allowed the damper to close completely following the motion tests. The potential fire performance concern is lack of smoke control, allowing smoke to spread from one compartment to another.

Non- rated, flexible HVAC ductwork, melted and ruptured during some of the fire tests. The potential fire performance concern is lack of smoke control, allowing smoke to spread from one compartment to another.

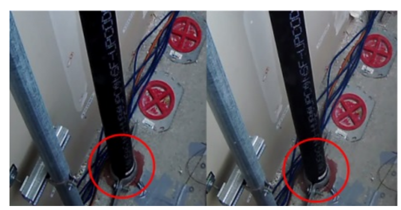


Significant gaps opened in several joint areas on Floor 3, as well as between steel brackets and the balloon framing. The gap between the balloon framing and slab was up to 10 cm (4 inches) in places (see Chen et al., 2013 and Pantoli et al., 2013 for more details). The potential fire performance concern is loss of compartment integrity and spread of fire and smoke. Smoke leakage was observed during the fire tests in several locations.

As noted above, the elevator was non-operable following the largest ground motion because the elevator doors and frames became distorted on several floors, with openings as large as 24 cm (9.4 inches) on the third floor. One potential fire performance concern is loss of compartment integrity and spread of fire and smoke, in this case allowing for vertical smoke (and fire) spread. The elevator shaft interior temperatures were greatly increased as smoke and hot gases from the elevator lobby fires were entrained into the shaft through the opening on Floor 3. An additional potential fire performance concern is the loss of elevators for occupant egress and for fire department rescue and suppression support operations.



Depending on the test, very high temperatures were realized and flashover conditions were observed, even with relatively small fuel loads. In some cases the ventilation conditions played a significant role.



A long vertical steel pipe went through thermal expansion under elevated temperatures during one fire test and the pipe shifted the fire stop material that was applied on the vertical pipe penetration opening. The potential fire performance concern is lack of intended smoke control, allowing smoke to spread between compartments.

Although it was not possible to test actual windows during these tests, window openings were provided and tested in various conditions, including completely closed, partially closed and fully open. In tests where the windows were fully opened, flame extension was observed, smoke venting was observed, and the test fires were exposed to wind-driven conditions, which affected the combustion rate, smoke spread and flame angle direction during the fire tests.

The potential fire performance concerns here are that loss of windows could facilitate floor-to-floor fire spread, and that wind-driven conditions resulting from loss of windows could result in much different fire conditions that the building fire protection systems are designed for or the fire department might expect. This would place occupants and the fire service at risk.

The above highlights some of the key initial observations from the fire test program portion of the BNCS test series. The full fire test program report, Kim, J.K., Park, H. and Meacham, B.J., *Full-Scale Structural and Nonstructural Building System Performance during Earthquakes and Post-Earthquake Fire: Fire Test Program and Preliminary Outcomes*, WPI, Worcester, MA, January 2013, provides much more detail on the fire test program and data collected, including component data sheets, sensor and data acquisition details, and thermocouple data from each of the fire tests.

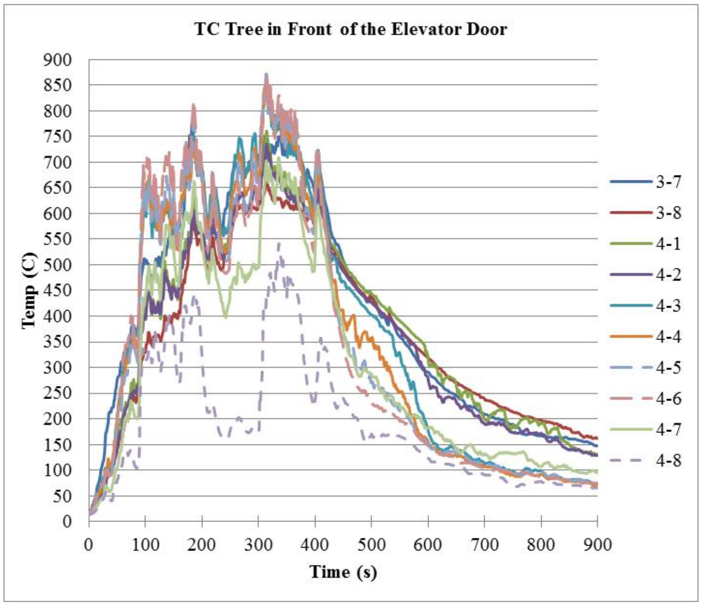
Looking forward, since very few full-scale post-earthquake fire tests have been conducted to date, more testing is warranted to investigate in more depth the above situations, to assess the performance of other building constructions, contents and configurations, and to fill the gap of knowledge on post-earthquake building fire conditions. Some additional observations for future testing include the following:

To best mimic real life conditions, it is important to have fully operating building and fire protection systems, including a fully functioning HVAC system.

To better assess the potential for vertical fire spread and potential for and the effects of wind-driven fires, a variety of exterior glazing systems and window configurations should be tested.

Post-earthquake fire experiments should be performed on a myriad of construction types as the code requirements, construction material and style vary across different regions. Test specimens utilizing lightweight steel construction, lightweight engineered wood construction, steel framed construction and combinations of construction (framing, interior and façade) systems should be tested. Multiple ceiling systems and components should be tested. Multiple door/frame systems, closers and hold-open devices should be tested.

Measurements of the heat flux, flow velocity, temperature, pressure and visual records of smoke and fire spread should be collected directly during the fire tests. This will provide more data on building performance and can be helpful in simulation or performance.



Instead of a fuel pan, a gas burner system should be used which allows for controlling the fire size and for measuring the heat release rate. This will allow more flexible test schemes, and larger and longer fires, which can be stopped as needed if the potential for structural damage exists.

Two sets of tests should be conducted on the same building conditions at the pre- and post-earthquake damaged state. Where possible, laboratory pre- and post-damage testing of representative configurations will help to yield additional data.

Tests should be repeated under the same testing environment for a more reliable set of test data.

Tests should be repeated under a range of test environments (e.g., relative humidity, temperature and wind speeds) for a broader data set.

Acknowledgments

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WPI FPE graduate student team A.J. Campanella, Jin-Kyung Kim and Haejun Park

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