A Conceptual Framework for Assessing Post-Earthquake Fire Performance of Buildings

by

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Abstract

Earthquakes can severely damage building structural and nonstructural systems and components, including active and passive fire protection and egress systems. If the occurrence of such damage is not anticipated at the design stage, the impact of a post-earthquake fire could be significant, as building and fire protection systems may not perform as expected. Unfortunately, even though both the seismic and fire engineering communities utilize performance-based approaches for designing well-performing and resilient buildings under earthquake and fire hazards respectively, each discipline carries out their associated building performance analyses independently. As a result, fire protection engineers have little guidance as to how to estimate structural and nonstructural building systems and component damage as inputs to help them develop post-earthquake building fire scenarios. To help bridge this gap, a conceptual framework is developed that illustrates how performance-based approaches for earthquake and fire engineering analysis and design can become more integrated for the development of post-earthquake fire scenarios. Using a fictional building in an earthquake prone area as an example, the conceptual framework is implemented to show (a) how earthquake-induced damage to building fire protection systems could be estimated using an earthquake performance assessment tool, (b) how the damage estimates might be translated into physical damage parameters in a way that is meaningful for developing post-earthquake building fire scenarios, (c) how the damage states might be implemented in terms of fire and egress modeling input parameters, and (d) how this information could be used to and compare post-earthquake building fire safety performance to a normal (undamaged) building fire conditions.

Executive Summary

History of previous earthquakes has shown how destructive post-earthquake fires can be in the built environment. In particular, earthquakes have the potential to damage building structural and nonstructural components and systems (NCS), which in turn can result in changes to the building fire performance. This was further illustrated through the building nonstructural components and systems (BNCS) project, where a full-scale five-story reinforced concrete frame test specimen erected on the nation's largest outdoor shake table at the Englekirk Structural Engineering Center at the University of California San Diego was subjected to various earthquake motions and post-earthquake fires (http://bncs.ucsd.edu/index.html). In this test series, damage to various building components, which can significantly degrade the building fire safety performance levels, was observed. Importantly for fire safety design, many of the damage conditions would not be normally expected or be a point of concern for fire protection engineers assessing building performance under non-earthquake conditions, indicating the potential to inadvertently miss hazards and conditions associated with post-earthquake building fires.

In part this is because most of the current building design practice for earthquake and fire is highly prescriptive, having been established over a long period of time. While the prescriptive codes have generally proven to work under most conditions, it is often following an event when shortcomings are identified. Since such a prescriptive approach does not necessarily provide a complete understanding of expected building performance in terms of potential loss of life, damage to property, business interruption and serviceability in case of earthquake or fire events, performance-based (PB) analysis and design approaches have been identified by the seismic and fire engineering communities as a means to achieve better building performance under these events. However, at the present time, these PB fire and seismic building analyses are being performed independently without any interaction. In addition, fire engineers lack guidance when it comes to identifying scenarios for post-earthquake building fire performance analysis.

When performing building performance fire analysis, a fire engineer can follow the *Society of Fire Protection Engineers (SFPE) Engineering Guide to Performance-Based Fire Protection* guideline. As per the SFPE Performance-Based Design (PBD) Guide, to perform PB fire analysis and design, a fire engineer needs to establish project goals, objectives, and performance criteria, assess fire hazards and risks to develop, select and evaluate design fire scenarios to come up with a final fire safety design. Although the fire protection goals and objectives will be relatively similar for most buildings, when dealing with earthquake prone buildings, the fire engineer has no guideline available which provides a method to (a) predict damage states or (b) take into account the effects of earthquake-induced damage and its impact on the building, occupant, and fire characteristics in a post-earthquake fire. Without interaction with seismic engineers, a fire engineer lacks understanding of how building components and systems will perform under seismic loads and what types of damages can be expected as a result.

To help fire engineers gain some indication of how earthquake engineers predict damage, a PB seismic analysis approach developed by Applied Technology Council (ATC) under project activity 58 (ATC-58) was investigated. The approach developed under ATC-58, which includes a Performance Assessment and Calculation Tool (PACT), involves assessing the probable earthquake performance of individual buildings based on their site, structural, nonstructural and occupancy characteristics. The performance measures which are determined based on the ground motion intensity, are provided in terms of potential casualties, repair and replacement costs. The PACT tool provides a probabilistic representation of damage states given the expected seismic hazard.

Despite the existence of such PB guidelines for the fire and earthquake engineering disciplines, and each working towards similar goals of designing buildings to ensure life safety of the occupants and to minimize the potential structural and property losses, there is little interrelationship. To bridge this gap, a conceptual framework integrating earthquake and fire engineering concepts is developed in an attempt to relate PB approaches for earthquake and fire analysis and design. The conceptual framework focuses on identifying what kind of building damage could have an impact on the building fire performance, how seismic engineers estimate damage to specific building components, what types of damage states are estimated, and how such data by seismic engineers if provided to a fire engineer can be used as meaningful data to develop accurate post-earthquake building fire scenarios and to implement as modelling input parameters.

Although the conceptual framework is only the first step towards achieving a fully-developed PB approach, it will allow fire and seismic engineers to be aware of potential post-earthquake building fire hazards, the connections that exist between the two engineering disciplines, and the data, procedures and steps required to successfully conduct post-earthquake building fire design and analysis.

To illustrate how the process works, a fictional building is used as a proof of concept test case wherein, a post-earthquake building analysis is performed using the conceptual framework. Step-by-step procedures are presented to show how the conceptual framework could be actually applied to practice. As part of the case study, a post-earthquake fire scenario and a normal fire scenario of the fictional building are modelled and analyzed to determine the impact an earthquake can have to the overall building fire safety performance. The case study results show that, using damage states assumed from the earthquake performance analysis, the building damage can result in untenable conditions and prevent occupants from safely evacuating the fictional building during a post-earthquake fire event.

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Contents

List of Figures

List of Tables

1 Introduction

Earthquakes occur every day on a daily basis, all over the world. Earthquakes can be extremely hazardous, and in general, the most destructive earthquakes for humans are those that occur in heavily built and populated areas as there is great potential for damage to building structural and non-structural elements. Furthermore, single or multiple ignitions could also occur and with the potential to spread to multiple buildings. The two largest peace-time urban conflagrations in history were fires following the 1906 San Francisco and 1923 Tokyo earthquakes, with the latter resulting in about 140,000 fatalities (Usami, 2006). More recently, the 1995 Kobe earthquake that only lasted 20-seconds and measured 6.8 on the Richter Scale, induced 148 separate ignitions and destroyed 6500 buildings over a total land area of 634,671m^2 (NFPA, 1996).

Predominantly, modern day buildings are designed in compliance with the prescriptive building codes to be resilient from earthquakes and fires. In developed countries where building codes address seismic issues, improved design methodology has significantly reduced the possibility of structural collapse and loss of life. However, the same cannot be said of the performance of building nonstructural components and systems (NCS) during earthquakes (Villaverde, 1997). Statistical data in the United States show that while only two people per year have died due to building collapse associated with earthquakes since 1970, economic losses have been about $2 billion per year during the same time span (ATC-69, 2008). Importantly, NCSs also consist of active and passive fire protection systems, where damage to these systems introduces the additional concern of post-earthquake fire performance of buildings. During the 1994 Northridge and 1995 Kobe earthquakes, damage to fire sprinkler systems and fire doors was reported to be over 40% and 30% respectively (Sekizawa et al, 2003). Damage to such fire systems can cause occupants to be placed at additional risk in case of post-earthquake fires.

To more systematically investigate earthquake and post-earthquake fire performance of buildings, a $5 Million collaborative effort between academia, government and industry was conducted from 2009 through 2012, referred to as the building nonstructural components and systems (BNCS) project (http://bncs.ucsd.edu/index.html). Key project aims were to help better understand and quantify the performance of structural and nonstructural building systems during earthquake and post-earthquake fire conditions. The project involved constructing a five-story reinforced concrete test specimen, complete with a wide range of nonstructural components and systems, on the large high performance outdoor shake table at the University of California San Diego, subjecting the specimen to a series of thirteen earthquake motion tests and six live fire tests, and collecting data on system responses to the motions and fires. In particular, these tests highlighted some of the hazards described above and also suggest that some compartment barrier components, façade and egress systems could be susceptible to severe damage as a result of earthquakes, leading to occupant life safety and emergency responder concerns during post-earthquake fire. (Kim et al, 2013).

1.1 Problem Statement

Prescriptive building codes generally result in tolerable levels of building fire safety. In part this is because building codes are modified to address shortcomings which emerge when unacceptable losses occur. However, it is not always clear how prescriptively-designed buildings will perform when subjected to events with different characteristics and what the associated risks might be. As a result, seismic and fire protection engineers, have turned to performance-based (PB) design approaches as an alternative to better understand and quantify hazard-related risks and the resulting building performance.

To date, PB seismic design and PB fire design have been performed independently. While this can be understood from the perspective of the different expertise in each discipline, the independent approach has resulted in a gap when it comes to assessing the fire performance of earthquake prone buildings. One of the biggest challenges for fire protection engineers (FPEs) when undertaking PB analyses of earthquake prone buildings is obtaining knowledge of how buildings are expected to perform, and what type and level of damage can be expected when a building is subjected to seismic loads. For example, previous research has shown that the chances of ignition in a building following an earthquake is greater than normal (Sekizawa, 2003) while building fire systems may not perform as expected due to the resulting earthquake associated damages (Collier, 2005, Sekizawa, 2003). These risks combined could severely impact the building fire safety performance level during post-earthquake fires. As a result, it is essential to understand how earthquake motions might distribute fuel load in a building, result in sources of ignition or additional fuel, or cause damage to passive or active fire protection systems, in order to more accurately predict post-earthquake building conditions, ignition scenarios, design fire scenarios, design fire loads, and performance criteria.

However, despite the causal linkage of earthquake and post-earthquake building fire performance, and the desire to have better performing buildings, currently the analysis of ground motions, building response, fire loads and fire performance are conducted independently with little or no interrelationship. For the most part, seismic engineers and fire protection engineers perform independent building design analyses without due consideration of the potential interaction between the two events: earthquake and fire.

In order to deal with the issues described above, and to bridge the gap between the seismic and fire communities, a basic conceptual framework that can be used by the seismic and fire engineers to comprehensively understand and identify key issues and potential hazards and the critical affecting factors that impact the building performance levels during earthquakes and fires and how all these components combine during post-earthquake fires is needed. Such a model can help seismic engineers understand what types of building damage measures are helpful to FPEs, to aid them during the fire scenario and mitigation development, as well as to FPEs that require better understanding of what types of physical damage could occur to a building, and where, as a result of an earthquake, and use such data to assess additional risks, and develop accurate design fire scenarios.

1.2 Thesis Objective and Approach

The objective of this thesis is to develop a conceptual framework for a performance-based (PB) approach that integrates both the seismic and fire engineering analysis and design processes. The framework will take concepts from existing PB design approaches. The framework will focus on key post-earthquake building performance conditions, that are identified through literature reviews as well as through testing results associated with the BNCS project, which could potentially degrade the overall building fire safety performance during a post-earthquake fire.

As a starting point, a literature review is conducted and the BNCS project outcomes are used to support the claims that a building subjected to high intensity seismic loads could become severely damaged, and such damage could have significant impacts on the post-earthquake building fire safety performance (Kim et al, 2012). In addition, data which were collected substantiated the need for FPEs to have accurate predictions of building damage states in order to quantify key hazards and risks for post-earthquake fire conditions.

However, since there is currently no framework which characterizes both fire and seismic hazards and their effects on buildings in a consistent and compatible manner, to emerge and connect these two separate seismic and fire building design practice approaches, the Applied Technology Council (ATC) Project 58 performance-based seismic design methodology and performance assessment calculation tool (PACT) and the Society of Fire Protection Engineering (SFPE) *Engineering Guide to Performance-Based Fire Protection Design* (PBD Guide) are reviewed.

The ATC-58 project was created to develop the next-generation performance-based seismic design guidelines for new and existing buildings (ATC-58). The ATC-58 methodology can be used to accurately predict the seismic performance of individual buildings and the response in several ways (e.g., total repair cost, total casualty and etc.) to be able to communicate the performance in an effective manner with decision making stakeholders based on their needs. The SFPE PBD Guide was developed to provide FPEs with a process for undertaking performance-based designs for fire in new and existing buildings. This guide is intended to help fire engineers, architects, building code officials and authority having jurisdiction (AHJs) by providing them with a clear set of definitions, documentation requirements, and a process for design and review for facilitating PB fire protection analysis design in a flexible yet consistent manner.

Considering (a) earthquake damage of concern to FPEs, (b) what factors are important in PB analysis and design for fire, and (c) how the ATC-58 methodology can be used to predict building damage states and their probability of occurrence, a conceptual framework for risk-informed performance-based analysis of post-earthquake building fire performance is developed. The conceptual framework is intended to provide and convey the perspective and informational needs of a fire protection engineer working with an earthquake prone building.

With the conceptual framework identifying key building components and their related earthquake damage that can influence the building fire safety performance, the conceptual framework is applied on a fictional building to show a detailed step-by-step process of the approach. Event trees are created and used as a risk assessment tool to incorporate probability of earthquake damage in the fire scenario development, with exemplar system damage states and failure probabilities for selected building components obtained from ATC-58, to develop post-earthquake design fire scenarios. These scenarios are then compared to fire scenarios which might be developed in non-earthquake damaged conditions to illustrate the degree of difference due to the seismic damage.

After identifying the design fire scenarios, a select few scenarios are modeled using FDS and Pathfinder to illustrate fire performance in normal and earthquake-damaged conditions. FDS modeling is conducted to analyze the building fire safety performance with respect to smoke and flame spread while Pathfinder modeling is conducted to analyze the building fire safety performance focusing on building evacuation. While not included in this work, structural fire modeling can also be conducted considering post-earthquake damage states.

While the conceptual framework is presented and exemplar event trees are presented for scenario development and computational modeling of exemplar building configurations are used to illustrate how PB seismic and fire protection analysis and design can become better integrated, this is simply a first step. Several areas of future research remain, including potential modification of the ATC-58 PACT approach to yield data in a format more useable to FPEs, creation of better data sets of failure probabilities for use in event trees for scenario development, more and better data on post-earthquake building and fire performance, and more complete guidelines for PB fire design for earthquake-prone buildings.

1.3 Thesis Overview

This thesis is organized into 11 chapters as follows:

Chapter 1 provides background and context of this research. The problem statement, and the objectives and approach are presented.

Chapter 2 provides background information on earthquakes in general and how they can affect the building fire safety performance levels. An overview of data collected during the BNCS project is presented. A brief overview of the project is provided along with description of building specimen and test procedures. All of the test result presented focuses on building response and damages that can have potential influence on the building fire safety performance levels. The main focus of discussion is on the performance of compartment barriers, egress components and structural integrity of post-earthquake fires.

Chapter 3 investigates the performance-based building design methodologies of both the fire and seismic engineering communities. The transition from prescriptive to performance-based fire codes in the fire engineering community is discussed and a brief overview of the SFPE PBD approach is provided. The development and evolution of the performance-based earthquake engineering guidelines are discussed with a detailed overview of the PEER PBEE and the ATC-58 methodologies.

Chapter 4 presents a side-by-side comparison and analysis of the earthquake and fire building design approaches. Goals, objectives, risks, and point of interests for both seismic and fire engineers are identified to highlight some of the commonalities and differences between the two engineering design processes.

Chapter 5 introduces a conceptual framework developed for the thesis that combines and integrates the seismic and fire engineering approaches to help fire protection engineers develop post-earthquake design fire scenarios. This conceptual framework is based on the materials discussed in Chapters 2, 3 and 4.

Chapter 6 looks at the electronic database created by the ATC-58 project to determine whether the building damage states from the database can directly be translated into meaningful data for fire protection engineers to implement for creating post-earthquake design fire scenarios. The structural and nonstructural components selected for review is based on the damages presented in Chapter. The usability of the ATC-58 damage states are assessed and for components where damage states are inadequate or provide no significance to fire protection engineers, possible damage states are suggested.

Chapter 7 uses the conceptual framework to develop sample post-earthquake design fire scenarios using an event tree. Two event trees are created, for a normal building fire condition as well as a post-earthquake building fire condition. Based on this, the required steps that are essential for fire engineers to determine building earthquake damage states are listed. These steps are integrated into the SFPE PBD guideline. This outline of the entire process of developing post-earthquake building fire conditions shows how the work should be divided between the fire and seismic engineers, and what type of interaction is required by both for successfully implementing the design process.

Chapter 8 provides information of a fictional building, its occupant characteristics and building components. The conceptual framework is implemented to perform PB analysis on the fictional building with the assumption that it is situated in an earthquake-zone. Using ATC-58 damage data, post-earthquake fire scenarios are developed and modelling tools are used to evaluate normal-undamaged and post-earthquake damaged building fire scenarios to determine if the fire design works.

Chapter 9 compares both results from the normal and post-earthquake building fire scenarios. Because of the uncertainties in the data used for the case study example, A simple sensitivity analysis is performed.

Chapter 10 presents the conclusions of the thesis.

Chapter 11 presents suggestions for future work.

References are then provided.

Appendix A and Appendix B presents papers published in the proceedings of the 11th International Symposium on Fire Safety Science as supplementary material to provide additional information about the BNCS project. These two papers were both associated with the BNCS project with the first focusing on the building specimen design, earthquake motions and outcomes of the ground motion tests. The second paper focuses on the fire test program and the outcomes of the fire tests.

2 Background

2.1 Earthquakes

The Earth's outer surface is comprised of a series of pieces called tectonic plates. Tectonic plates are constantly in slow motion moving towards, apart, or past each other. These movements cause stress to build up, and if the rocks cannot withstand any more stress, they break leading to the sudden movement of the tectonic plates. Earthquakes occur when energy stored in the Earth's crust is suddenly released as two tectonic plates slip past each other. This movement creates seismic waves and shaking of the ground. The size of the earthquake, commonly referred to as the magnitude, depends on the size of the blocks and the amount of the slip. Seismographs located on the surface of the earth are used to measure the magnitude of earthquakes (Kanamori, 1978).

Earthquakes cause little direct harm to humans. It is the building damage or collapse caused by the ground shaking or ground ruptures that threatens life safety. The aftereffects of an earthquake can sometimes be even more destructive than the earthquake itself. Some of the common aftereffects include landslide, avalanche, tsunami, flood, soil liquefaction and fire.

One of the main hazards of earthquakes is post-earthquake building fires, which will be the focus of this thesis. Following an earthquake, the risk of fire in buildings is significantly escalated (Scawthorn, 2011). Although the probability of post-earthquake fires occurring is low, the chances of ignition are still greater than normal. In history, ignitions have occurred during and after earthquakes due to motion-induced damage to a wide range of systems and equipment, including utilities (e.g., gas and electrical systems), building equipment (e.g., boilers or furnaces) and contents (e.g., electrical appliances and chemicals and other hazardous materials). The Los Angeles Fire Department (LAFD) data from the 1994 Northridge Earthquake indicates that earthquake related fire ignition sources were attributed to electrical, gas-related and other at 56%, 26% and 18% respectively.

Earthquakes can leave buildings severely damaged. If ignitions occur, leading to building fires following an earthquake with the building being at a damaged state, this can greatly influence several aspects of the building fire safety performance.

For structures designed and built in compliance to the seismic codes, the greatest variable which can influence the building fire safety performance in post-earthquake fire conditions is the magnitude and duration of an earthquake. This variable is uncontrollable and unpredictable at the same time. This factor alone can be the deciding factor on the extent of the building damage. Although most modern day buildings have been built to prevent total collapse, damage to building structural and nonstructural systems and components are inevitable. Building damage factors affecting the building fire safety performance can be grouped into the three major categories of compartmentation, egress components and structural integrity.

There are some data collected from earthquakes in the past and experimentally derived data on performance of building components under seismic loads. However, there are not enough data available to confidently and accurately predict the extent of the damage to a myriad of building systems for various earthquake intensities. This is the area where FPEs might have trouble when it comes to working with earthquake prone buildings. Because FPEs currently do not have general guidelines for developing post-earthquake design fire scenarios, the scenarios may delineate a totally inaccurate picture of a post-earthquake damaged building condition from reality and not take into consideration some of the risks associated with such conditions.

As a result, FPEs need a methodology which will help them to better estimate the building damage conditions for post-earthquake building fires. However, because it is not expected or required that a FPE has seismic engineering knowledge or background, a framework that integrates both the fire and seismic engineering building design methodology can help build more resilient buildings under both earthquake motions and post-earthquake building fires.

A literature review, presented in the next section, is conducted to review effects of past post-earthquake fire events and what kind of earthquake related building damage is available. The focus is to see if data is available for specific building items that affect the building fire safety performance. Additional literature review is conducted to see if there are any frameworks developed that deal with the issue of estimating building damage and identify potential risk factors for post-earthquake building fire conditions. An overview of the BNCS project and the findings and key issues are also presented to provide additional data on how building NCS could be damaged due to seismic loads.

2.2 Literature Review

2.2.1 Past Post-Earthquake Fire Events

History has shown that fires following earthquakes rather than the ground shaking itself can be a major cause of damage. Although large post-earthquake fires are low probability events, if they do occur, the consequences are catastrophic. From the post-earthquake fire that resulted from the 1906 San Francisco Earthquake, about 3,000 casualties were reported with 28,000 buildings being destroyed as fires burned over three days due to lack of water. The post-earthquake fire resulting from the 1923 Tokyo Earthquake, caused an about 140,000 deaths and destroyed 575,000 houses (Scawthorn et al. 2005). The 1994 Northridge earthquake resulted in approximately 110 fires, killing more than 6,000 people and leaving more than 300,000 people homeless. The 20-second ground shaking from the 1995 Kobe earthquake resulted in 148 separate fires and destroyed 6,513 buildings.

2.2.2 Performance of Building Fire Protection Systems in Post-Earthquake Fire Conditions

The impact of damage to fire protection systems has been observed in numerous earthquakes. In both the Northridge and Kobe earthquakes, for example, it was found that damage to fire sprinkler systems and fire doors was reported to be over 40% and 30% respectively (Sekizawa et al., 2003; Chen et al., 2004). Research has also been conducted on post-earthquake building fire performance. Collier (2005), for example, analyzed the performance of passive fire protection systems under post-earthquake fire conditions. Plasterboard lined lightweight timber and steel-framed walls were subjected to simulated earthquake racking test under various intensities, then to a fire resistance test. Results showed that the fire resistance rating of these walls could be reduced as much as by 50% due to the gaps formed in the wall linings from the seismic motions. A comparison between the damage mode to the walls from racking tests and the temperature recordings from fire resistance tests are made to provide a subjective judgment on estimating fire resistance rating reduction.

2.2.3 Current Situation in Building Design for Hazards

Current buildings, even for extreme events, are mostly designed and built in accordance to the prescriptive building codes. However, because the prescriptive codes fail to tell how much safety is provided and expected building performance levels, performance-based design (PBD) has been identified by both the seismic and fire engineering communities as a means to better understand building performance as a result of such events. Furthermore, it is rooted in the concept of supporting design more resilient buildings, which meet stakeholder risk tolerance objectives (e.g., see Hamburger et al., 1995; ATC-58, 2009; Meacham, 1998, 1999, 2004; Meacham and Johann, 2006; NIST, 2009).

Currently, there is no integrated approach that characterizes hazards and risks and their effects on buildings between different events. Also, there is a disconnect between the engineering characterization of performance and metrics that are relevant to different engineering disciplines and the various stakeholders who must make risk-informed decisions.

Deierlein and Hamilton (2003), tried to address this issue by developing a performance-based fire engineering framework by taking the key concepts of performance-based earthquake engineering. A side-by-side comparison of fire and earthquake engineering was made to create a parallel approach between the two. The performance-based fire engineering framework is focused on the performance of structural members under fire conditions and producing performance metrics that are meaningful to building stakeholders.

Sekizawa et al. (2003) developed a framework that assesses the seismic-induced fire risk in a building and also the building fire safety performance level. This framework requires predicting the earthquake response of a building by taking into consideration the frequency and vibration characteristics of an earthquake and a building respectively. The structural response data is used to determine the damage levels of active and passive fire systems. A fault tree analysis is used to determine the dominant failure mode as well as the overall functional failure of a sprinkler system for active systems, while data from literature are used to reduce fire resistance time of compartments such as walls and fire doors due to lack of data. These failure probabilities of fire systems are used to predict transition probability of fire phases and burned area for a post-earthquake fire scenario.

Efforts such as these provide a starting point for thinking about both the structure of performance-based design for earthquake and fire, and how scenarios for consideration in performance analysis might be considered. They also provide an indication of the type of data needed for such analysis. Efforts like the BNCS project provide one source of such data.

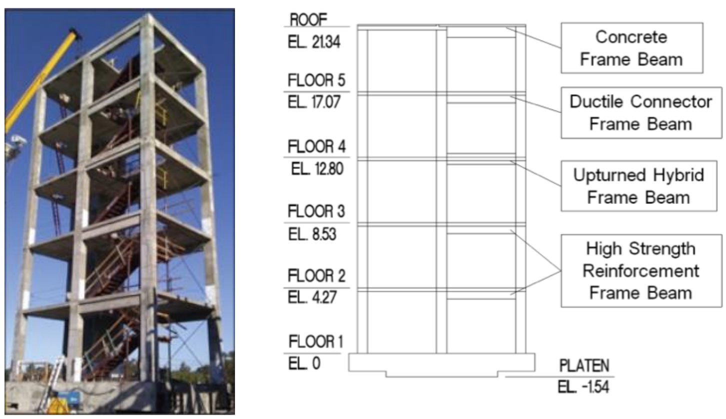
2.3 BNCS Project

To systematically investigate earthquake and post-earthquake fire performance of buildings, a $5 Million collaborative effort between academia, government and industry was conducted from 2009 through 2012, referred to as the building nonstructural components and systems (BNCS) project (http://bncs.ucsd.edu/index.html). Key project aims were to help better understand and quantify the performance of structural and nonstructural building systems during earthquake and post-earthquake fire conditions. The BNCS experiments were performed in April and May of 2012 on the large high performance outdoor shake table (LHPOST) at the Englekirk Structural Engineering Center of the University of California, San Diego. A five-story full scale concrete building specimen was built on the LHPOST as shown in Figure 1. This building specimen was subjected to 13 seismic motions. Following the sequence of seismic motion tests, six pan fire tests for conducted in four different compartments of the building specimen. The main objective of this project was to assess how BNCS perform under seismic loads and post-earthquake fire conditions. More details on the building specimen design, motion tests and motion test outcomes, and the fire test program and fire test outcomes can be found in Appendix 1 and Appendix 2 respectively.

Figure 1. Building specimen built on top of the LHPOST

2.3.1 Building Specimen Design

The building specimen was designed with the assumption that it was to be located in a high seismic zone in Southern California (Site Class D). The building specimen was constructed of poured-in-place concrete and had plan dimensions of 6.6 m by 11m with floor-to-floor heights of 4.27 m at all levels. A 0.2 m thick concrete slab was placed at each level, with two large openings of 2.1 m by 2.6 m and 2.3 m by 4.2 m at all floors to accommodate an operable elevator and complete stair assembly, respectively. Seismic resistance for the building was provided by special one-bay moment resisting frames in the Northeast and Southeast bays. Different types of moment resisting beams were present at each floor and are presented in Figure 2.



(a) (b)

Figure 2. Building specimen (a) skeleton; (b) elevation view (elevation in meters) [images and schematic from Chen et al. 2014].

2.3.2 Building Components

The building specimen was outfitted with various nonstructural components and systems (NCSs). These NCSs could be categorized into architectural, mechanical electrical and plumbing (MEP), egress systems, and contents. All of these components were incorporated into the building specimen to reflect a typical multi-story building. Additional details on the building components and contents can be found in Kim et al. 2013, and Pantoli et al. 2014.

The architectural systems consisted of façades, ceilings, and partition walls. Floors 1 to 3 were outfitted with balloon framing façade system with vertical metal studs and exterior insulation finishing system (EIFS) while Floors 4 and 5 were outfitted with 2 concrete cladding panels on each side of the building. There were different types of ceiling systems and partition walls with different configurations at each floor level.

There were numerous MEP components installed throughout the building specimen. All five floors consisted of a charged wet pipe automatic sprinkler system with various pipe materials and sprinkler heads at each level. There were fuel gas piping and electrical systems. Heating, ventilation air-conditioning (HVAC) ductwork was installed on Floor 3 and vented to the outside through a vertical duct on Floor 4. There were 3 fire dampers installed inside the horizontal ductwork on Floor 3.

The egress systems consisted of a prefabricated stair assembly and a fully functioning elevator. Each floor consisted of lower and upper flights and an intermediate landing for the stairs. The elevator was able to travel through all the floor levels.

Open spaces in the building were furnished with real life contents and mimicked real life occupancy. Floors one to the roof level were filled with electrical conduit, chemical lab space, rooms, intensive-care unit (ICU) equipment, hospital operating equipment, and water cooling tower respectively.

2.4 Earthquake Motion Tests

A total of 13 earthquake motion tests were conducted while the building was base-isolated (BI) and fixed base (FB). Seven tests were conducted while the building was BI and six while it was FB. Four high damping rubber isolators were installed at the four corners of the building for the BI tests and subsequently removed for the FB tests. Design earthquakes were selected to progressively increase the seismic demand on the building specimen. Details of the selected design earthquakes can be found in Chen et al. 2014. During these motion tests, acceleration, displacement and visual data of the building specimen and its contents were collected. Following each earthquake motion test, building inspection was conducted to identify any damage to building systems that might affect the building fire safety performance, and compartment integrity tests were conducted using a blower door fan on two fire test compartments on Floor 3 to measure the leakage area created due to the motions.

2.5 Fire Tests

Six fire tests were conducted in four different compartments on Floor 3 of the building specimen following the last earthquake motion test with the building being in a post-earthquake damaged state. Each fire test consisted of varying heptane amounts, number of pans and ventilation configurations. Video cameras were used to obtain visual data of the fire tests as well as to check for the activation of sprinklers and fire door. Thermocouples were used to measure gas and surface temperatures of fire test compartment and check for smoke spread to its adjacent compartments. The fire test program can be found in Kim et al. 2013, Appendix A and Appendix B.

2.6 BNCS Data Summary

The BNCS project validated the fact that multiple building components could be damaged when subjected to seismic loads. Observations made on damage to specific building components that could have an impact on the building fire safety performance which resulted from the seismic motion tests, and the observations made during the fire tests conducted in post-earthquake fire conditions are presented briefly. All the seismic test results can be found in Chen et al. 2014, and all the fire test results can be found in Kim et al. 2013.

The motion tests induced damage to numerous compartment barrier components. Gaps formed in building joint areas, ceiling tiles were dislodged, door frames were distorted or door locks were damaged failing to close completely. Egress component damage included disconnected stairs from the floor slab, disconnected stair handrails, elevator door failure, dispatched gypsum wallboard on stair landing areas, and displaced building contents providing obstructions in possible egress routes. Concrete spalling occurred in beam-column connections, leaving the steel reinforcing bars exposed which would yield easily under elevated temperatures. Rigid steel pipe, representative of a fuel gas pipe was damaged and disconnected at the connection, which would have increased the chances of ignition in a real building.

The fire tests were conducted in building compartments in post-earthquake damaged building conditions which would not be seen under normal building conditions. The post-earthquake fire tests showed smoke spread beyond the compartment of fire origin through openings and gaps formed in the building envelope. Flame extension out the window openings and areas with significant gaps were observed. Vertical thermal expansion of a metal pipe lifted the fire stop sealants a few millimeters from the penetration opening, although there was no degradation to its functionality.

3 PB Building Analysis and Design Approaches

3.1 Performance-Based Fire Protection Design (PBFPD)

Significant efforts over many years to improve fire safety have resulted in advancements in technology for assessing and creating fire safety design for buildings. These advancements have also helped facilitate a transition to performance-based (PB) building codes and design methods, which began in the 1980s and 1990s (Meacham, 1998; Meacham, Bowen, & Traw, 2005).

The traditional prescriptive based building codes, such as introduced in the early 20th century in the USA, generally provide fire safety with a combination of prescriptions according to the hazards presented by common occupancy groups. These codes are typically based on judgment and experience rather than on science and engineering. By contrast, performance-based building codes require scientific knowledge and engineering principles. The performance-based approach requires identifying hazards and risks to establish safety goals and appropriate design scenarios for specific applications. The design scenarios need to be evaluated for verification which may be done by implementing computer models or running experiments. This approach of considering hazard identification, scenario development, and evaluation of buildings against the scenarios of concern is called performance-based design PBD (Meacham, 1998).

Although PBD practice started becoming more common and practiced, there were no established guidelines a FPE could follow in the United States until SFPE published the *SFPE Engineering Guide to Performance-Based Fire Protection* in 2000. This document was based in part on the current regulatory structure in the United States, using structural provisions as a guide, and in part on key features on the regulatory structures of countries (including Australia, New Zealand and the United Kingdom) which already had a performance-based regulatory system in planning or in place (Meacham, 1997). This guide was developed to identify the key processes that are required for a PBD in a flexible manner. The processes required for the fire engineering PBD approach are shown in Figure 3 and each step is explained in detail in the guideline. Although multiple chapters are included in the SFPE PBD Guideline, these procedures can be divided into three major steps which will be described in the following sections.

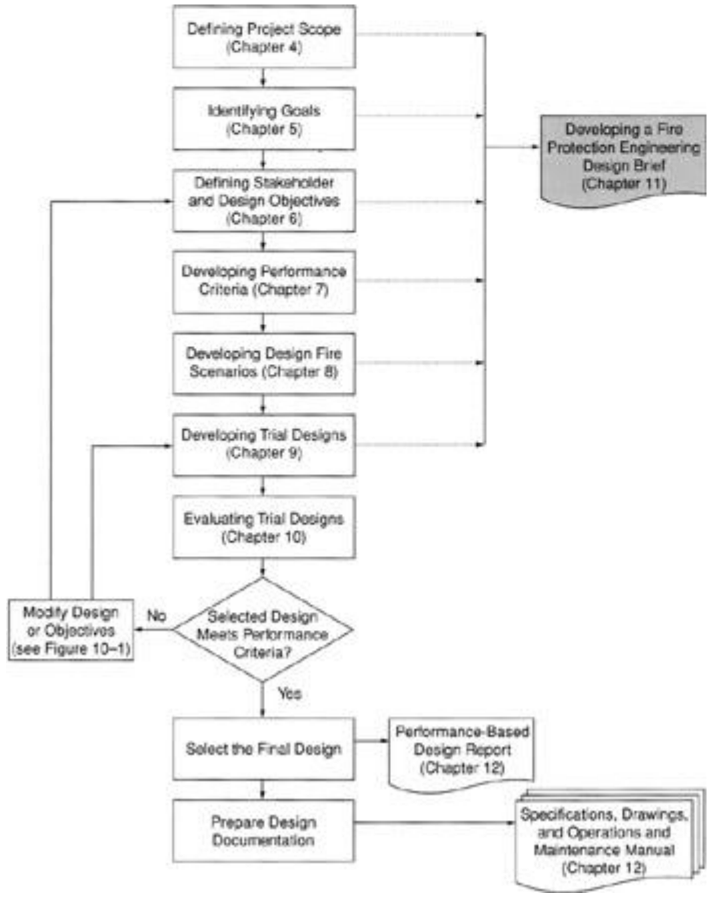


Figure 3. SFPE PBD Methodology

3.1.1 Establishing Project Scope, Goals and Objectives, Performance Criteria, and Design Scenarios

Before taking on a project, a FPE needs to know who the building owner and the associated stakeholders are and what the building occupancy and intended use will be. These factors will help better understand what the stakeholders' needs are and help establish and prioritize fire safety goals of interest to stakeholders. Defining the scope of the project will help realize the constraints on the design and project schedule, better understand the proposed building construction and features desired by the owner or tenant, occupant and building characteristics, intended use and occupancy of the building, applicable codes and regulations and the project management and delivery methods. There must be a mutual understanding and agreement of these aspects between the fire protection engineer and the stakeholders to ensure that all the deliverables desired by the stakeholders are met by the PBD. A main focus of this thesis is to help FPEs accurately estimate and characterize post-earthquake building conditions as input / initial conditions for post-earthquake fire performance assessment.

With a well-defined project scope, the fire safety goals of the stakeholders must be identified. These fire safety goals may vary and depend on the stakeholder's needs and the building use. Such goals may incorporate life safety, property protection, business continuity, structural safety, historical preservation and environmental protection. The fire safety goals should be discussed, prioritized, and agreed upon by the stakeholders to avoid conflicts and problems in the later design process. The established stakeholders' goals and objectives are taken by the FPEs and translated into possible fire safety goals and design objectives in quantifiable fire protection engineering terms. These design objectives could be to mitigate consequences of a fire expressed in terms of loss of life, loss of property and dollars, building downtime, and maximum allowable fire conditions such as maximum temperature, flame spread and fire size.

3.1.2 Developing Performance Criteria, Design Fire Scenarios and Trial Designs

When the goals and objectives are established, feasible performance criteria that help meet the design objectives must be identified, which will later be used to evaluate the trial designs. These performance criteria are expressed in numerical terms that can be compared to the expected performance of the trial designs. These performance criteria could be threshold values of the gas temperature, material temperatures, smoke obscuration, visibility levels, upper gas smoke layer height, toxic gas levels, and thermal exposure levels.

Based on the performance criteria, the FPE must develop and analyze design alternatives to meet the performance criteria under a wide range of possible fire scenarios. This process requires identifying possible fire events and design fire characteristics by identifying the risks and hazards possessed by the building and occupancy characteristics, and building usage. Some of the key factors that may influence the design fire scenarios may be the ventilation, fuel configuration and materials, fire characteristics, occupant location and behavior, building contents, and fire protection systems. The fire scenarios must take into consideration a sequence of possible events, conditions that describe the fire development process and spread of combustion products to various parts of the building. Guidance on establishing scenarios for post-earthquake fire performance analysis is lacking, which is why it has been focused on as part of this research effort.

Based on the established performance criteria and design fire scenarios, the designer develops trial designs which are preliminary designs that meet the project requirements. The trial designs require implementation of all the proposed fire protection systems, construction features and operations that satisfy the performance criteria.

3.1.3 Evaluation of Design Fire Scenarios, Selecting the Final Design, and Documentation

Some of the fire scenarios chosen for trial designs are evaluated using tools such as models, computer software, and other adequate methods that are proven to be valid. This evaluation process should demonstrate that the design does not exceed the selected performance criteria. If the trial design evaluation proves to be unsuccessful in meeting the performance criteria, the design should be modified and retested, or replaced with a new design. These trial designs might incorporate several different design alternatives and all must be evaluated to see if the performance criteria are successfully met. These trial designs must evaluate the development of the fire, structural response under the fire conditions and the evacuation of the building occupants (SFPE, 2007).

Once the trial designs have proven to satisfy the performance criteria, these become candidates to be considered for the final project design. Analysis is required to select the final design and the decision may be made depending on various factors such as financial reasons, installation and maintenance feasibility and etc. A documentation of the selected final design needs to be prepared which incorporates all of the necessary implementation, maintenance, operation requirements of the fire protection design. This document must also include the design brief, performance design report, detailed specifications and drawings and operation procedures.

3.2 Performance-Based Seismic Engineering Design

As recent earthquakes have demonstrated that even buildings designed to the rigorous standards of the contemporary building codes can at times be unfit for normal occupancy and continued use following an earthquake, calls for advancements in technology of PBD in the field of seismic engineering was seen by many as necessary. To take on this approach, Federal Emergency Management Agency (FEMA) funded the Earthquake Engineering Research Center (EERC) in 1993 to develop a program that could be implemented in developing performance based seismic design guidelines. The 6 year research and development program recommendation and proposal by EERC were published in the FEMA 283 Performance Based Seismic Design of Buildings in 1996. Earthquake Engineering Research Institute (EERI) was asked by FEMA to review the proposal for appropriateness. EERI took similar approach as the EERC and the project led to a 10-year process in development of an action plan which was published in FEMA 349 Action Plan for Performance-Based Seismic Design, in April 2000. The ATC-58 (also known as FEMA P58) project was inaugurated by FEMA in 2001 as they asked Applied Technology Council (ATC) to implement the FEMA 349 as the foundation for developing next-generation seismic design guidelines. FEMA envisions that the ATC-58 guidelines could be incorporated into existing seismic design guidelines such as FEMA 368 NEHRP, FEMA 273 NEHRP and FEMA 356 (ATC-58, 2012).

Performance-based earthquake engineering (PBEE) provides a design framework for achieving performance goals for an earthquake prone building. Designing a building using PBEE methods indicate that its performance can be predicted under certain anticipated seismic load. In the early days of earthquake engineering practice, performance was categorized in to poor - meaning failure, or satisfactory - which was concluded as a result of lack of failure. As the practice has developed, the way in which performance is characterized has become more refined. This has been possible as the advent of high performance computers and development of numerical tools with great capabilities have allowed performance to be defined, characterized, and predicted with more precision and accuracy (Kramer, 2008).

As performance can be interpreted differently by different people, it is imperative that seismic engineers define performance in terms that are easily understandable to a wide range of decision makers, building officials, and stakeholders. For example, for a seismic engineer, inter-story drift (IDR) would be the best way to measure performance. However, for a building owner, the economic loss resulting from earthquake damage would be the best way to measure performance. To accurately evaluate all interests the earthquake engineering process requires correctly predicting an earthquake inducing ground shakes leading to response of a structure. Often times the response produces physical damage to the structure and thus leads to losses.

Vision 2000 report developed by the Structural Engineers Association of California (SEAOC) has been widely recognized as being the first document in the United States to have established procedures for PBEE design approach for new structures. For structures, which are classified into three categories, four discrete performance levels are coupled with four ground motion hazard levels in Vision 2000 report. The damage to numerous building components is provided along with the allowable IDR ratios that satisfy the four performance levels. This framework allows for designing buildings based on desired performance and hazard levels (Porter, 2003).

FEMA 273, FEMA 274, and FEMA 356, all subsequent efforts following the Vision 2000 report, provided PB frameworks similar to that of Vision 2000 with variances in defining performance and hazard levels and estimating earthquake demand. These first-generation PBEE frameworks consisted of few limitations such as the engineering demands and component performance criteria being based somewhat inconsistently on relationships measured in laboratory tests, calculated by analytical models, or assumed on the basis of engineering judgment (Porter, 2003). A more robust PBEE framework has been developed by the Pacific Earthquake Engineering Research (PEER) Center to replace the first-generation PBEE methodology. Figure 4 shows the evolution of the PBEE codes in the United States.

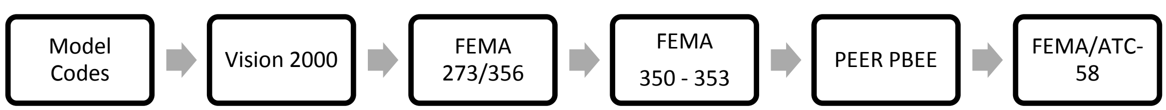


Figure 4. Evolution of PBEE codes

The probabilistic approach by PEER provides estimates of the repair costs, casualties, and building downtime, and is broken up into four stages that consist of hazard analysis, structural analysis, damage analysis, and loss analysis (Gunay et al, 2013).

The seismic hazard of a structure is evaluated by developing design ground-motion time histories with the intensity measure (IM) representing varying hazard levels in relation to site location, site distance, site conditions, etc. This leads to the development of a hazard curve that shows the relation between the variation of a selected IM to the mean annual frequency of exceedance (Gunay et al, 2013).

Structural analysis is performed to determine the structural response of a structure to various earthquake hazards. The structural response, when subject to the specific IM seismic hazard, is calculated by performing a nonlinear time-history structural analysis. The structural response is presented in terms of selected appropriate engineering demand parameters (EDP). It is possible to use different EDP variables for different damageable item of a structure (Gunay et al, 2013).

Damage-analysis is conducted using the EDPs with building component fragility functions to determine the measures of damage (DM) to specified building components (Gunay et al, 2013). Fragility curves, which correlate seismic intensity with the probability of an element at risk reaching or exceeding a level of damage, are used to conduct seismic risk assessments. A sample fragility curve showing the plot of failure probability vs. EDP is shown in Figure 5. The ground shaking can be quantified and expressed in various different earthquake intensity parameters such as peak ground acceleration or velocity. In general, there are several approaches that can be used to create fragility curves. These approaches can be distinguished as empirical, judgmental, analytical and hybrid (SYNER-G Reference Report 4, 2013).

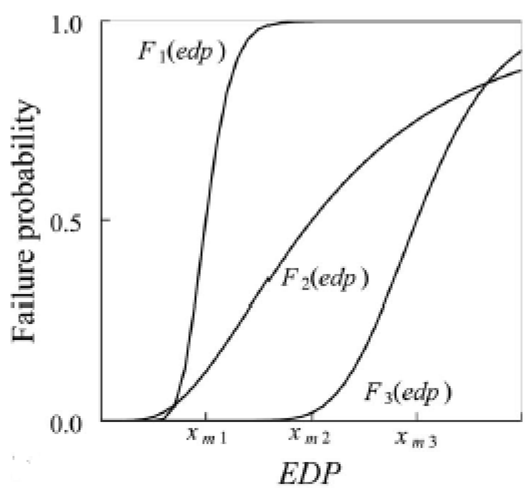


Figure 5. Generic fragility curve (Porter et al, 2007)

Empirical fragility curves are created specifically to a particular site and structure as empirical method is based on surveys from past earthquakes. Judgmental fragility curves are based on expert opinion and experience so they are heavily dependent on the knowledge and experience of the experts. Analytical fragility curves are based on the damage distributions simulated from the analyses of structural models under a gamut of earthquake loads. Hybrid fragility curves can be created by combining any of the methods explained above (SYNER-G Reference Report 4, 2013).

Loss analysis is conducted using the DM obtained from the damage analysis stage. Using the DM, the repair costs, building operability, downtime, and potential casualties can be evaluated. These measures provide building owners and stakeholders with the appropriate decision variables (DV) to make the final decisions. There is uncertainty associated with all of the variables, which are determined probabilistically (Gunay et al, 2013). Figure 6 shows the PEER PBEE methodology process.

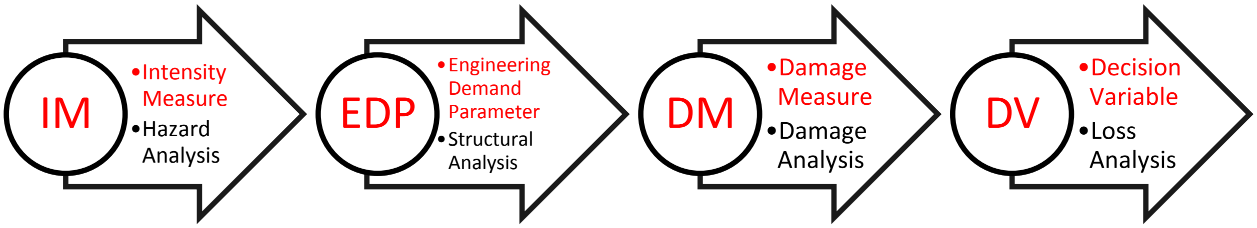


Figure 6. PEER PBEE methodology process

Because the ATC-58 project is the most up-to-date seismic design method and takes into consideration previous Seismic PBD guidelines as mentioned above, the ATC-58 methodology was reviewed to obtain better insight to seismic design. The basis of the ATC-58 methodology is derived from the PEER PBEE framework. Only the pre-release versions for the guide reports are currently available, which was completed in 2012 and the final reports are expected to be released soon. The ATC-58 methodology is reviewed to see if any seismic engineering results could be used as input data by a fire protection engineer to assist in design fire scenario of a post-earthquake fire scenario of an earthquake prone building (ATC-58, 2012).

3.2.1 ATC-58 Methodology

The ultimate goal of the ATC-58 methodology is to provide the probability of consequences of building response to earthquakes in terms of casualties, direct and indirect economic losses. To achieve these set of results, the general steps of the procedure can be seen in Figure 7. The following subsections summarize key concepts of each of the steps while disregarding the procedure of ‘Develop Collapse Fragility’ since building fire safety analysis would not be required for a collapsed building (ATC-58, 2012).

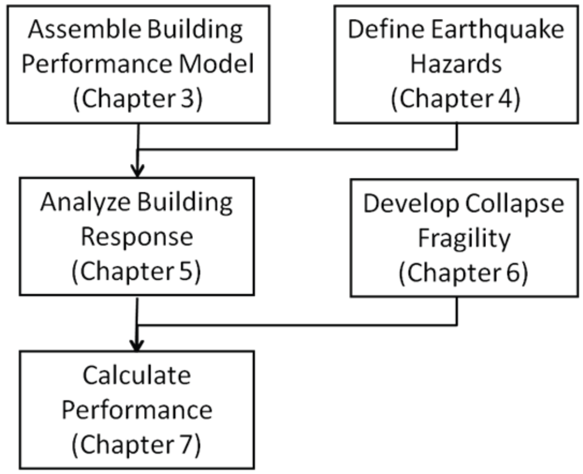


Figure 7. ATC-58 methodology for predicting earthquake building performance (ATC-58, 2012)

3.2.1.1 Assemble Building Performance Model

Building performance model is a set of data which defines the building components that are damageable when a building is subjected to seismic loads. Compiling information on building size, replacement cost, replacement time, occupancy, and type, quantity and location of structural and nonstructural components is required to create a comprehensive building performance model. Building elements that are vulnerable to damage under seismic loads are assigned a fragility within the building performance model. Building elements that are not vulnerable to damage under seismic loads are excluded from the building performance model (ATC-58, 2012).

Fragilities describe and provide the probabilities of damage modes or states that could occur to building structural or nonstructural systems under seismic load or intensity with the demand parameters typically expressed in the form of story drift or floor acceleration at the level of the component location. Fragility function, “a mathematical relationship that defines the probability of incurring a damage state conditioned on the value of a single demand parameter,” are derived by analyzing damage data which may be empirical, analytical or from expert opinion. However, because there are currently a lack of research and test data, most of the ATC-58 fragilities were developed based on judgment and expert opinion (ATC-58, 2012).

There are over 700 fragilities developed in the ATC-58 and they are organized into fragility groups and further categorized into performance groups. “Fragility groups are sets of similar components that have the same potential damage characteristics in terms of vulnerability and consequences. Performance groups are subsets of a fragility group that will experience the same earthquake demands in response to earthquake shaking” (ATC-58, 2012).

A fragility group can consist of either individual components (such as lighting fixtures) or assemblies of components (such as fixed partitions with metal studs and gypsum wall boards). All individual or assemblies of components in a fragility group must encompass similar construction type and technique, potential modes of damage, susceptibility to such damage modes, potential consequences resulting from the damage. The performance group is further classified into fragility group members organizing group members that are subject to the same earthquake demands such as acceleration, velocity and drift (ATC-58, 2012).

Along with the fragility, each component carries a consequence curve where the component quantity is expressed as a consequence measure (i.e, repair cost, repair days and etc.). Because the performance level of a building component is ultimately represented in repair cost and building downtime, the damage states in the component fragility are categorized by the various damage levels in which a different repair technology is required which would alter the repair cost. The damage states are assigned to each fragility group and characterize different levels of damage that can occur. There are three types of relationships expressed by the damage states. When damage states occur in a sequential order, meaning one state must occur before another is possible, it is termed sequential relationship. When the occurrence of one damage state prevents the occurrence of other damage states, it is termed mutually exclusive relationship. When damage states occur independently of other damage states in a simultaneous manner, it is termed simultaneous relationship. Figure 8 shows an example of a sequential fragility curve associated with 3 damage states (ATC-58, 2012).

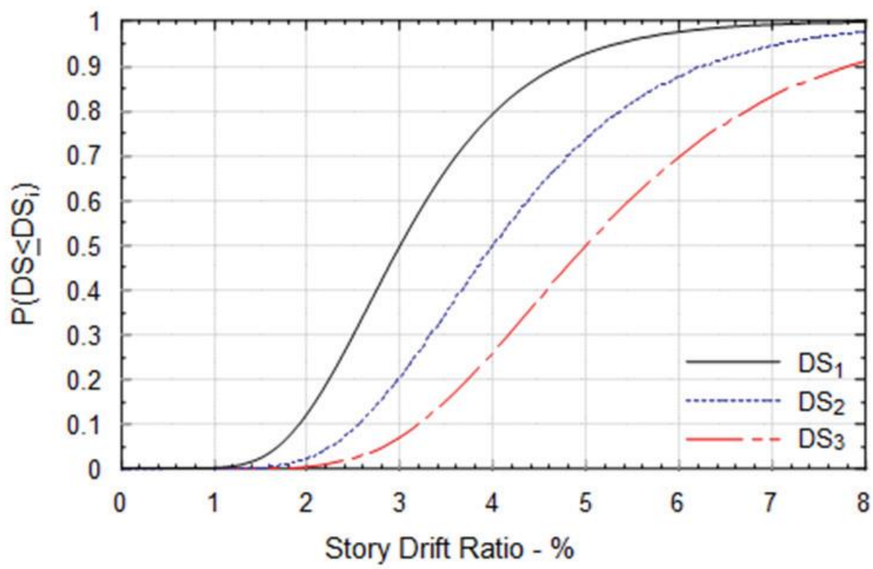


Figure 8. Example of a fragility curve (ATC-58, 2012)

Based on Figure 8, the following probabilities can be inferred;

- When the drift ratio is 3%, the probability of damage occurring is 50% (DS1) since damage state 1 must occur before any other damages can occur
- When the drift ratio is 3% the probability of damage state 1 occurring is 30% (50%-20%)
- When the drift ratio is 3% the probability of damage state 2 occurring is 12% (20%-8%)

- When the drift ratio is 3% the probability of damage state 3 occurring is 8%
- When the drift ratio is 3%, the probability of absolutely no-damage occurring is 50%

ATC-58 has developed over 700 fragility specifications for structural and nonstructural components. Although test data and real post-earthquake observations are favored to be used in creating the fragilities, where such data was limited, a group of expert's knowledge and experience was used instead. All of the ATC-58 damage, fragility, and consequence data related to the fragility groups are incorporated and available in an electronic database.

For each damage state presented in fragility definitions, a consequence function is provided. For each consequence function, the repair descriptions are provided which are used to determine the associated repair cost and time. All the necessary construction activities required to reinstate the damaged components to the pre-earthquake state are included in the repair cost. A repair cost vs. quantity function and a repair time vs. quantity function are provided to calculate the total repair cost and time of a certain fragility component respectively.

3.2.1.2 **Define Earthquake Hazards**

The intensity level of the ground shaking greatly affects the building damage level. Earthquake intensities are selected based on the building site location and the probability that the site will experience the intensity. The design earthquake selection can be based on various approaches which look at the specific acceleration response spectrum or specific earthquake scenario from the past or all possible earthquakes over a period of time specifically referred to as intensity-based, scenario-based and time-based respectively. Although there are other earthquake hazards besides ground shaking such as landslide and ground fault rupture, the current methodology does not address these issues (ATC-58, 2012).

3.2.1.3 **Analyze Building Response**

Structural analysis is performed using the selected earthquake motions to determine the building's response from the ground shake. There are several ways to assess the building response using the design earthquakes selected. The effects of the earthquake on a building are simulated using modeling tools. The response is usually quantified in building component response quantities or demands that can be associated with damage to building components. These response values usually are expressed as peak inter-story drift ratios (PIDR) and peak ground accelerations (PFA). IDR and PFA are commonly used earthquake demand parameters, where IDR is defined as the relative story displacement divided by the story height and PFA is defined as the maximum absolute floor acceleration (ATC-58, 2012).

3.2.1.4 **Calculate Performance**

To calculate the performance of the building in response of an earthquake, often times expressed as the probable damage and the consequences that follow as a result of the building's response to the ground motion, using the ATC-58 methodology, Performance Assessment Calculation Tool

(PACT) software is used, which is shown in Figure 9. PACT is an open-source engineer friendly software available at the ATC website (https://www.atcouncil.org/Projects/atc-58-project.html). PACT is an application of the PEER PBEE methodology and is intended to provide the probability of death, dollars and downtime of an earthquake damaged building.

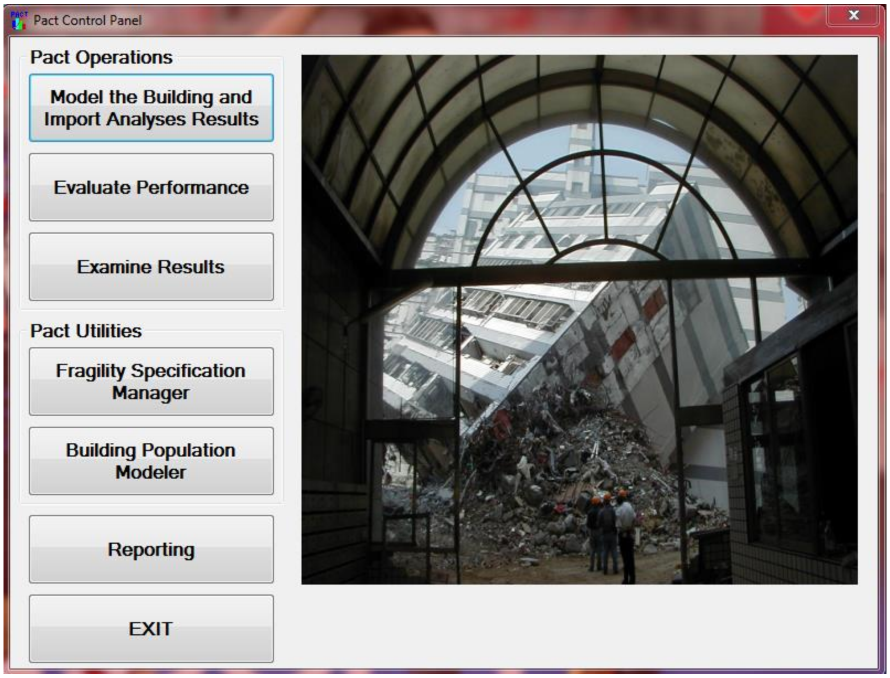


Figure 9. PACT software used to calculate performance

All of the building system and component information gathered for the Building Performance Model (see Section 3.2.1.1), are input values that must be entered into PACT. There are several tabs in the software interface where all the appropriate information can be entered in. This procedure starts by establishing the basic building information such as the number of stories, building size, number of occupants and etc. To accurately determine the physical damage conditions, both the structural and nonstructural components susceptible earthquake damage are identified. Based on the damage mode, method of installation and consequences of damage, these structural and nonstructural components need to be assigned a fragility group. There are two tabs in PACT in which this information needs to be provided with the first tab requiring the user to select the appropriate fragility groups for all of the identified damageable components on each floor of the building as shown in Figure 10, and the second tab requiring the user to enter in the quantity of the components at each floor level.

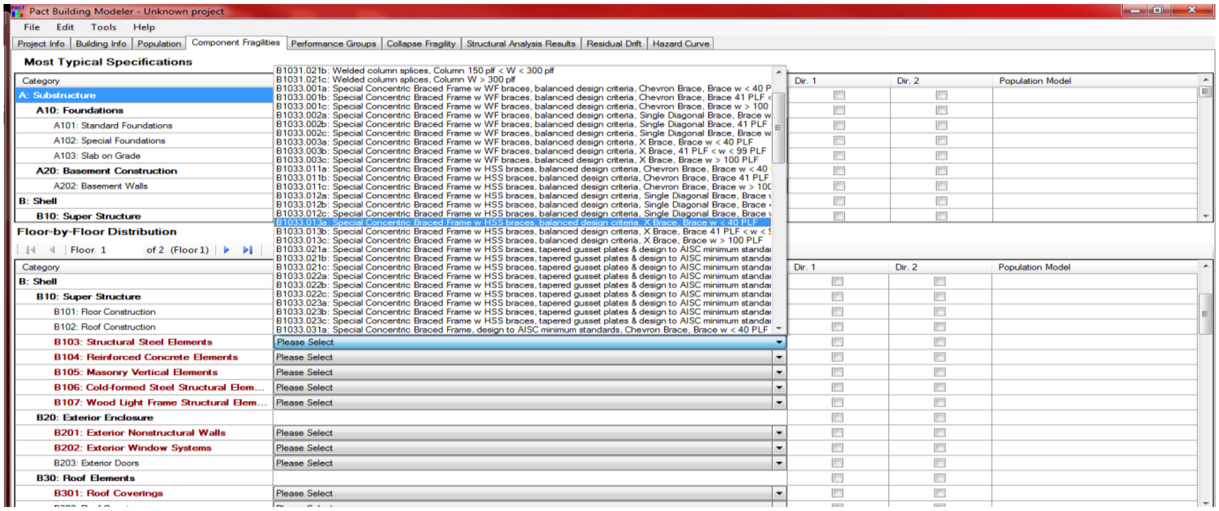


Figure 10. Identifying fragilities for damageable building components

After all of the building information has been provided and damageable building components have been assigned appropriate fragility groups, the structural response values that were obtained during the building response analysis stage (see Section 3.2.1.3) need to be entered into the "Structural Analysis Results" tab as shown in Figure 11. As structural analysis modeling may have been performed several times using different earthquake motions, multiple structural response values can be provided.

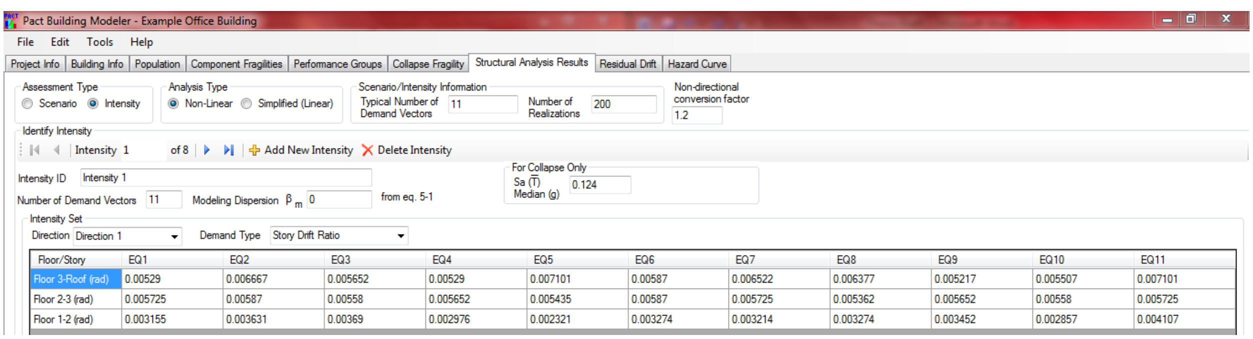


Figure 11. PACT "Structural Analysis Result" tab

All the input data provided into PACT is used to perform a Monte Carlo simulation to check the variability of the building performance outcomes for a specific ground motion intensity. The building demand parameters along with the fragility and consequence functions are used to provide building repair cost and casualties. Each simulation providing possible earthquake demands from the demand distribution, damage, and performance consequences is called a realization. The total number of simulations to be executed during the PACT analysis can be adjusted by the user. During each simulation, for a specific demand parameter value, a random number generator generates a number in the range of 1 to 100. This number, which represents a percentile, is used to define a damage state from the fragility curve for each component. Based on the selected damage state by the random number, the repair cost and time is calculated using the consequence functions (ATC-58, 2012). The ATC-58 methodology process for calculating performance using PACT is shown in Figure 12.

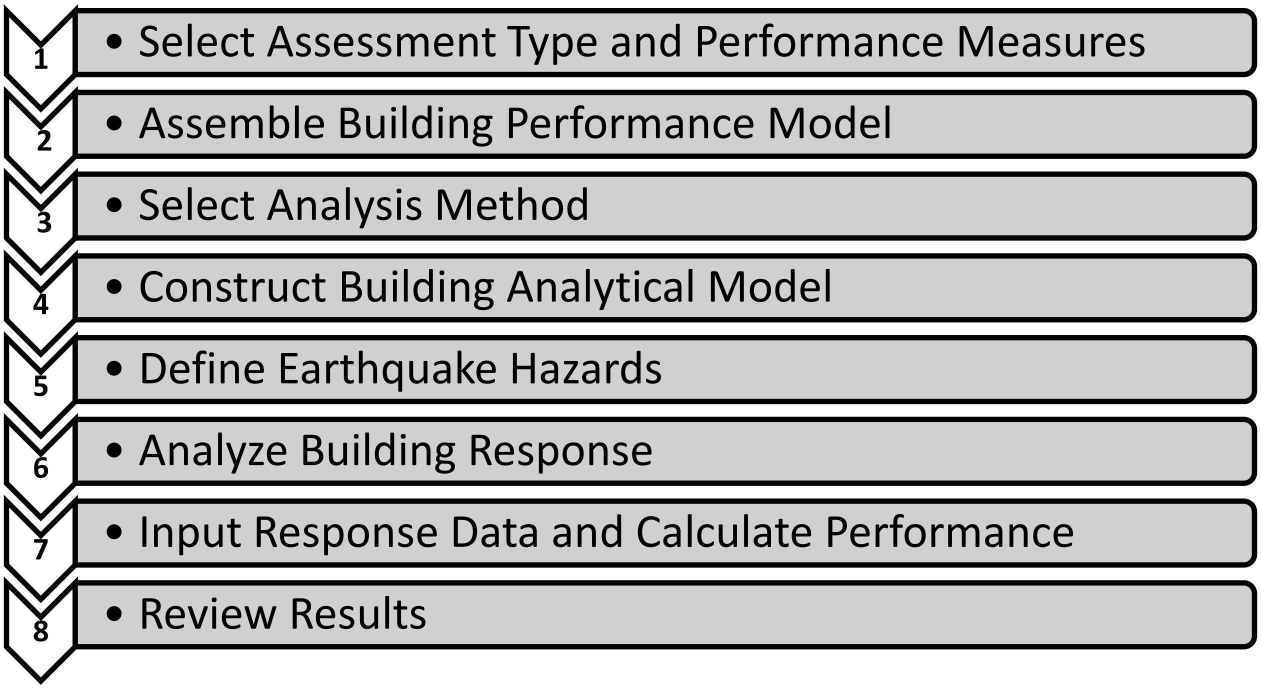


Figure 12. ATC-58 performance assessment process (ATC-58, 2012)

4 Identifying the Commonalities and Differences between Fire and Seismic Engineering

Fires and earthquakes are common in that they are both low-probability hazardous events with high consequences. Fire and seismic engineers both work with the aim of mitigating the unwanted effects of a fire or an earthquake respectively in buildings and both engineering communities have identified PB approach as a means to better understand building performance in such events. Currently, PBD method exists for both fire and seismic engineering. However, despite the fact that often times post-earthquake fires could be more hazardous than the earthquake itself, there is yet no PBD approach dealing with post-earthquake fire conditions. The BNCS project validated that building conditions could be subject to severe damage and changes under seismic conditions.

For example, a FPE would not consider building conditions where stairs are missing and windows are broken under normal fire conditions, which may be regular occurrences for a post-earthquake damaged building. Unfortunately, no current guidelines provide such specific building damage conditions for FPEs to develop accurate delineations of post-earthquake building design fire scenarios. The details and concepts of the PBEE and PBFPD methodologies are introduced in Chapter 3. PBEE is explored in detail to investigate if and how seismic engineers predict damages to building components when subjected to seismic loads. Although the procedures and point of focus may vary between the PBEE and PBFPD methodologies, both methodologies require quantifying the hazards, setting performance criteria and ensuring that the building design meets the performance criteria to minimize casualties, property loss and building downtime in case of fires or earthquakes. In order to assess and compare the two engineering approaches, different parameters that affect the building performance are identified for both fire and earthquake.

4.1 Direct Comparison of PBFPD and PBEE

To begin the comparison, the first step involves identifying all building stakeholders that may be involved involved during the building planning process. As an example, based on the stakeholder's title and profession, and profession, the goals and concerns are listed for a general building and a hospital floor containing ICU, containing ICU, operating rooms, patient area and mechanical and electrical room as shown in

Table 1 and Table 2 respectively.

Table 1. Example of building stakeholders, goals, and concerns for a general building

Stakeholders	Goals	General Concerns	Specific Concerns
Owner	- Occupant safety - Provide excellent medical Service - Efficient - Cost Effective - Profitable	- Provide sterile environment - Provide numerous medical services - Good building layout - Building Cost - Operational cost - Building damage - Working space - Disruptive events	- Damage to medical machines - Repair cost - Extent of damage - Downtime - Infection - Medical procedure
Architect	- Lots of lights - Aesthetics - Innovative design - Functionality		
Tenant	- Clean and spacious working space - Sterile environment - Safe environment		
Building Manager	- Maintenance of building - Functionality - Security		
Developer	- Cost effective - Profitable		
AHJ	- Compliance with codes - Safety	- Safe building design - Proper construction	
Insurance	- Property protection - Full operation after extreme event - Business continuity - Code compliance - Patient safety - Liability	- Good building maintenance - Structural damage - Contents damage - NCS damage - Infection control - Survivability of critical systems	
FPE	- Minimize fire-related injuries and prevent undue loss of life - Minimize fire-related damage to building and contents - Minimize loss of operation and business	- Limit fire and smoke spread - Prohibit flashover - Provide adequate time for evacuation of occupants	- Thermal damage to equipment and building contents - Tenability criteria - Structural integrity - Compartmentation

	due to fire - Limit environmental impact of fire		
Seismic Engineer	- Minimize earthquake-related injuries and prevent undue loss of life - Minimize earthquake-related damage to building and contents - Minimize loss of operation and business due to earthquake especially in critical facilities		- Physical damage to equipment and building contents - Building functionality - Building damage collapse - Structural Integrity - Compartmentation

Table 2. Example of building stakeholders, goals, and concerns for a hospital floor containing ICU, operating rooms, patient area and mechanical and electrical room

Stakeholders	Goals	Objectives	Concerns
Stakeholders	- Sterile environment - Working space - Maintenance - Medical services - Security - Spacious - Cost Effective - Efficient - Safe from disasters	- Sanitary - Equipment damage - Building damage - Intruding of electrical and mechanical rooms - Disruptive events - Quality and quantity of medical services provided - Building cost - Operational cost - Floor layout - Noise level	- Equipment damage - Building damage - Downtime - Repair cost - Spread of disease - Loss of medical records - Failure to mechanical or electrical rooms - Inoperable conditions
FPE	- Life safety - Business continuity - Property damage - Building fully operational	- Ignition sources - Limit fire and smoke spread - Limit property damage - Limit structural damage - Safe evacuation of occupants	- Storage of flammable liquids - Frequent maintenance of electrical and mechanical rooms - Mental and physical ability of patients for evacuation - Untenable conditions in the

			ICU and operating rooms - Compartmentation especially to the operating / ICU / electrical / mechanical rooms - Thermal damage to equipment - Fire-related damage to electrical or mechanical room - Evacuation plan and strategy - Structural integrity
Seismic Engineers	- Life safety - Business continuity - Property damage - Fully Operational	- Limit property damage - Limit structural damage	- Physical damage to equipment - Structural integrity - Building performance - Building collapse - Compartmentation - Damage to water, gas, electricity supply pipes - Displacement of contents

As shown in the

Table 1 and Table 2, both seismic and fire protection engineers work towards similar goals and objectives to design a building that will ensure the life safety of the occupants and limit structural and property damage. The goals and objectives of the seismic and fire protection designs are affected by the building and occupant characteristics for both disciplines. What inevitably links the seismic and fire protection engineers is an earthquake hitting a building situated on an earthquake zone, although their major concerns lie at different phases of an earthquake; Seismic engineers perform design analysis based on the potential earthquake hazards while fire protection engineers perform design analysis based on the potential post-earthquake fire hazards.

It is common that regardless of the quality of the design and construction, various buildings possess different seismic risks. The major factors that have a direct relationship to the seismic risks are the intensity of the earthquake, building characteristics and occupancy. Building characteristics such as the location, occupancy (usage), facilities and site conditions can be the deciding factors for specific design goals and objectives. If a building is located in an area where the probability of an earthquake occurring is minute or negligible, then there may be no requirements for seismic design as seismic risks are minor and a basic structural design may suffice. On the contrary, critically important buildings such as a nuclear plant located near a fault where earthquakes are more frequent and more strongly impacted, pose greater seismic risks.

Just like the nuclear plant mentioned as an example, occupancy characteristics determine the occupant load, building usage and contents of a structure. These characteristics help identify further risks and establish the acceptable risk levels and the building performance levels. A public facility or a high-rise office building where the occupant load is large would probably require higher performance levels than a building that is not subject to frequent human occupancy. There are buildings such as hospitals which require fully continuous operation following an earthquake. Based on the seismic risks, different types of construction and materials may be implemented to negate the risks and achieve an acceptable level of performance as different materials or configurations will respond in different manners when exposed to earthquakes.

The major factors that affect the building fire risks are the size of the fire, building characteristics and occupancy characteristics. Based on the building usage fire risk levels differ. A residential house does not pose the same fire risk level as an industrial storage building where flammable liquids might be stored. Also, fire risk is increased for structures that are constructed of combustible materials such as timber.

Not only are the building characteristics important for identifying fire risks, the occupancy characteristics are also important in determining how the fire risks may affect the safe evacuation of occupants for establishing design life safety goals. Different occupancies possess occupants with varying physical and mental abilities which will affect the evacuation process during a fire event.

The major factors and aspects which affect the building design for the seismic and fire protection engineers are mapped in Figure 13. This diagram identifies the key factors which influence the building performance in separate events of an earthquake and a fire. The blue text on the left side of the building indicates the major factors affecting the building performance during a fire, which are linked with boxes that breakdown the major factors into smaller aspects. The same factors are laid out for seismic design on the right of the building in brown text.

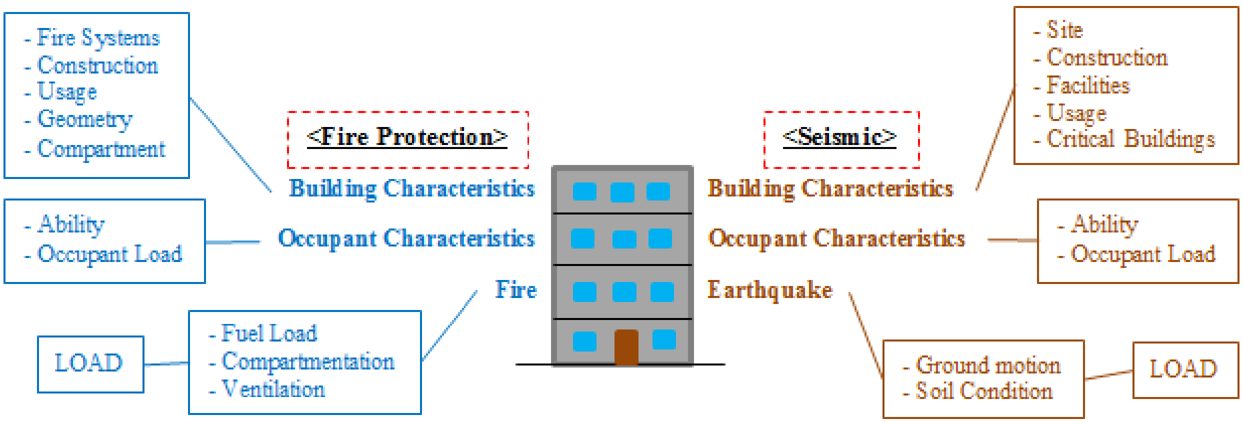


Figure 13. Building features which can affect the design

As the factors attributing to the building performance levels are identified, which can also be seen as risks, the appropriate building performance levels are selected along with the design objectives and goals to make sure the risks are mitigated. The performance of many of the risk-inducing factors mentioned previously often times are interconnected with the process of setting design objectives, and play crucial roles in the performance-levels of the building during both earthquake and fire events. The main goals of a seismic engineer are to limit structural damage, property damage and ensure life safety of the occupants when a building is hit by an earthquake. The main goals of a fire protection engineer are to make sure occupants are safely evacuated out of the building or to a safe place, to limit the structural and property damage, and to contain and limit fire spread during building fires.

The seismic building performance objectives may vary from building to building and may be categorized into levels such as fully operational, minor damage, inoperable or collapse. This is dependent on the type of construction and materials used and location of the building. To limit the damage to contents and nonstructural components may be the biggest factors for achieving the objective of limiting the overall building property damage. The life safety of occupants may be dependent on how flawlessly the building has been constructed and the installation of building systems in accordance with the design. All of these objectives are set based on the idea that a certain magnitude earthquake can hit the building during the building’s entire lifecycle. As a result, the magnitude of the earthquake could be deemed as the most influential deciding factor for all of the seismic engineering design objectives.

For fire protection objectives, the safe evacuation of occupants during a building fire is highly dependent on the state of the egress components and the number of occupants inside the building during a fire. Structural and property damage could be kept at a minimal level if the fire is suppressed or contained by active or passive fire systems respectively and by providing compartmentation to limit the fire spread. All of these objectives are based on the idea of a fire occurring in the building and as a result, the size of the fire can be identified as the most influential factor which could affect the fire protection objectives.

The primary design objectives for seismic and fire protection engineers are mapped out in Figure 14. This diagram shows what the key deciding factors are when FPEs and SEs conduct building design and analysis. The green text on the left identifies some of the primary fire protection engineering concerns for a building design and each objective is linked to a box that contains factors that affect the objective. The same concepts regarding the seismic engineering design are shown on the right in red text.

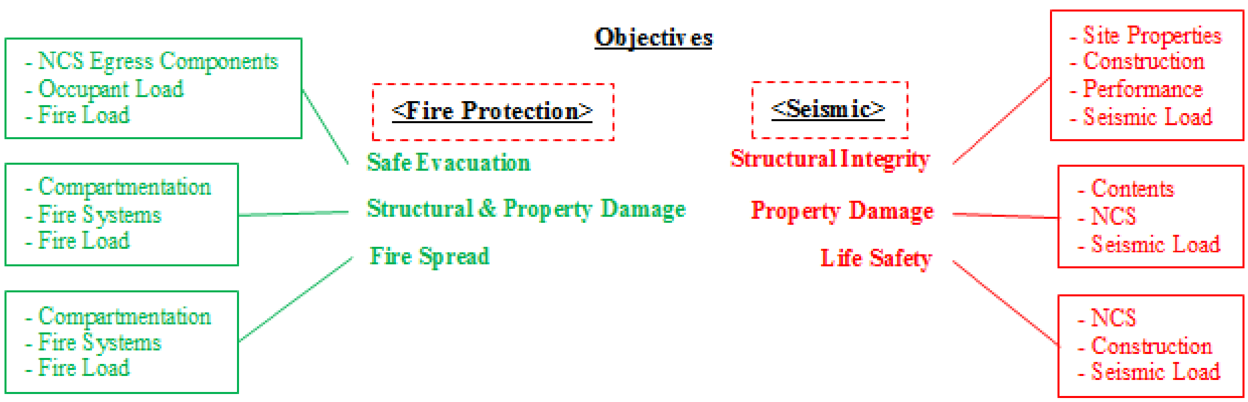


Figure 14. PBFPD and PBEE objectives

4.2 Relationship between Earthquake and Fire Hazards

All the risks identified and design objectives established help better prepare for possible future events of disasters (i.e, earthquakes and fires). Earthquakes and fires in buildings are definitely not a common, everyday event. Despite the low probability of such events occurring, post-earthquake fires are very common and often times cause more damage than the earthquake itself. Post-earthquake fire is a challenging aspect for fire protection engineers as an earthquake provides a new complexity in which the building may be in an unexpected damaged state.

A typical building performance during an earthquake is shown Figure 15. As both the displacement and spectral acceleration increases, which could both be building response measures during earthquakes, it can be seen that the performance level of a building decreases. The increase in the intensity of the earthquake also has a direct influence on the building performance level. It can be seen that the building goes from no damage to collapse level as the building displacement and acceleration increases. The building damage level constantly increases until a point of collapse is reached.

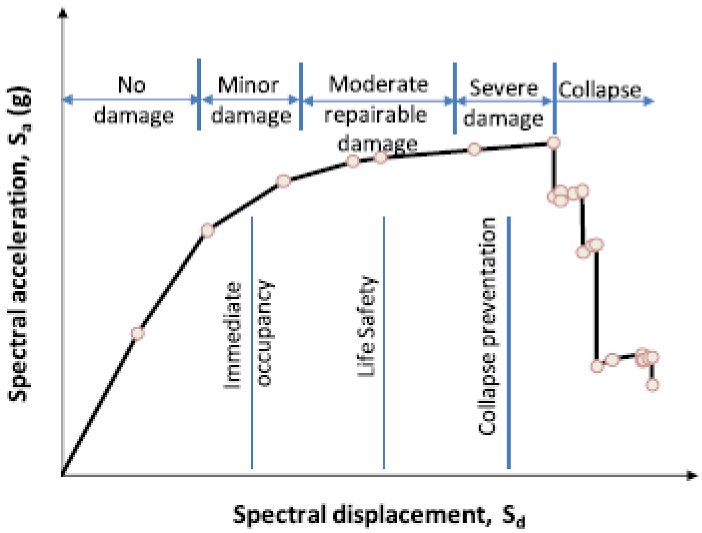


Figure 15. Building performance with regards to earthquake response

With the increase in damage level of a building, compartmentation will be greatly challenged. Nonstructural systems such as glazing, ceiling, walls, partitions and doors will also experience damage in the forms of cracking or openings, which will also be more severely damaged as the intensity of the earthquake is increased. Damage to compartmentation is a great risk for building fire protection. Loss of compartmentation means potential for fire spread and through the newly created openings and gaps, and additional ventilation is provided to provide additional oxygen to the fire resulting in faster combustion rates and more intense burning fire.

Building contents that may be subject to damage as a result of an earthquake are egress systems. Stairs or elevators could be damaged providing an impediment or failure of evacuation and firefighting operations. Doors could be jammed or dysfunctional as door frames could be distorted and locks could be damaged. Contents could be dislodged and end up being in egress paths creating an obstruction for the evacuating occupants. All such conditions will add to the fire risk and in particular present the greatest risk to the life safety of the occupants.

NFPA 921 defines fire as a rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities. For a fire to start, heating of fuel is required. As the fuel gets heated up, flaming combustion occurs setting an ignition in which the fire starts to grow. Fire spread is relatively slow in the initial stages of development as it spreads onto combustible surfaces. The fire spread speeds up with the growth in fire due to radiative heat transfer that occurs from the flames to other fuel items. The growth in the size of fire varies on the fuel load and quantity, geometry of compartment, location of fire, ventilation and the environment. Once the upper layer temperatures exceed 600C, flashover, also known as 'full-room involvement', occurs, which is considered to be the most dangerous stage of fire development. Unless fire is suppressed either manually or automatically by active fire protection systems, it will keep burning until all the fuel has been consumed. A generalized fire development curve with finite fuel load is shown in Figure 16. It is in the fully developed stage of the fire where the greatest fire risks are presented.

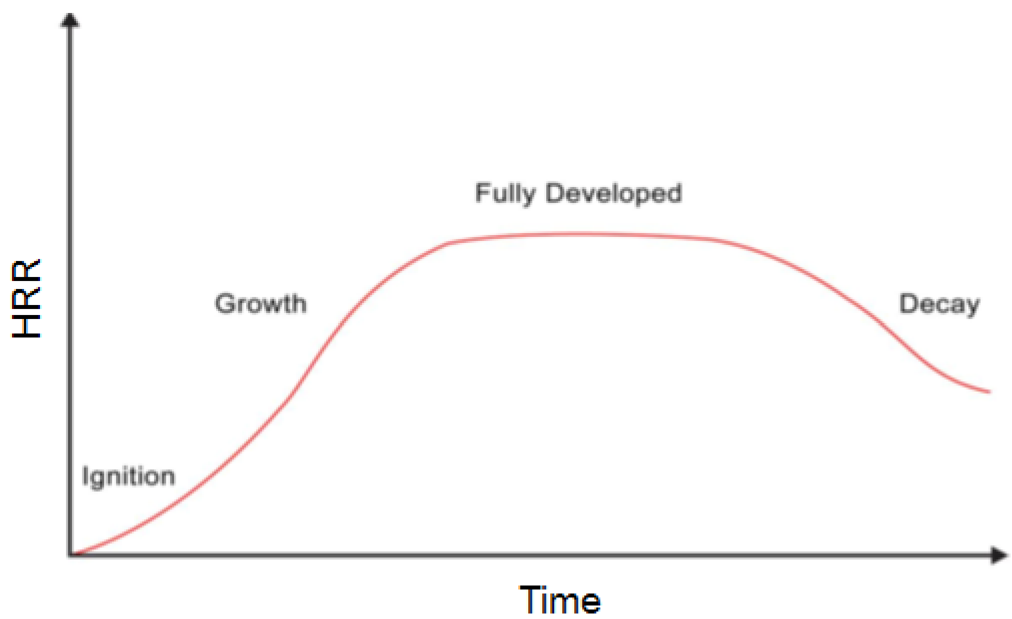


Figure 16. Generalized fire curve

The generalized fire curve shows that over time, the heat release rate (HRR) increases until the fire is fully developed, and as all available fuel is consumed, the fire decays. However, the increase in HRR is not only dependent on fuel. The ventilation, compartment geometry and type and configuration of the fuel load all affect the fire size and duration. If uncontrolled, the fire can spread to other compartments. Earthquake damaged buildings could leave compartment barriers damaged, fire protection systems damaged and combustible fuel items displaced. A fire occurring in a compartment with open windows will burn more intensely than a fire occurring in a compartment that is fully compartmentalized and lacking any supply of air. The probability of such consequences as well as the severity of the damage level occurring to building increases as the shaking intensity of the building is increased.

If one them combines the concepts presented in Figure 15 and Figure 16, one could construct a graph that qualitatively illustrates the relative relationship between increase in earthquake damage and increase in fire risks (Figure 17).

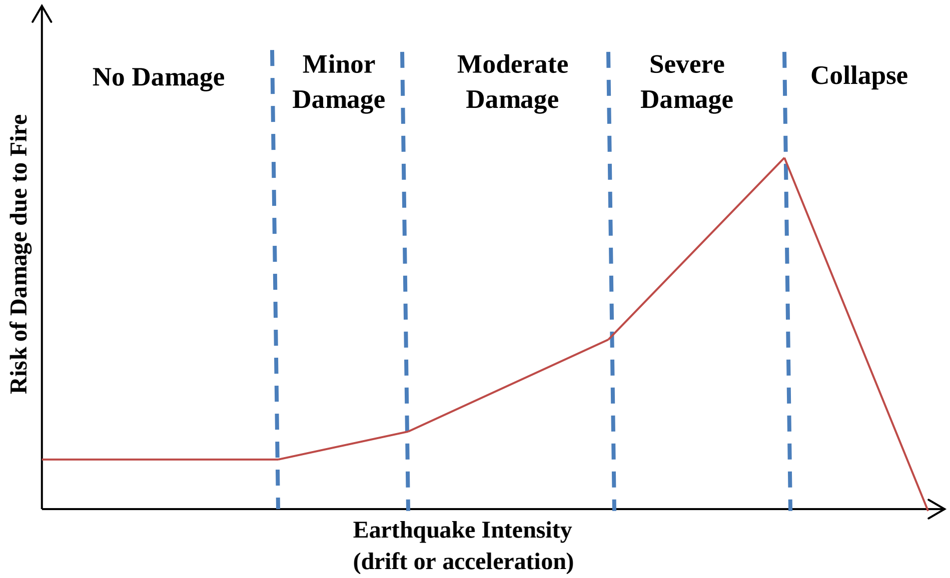


Figure 17. Risk of damage due to fire in relationship to the earthquake intensity

It can be seen that the risk of damage due to fire has a direct relationship with the earthquake intensity. With the possibility of higher intensity earthquakes providing more severe damage to a building, this could directly translate into greater fire risks. For example, a normal building would have a complete set of intact compartment barriers which would function as intended in case of a building compartment fire. However, if a building is severely damaged with window breakage, dislodged ceiling tiles, and gaps in joint areas, as a result of an intense earthquake, this would mean that the compartment barriers have been breached and would not function as intended in case of a building compartment fire. This would result in smoke and flame spread beyond the compartment of fire origin, limiting occupant evacuation and firefighter access. Figure 17 clearly delineates this relationship of fire risk having a direct relationship to the earthquake intensity and building damage levels. Understanding this connection helps form the basis of a conceptual model that can better link earthquake and fire engineering.

5 The Conceptual Framework for Post-Earthquake Fire Condition Building Design

Fire engineers need to know the building condition and state to correctly analyze fire risks and set up accurate design fire scenarios. Such knowledge of building conditions in post-earthquake situations are not simple to estimate by a fire engineer alone and thus requires specific information provided by a seismic engineer. However, such interaction between the two engineering communities is currently lacking and the engineering practices are being conducted separately. The integration of these two engineering disciplines is intended to help FPEs conduct analyses of buildings prone to earthquakes more accurately. Establishing this framework helps identify what type of information is required by the FPEs from seismic engineers and during which stage of the PBFPD process such information could be useful.

Previously, Sekizawa et al. (2003) developed a framework to deal with such earthquake building damage and fire risk in post-earthquake building fire conditions. While this approach is a good starting point, the framework focuses mainly on estimating damage to active fire protection systems (mainly sprinkler systems). While this is one approach that could be used by FPEs, it is not implemented in this thesis, as a conceptual framework that can estimate building damage to various building components to provide a more holistic approach is the main objective.

As a result, the conceptual framework is developed based on factors that can affect the overall building performance levels and the building design objectives during fire and earthquake as shown in Figure 13 and Figure 14 respectively. Also, the damages to the building specimen observed and identified following the seismic tests during the BNCS project are incorporated into this conceptual framework. The conceptual framework diagram is shown in Figure 18 with the main aim to show where the direct and indirect relationships lie between earthquakes and fires that occur in a building. The diagram shows a building and given its characteristics, identifies what the possible consequences could be when an event of either fire or earthquake occurs. The relationship between the two events is mapped out to show what type of post-earthquake building fire conditions could be expected.

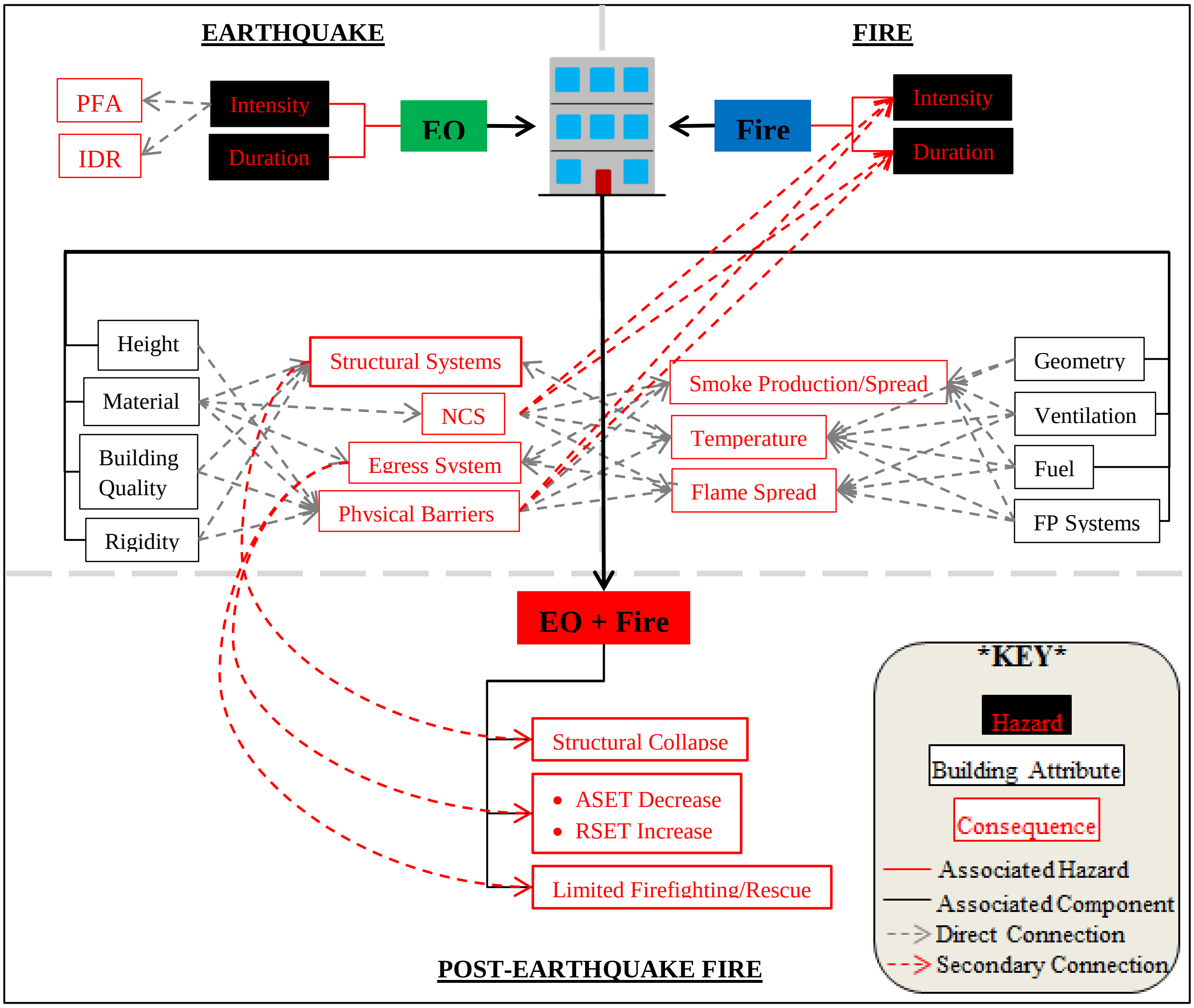


Figure 18. Conceptual framework

The diagram is separated into three areas with the upper left, upper right and bottom half sections dedicated to earthquake, fire and post-earthquake fire respectively as separate events. The model is intended to show what the hazards, the consequences and their effecting building attributes are for the separate events of an earthquake and a fire and also how these consequences combine to affect the building fire safety performance during a post-earthquake fire scenario.

The major hazards that can severely affect the building performance for both events are identified with red text in black colored boxes and some of the building attributes that can also influence the outcomes are identified with black text in black boxes. For both an earthquake and a fire, the intensity and duration of the event are considered to be the key hazards. What happens as a result of the event are termed ‘consequences’ and are identified with red text in red boxes and the building factors that may have a direct impact on certain consequences are mapped out by dotted grey arrow lines to show the connections. The red dotted arrow lines are termed as secondary connections and are mapped to show which consequences could affect a post-earthquake building fire performance and to highlight the concerns in which a fire protection engineer should consider when developing fire safety designs for earthquake prone buildings.

Because the major focus of this model is on how the earthquake building damage could ultimately influence the building fire safety performance during a post-earthquake fire, the general consequences as a result of an earthquake only show the possible damages that could occur to the building components which could possibly effect building fire conditions, while during a fire, these consequences are shown as the general phenomena that occur during a fire.

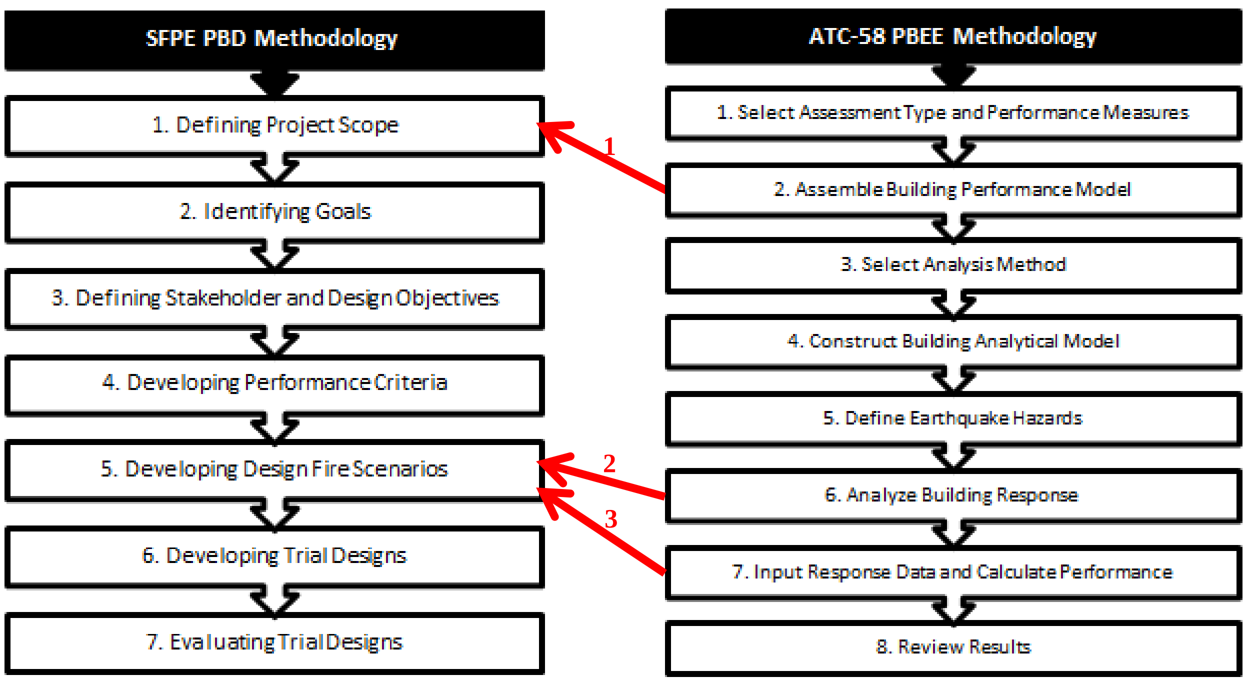
Looking at Figure 18, one can see that if a high intensity earthquake hits a very rigid building, there could be structural damage. This structural damage could be in the form of spalling of concrete leaving steel rebar exposed. A specific factor which could influence this structural member is elevated thermal condition. Now if there is a post-earthquake fire with such structural damage, the fire would provide increased temperatures where steel would lose its properties such as yield strength and elasticity, which may lead to the structural member failing to provide its intended load-bearing capacity and ultimately even lead to structural collapse of a building.

For the earthquake section of the diagram, because there are a myriad of various building components, the components are grouped into the general structural systems, building nonstructural components and systems, egress systems and physical barriers. Table 3 shows what the general consequence components should incorporate and are broken down into specific components.

Table 3. Building components classification

General Consequence Components	Specific Consequence Components
Structural Systems	Spalling
	Connections
NCS	Fire Protection Systems
	MEP
	Lighting
	Building Contents
	HVAC
Egress System	Stairs
	Elevator
	Doors
Physical Barriers	Interior Walls
	Exterior Walls
	Doors
	Glazing
	Joints

As mentioned in the previous chapter, ATC-58 methodology requires information of all of the building components that are subject to damage during earthquake motions. Such information could help FPEs identify the important building components that may affect the building fire safety performance level and set the tone for defining the project scope. When a seismic engineer performs building analysis using the selected design earthquake motion, the results and building demand parameter values obtained should be passed on to the FPEs. Also, the fragility curves associated with each building component used to calculate damage states to calculate the overall building performance during an earthquake is essential information for the FPE. A FPE could use the building demand parameter and the fragility curves to determine damage conditions of specific building components which could help in setting up design fire scenarios for post-earthquake building fires. Figure 19 shows the processes of the SFPE PBD and ATC-58 methodology and at which steps information (and what type of information) from the seismic engineer is required by the FPE.



Arrow	Type of Information Required
1	Building components
2	Building response values
3	Component Fragility curves

Figure 19. Link and information trade-off between seismic and fire engineering processes

6 Identifying Earthquake Building Damage Required by FPE

6.1 Checking Fragility Curves and Damage States Established in ATC-58

Building systems which could have an effect on the building fire performance when damaged are selected and picked out from the ATC-58 database to determine what type of damage states are being estimated and predicted by ATC-58. Most of the building components selected for this section are based on the damage observed from the BNCS project. The selected components and systems, and their damage states are tabulated in Table 4. The damage states are reviewed to check if ATC-58 data could directly be used by FPEs as parameters for post-earthquake fire scenarios. The last column in Table 4 provides commentary on the applicability of the presented damage states, and if the damage state means nothing significant in terms of building fire safety performance, possible damage states required are suggested.

Table 4. Summarization of ATC-58 building system damage states

NISTR Classification	NISTIR Name	Type of Damage State	Damage State	Comments
B1041.031a	ACI 318 OMF with weak joints and beam flexural response. Conc Col & Bm = 24” × 24”, Beam one side	Sequential	**DS1:** Beams or joints exhibit residual crack widths > 0.06 in. No significant spalling. No fracture or buckling of reinforcing.	DS2 and DS3 could be used to set up scenarios with exposed beam and joint reinforcement structural members as spalling of the concrete cover would leave such members exposed to direct heat.
		Sequential	**DS2:** Beams or joints exhibit residual crack widths > 0.06 in. Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing.	
		Sequential	**DS3:** Beams or joints exhibit residual crack widths > 0.06 in. Spalling of cover concrete exposes a significant length of beam longitudinal reinforcement. Crushing of core concrete may occur. Fracture or buckling of reinf. Requiring replacement may occur.	
B2023.001	Generic Storefront	Sequential	**DS1**: Gasket seal failure	DS3 could be used to set up scenarios with open windows in compartments due to glass falling out. However, it would be more helpful if quantitative information on the size of the glass falling out is provided.
		Sequential	**DS2**: Glass cracking	
		Sequential	**DS3**: Glass falls out	

C1011.001b	Wall Partition (gypsum with metal studs, partial height, fixed below, lateral braced above)	Sequential	**DS1**: Screws pop-out, minor cracking of wall board, warping or cracking of tape	DS4 or DS5 could be used to set up scenarios with openings around the partition wall joints.
		Mutually Exclusive	**DS2**: Buckling or connection failure of top braces	
		Mutually Exclusive	**DS3**: Buckling or connection failure or top braces	
		Mutually Exclusive	**DS4**: Tearing or bending of top track, tearing at corners with transverse walls	
		Mutually Exclusive	**DS5**: Tearing or bending of top track, tearing at corners with transvers walls	
C2011.001a	Prefabricated steel stair with steel treads and landings with seismic joints that accommodate drift	Sequential	**DS1**: Nonstructural damage, local steel yielding	DS3 could be used to set up scenarios with unusable stairs during evacuation.
		Sequential	**DS2**: Structural damage but live load capacity remains intact. Buckling of steel, weld cracking	
		Sequential	**DS3**: Loss of live load capacity. Connection and or weld fracture	
C3032.001a	Suspended Ceiling, SDC A, B, Area (A): A <250, Vert support only	Sequential	**DS1**: 5% of tiles dislodge and fail	DS1, DS2 and DS3 could be used to set up scenarios with openings in the ceiling system. The quantification of the ceiling tiles in percentile value will be accurate and valuable information for FPEs.
		Sequential	**DS2**: 30% of tiles dislodge and fall and t-bar grid damaged	
		Sequential	**DS3**: Total ceiling collapse	
D1014.011	Traction Elevator – Applies to most California installations 1976 or later, most western states installations 1982 or later and most other U.S installations 1998 or later	Simultaneous	**DS1**: Controller anchorage failed, and or machine anchorage failed, and or motor generator anchorage failed, and or governor anchorage failed, and or rope guard failures.	DS3 could be used to set up scenarios with elevator doors open, providing openings for possible smoke or flame spread to the elevator shaft.
		Simultaneous	**DS2**: Rail distortion, and or intermediate bracket separate and spread, and or counterweight bracket break or bend, and or car bracket break or bend, and or car guide shoes damaged, and or counterweight guide shoes damaged, and or counterweight frame distortion, and or tail sheave dislodged and/or twisted	
		Simultaneous	**DS3**: Cab stabilizers bent, or cab walls damaged, or cab doors damaged	

		Simultaneous	**DS4**: Cab ceiling damaged	
D3041.011a	HVAC Galvanized Sheet Metal Ducting less than 6 sq. ft in cross sectional area, SDC A or B	Sequential	**DS1**: Individual supports fail and duct sags – 1 failed support per 1000 feet of ducting	DS2 could be used to set up scenarios where openings are created in HVAC ductwork.
		Sequential	**DS2**: Several adjacent supports fail and sections of ducting fall 60 feet of ducting fail and fall per 1000 foot of ducting	
D3041.031a	HVAC Drops / Diffusers in suspended ceilings – No independent safety wires, SDC A or B	Sequential	**DS1**: HVAC drops or diffusers dislodges and falls	DS1 could be used to set up scenarios where openings are created in places of HVAC drops or diffusers.
D4011.021a	Fire Sprinkler Water Piping – Horizontal Mains and Branches – Old Style Victaulic – Thin Wall Steel – No bracing, SDC A or B, Piping Fragility	Sequential	**DS1**: Spraying & Dripping Leakage at joints – 0.02 leaks per 20 ft section of pipe	DS1 or DS2 could be used to set up scenarios where sprinkler systems malfunction and fail to activate due to pipe leakage.
		Sequential	**DS2**: Joints break – major leakage – 0.02 breaks per 20 ft section of pipe	
D4011.031a	Fire Sprinkler Drop Standard Threaded Steel – Dropping into unbraced lay-in tile SOFT ceiling – 6ft. long drop maximum, SDC A or B	Sequential	**DS1**: Spraying & dripping leakage at drop joints – 0.01 leaks per drop	DS1 or DS2 could be used to set up scenarios where sprinkler systems malfunction and fail to activate due to pipe leakage.
		Sequential	**DS2**: Drop joints break – major leakage – 0.01 breaks per drop	
E2022.103a	Bookcase, 3 shelves, unanchored laterally	Sequential	**DS1**: Book case falls over and contents are scattered. Likely damage to bookcase	DS1 could be used to set up scenarios where certain areas or corridors are unusable by occupants during evacuation.

To create an accurate representation of a post-earthquake damaged building, a FPE needs to know what the extent of the damage may be to specific building components that may affect the building fire safety performance. It was presented in Section 3.2.1 how seismic engineers predict damage to a specific building component when using the ATC-58 methodology. FPEs could take advantage of this method and in particular the fragilities provided in the ATC-58 database. Fragility is a description of the possible damage modes for a specific building component and an indication of what the probability of carrying such damage mode is, as a function of a building response parameter usually expressed in story drift or floor acceleration. If seismic engineers collaborate with FPEs and provide the building component damage modes, building response parameters, and the fragility curves (probability of damage mode occurring), a more accurate post-earthquake building condition can be estimated.

Obtaining probabilities of the occurrence of damage to specific building components could become handy when performing event tree analysis. Setting up the initiating event as being a post-earthquake building fire and identifying a sequence of events or mitigation measures, it will require an FPE identifying what building component may affect the performance of the mitigation measure and obtaining the appropriate data from the seismic engineers regarding the identified building component to correctly assess fire risks.

Selecting some of the building systems that may be susceptible to damage during earthquakes and which could also affect the building fire safety performance, and also taking into consideration building systems in which damages were observed during the BNCS project, event trees are developed to help create post-earthquake fire scenarios.

Often times risk analysis is conducted by obtaining the overall risk from the sum of the risks associated with individual potential scenarios of a specific type. A typical way of performing these analyses is by using event trees, which is based on binary logic and assumes either an event has or has not happened or a component has or has not failed. Event trees start with one initiating event and the resulting consequential events that may follow through a series of possible paths. Each consequential event or paths are assigned a probability value of the likelihood of the event occurrence and these values are used to calculate the probabilities of the various possible outcomes.

Two event trees for a building fire are shown in Figure 20 and Figure 21 showing the sequential events of the building fire safety systems responses and occupant evacuation procedure respectively.

The typical building fire safety systems or mitigation measures are detection, suppression and compartmentation and structural fire resistance. For the event of a post-earthquake building fire, the mitigating measures are detectors, sprinklers, compartmentation, and structural fire resistance. This event tree is intended to be used by FPEs to assess risks in post-earthquake building fire conditions and determine how the thermal environment might be affected.

During evacuation process is a post-earthquake building fire, the possible sequence of events are passing through unobstructed room, exiting through undamaged compartment door, passing through unobstructed exit access, passing through undamaged exit access door, safe evacuation from undamaged exit discharge door. This event tree is intended to be used by FPEs to perform evacuation risk analysis.

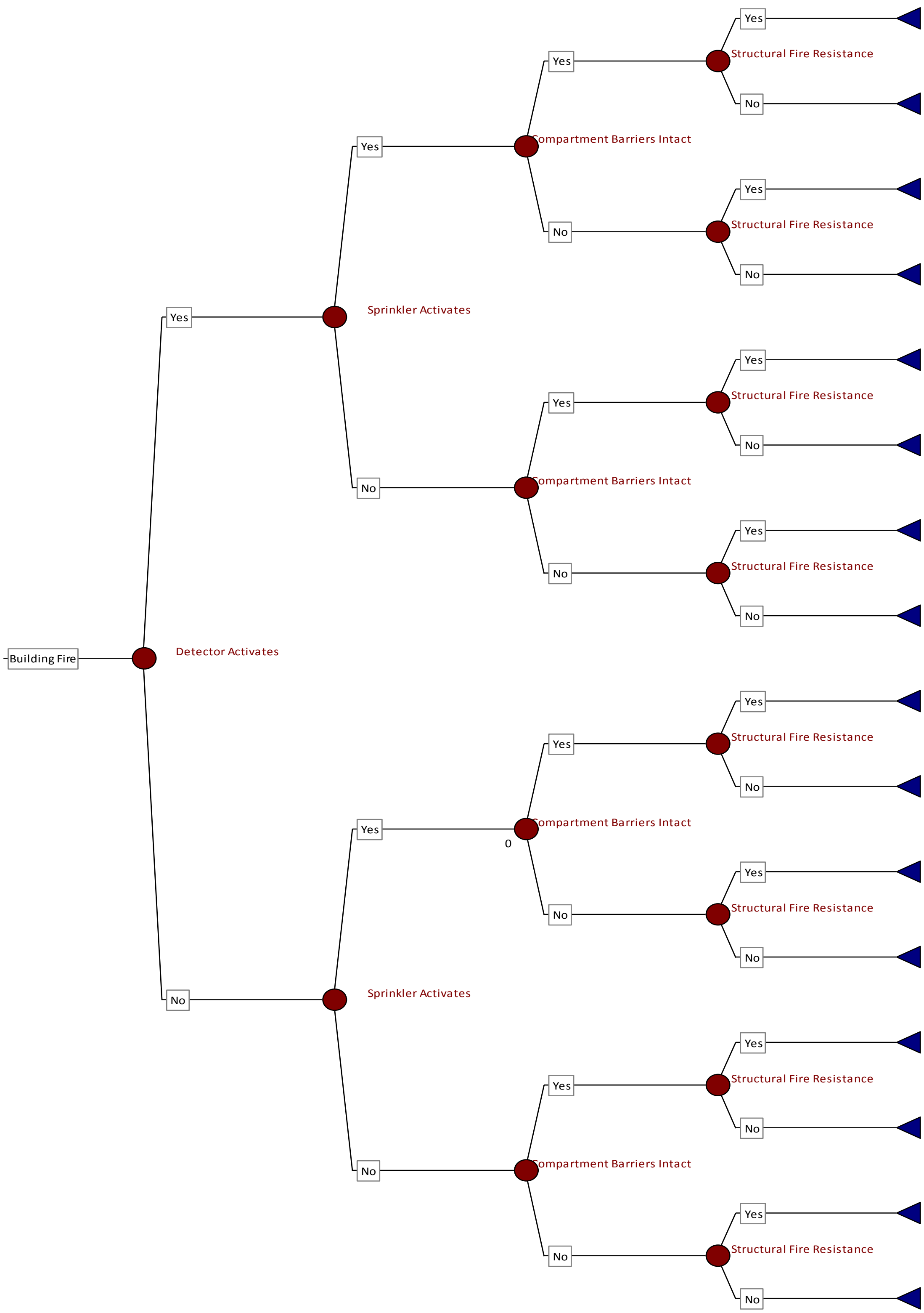


Figure 20. Building fire event tree

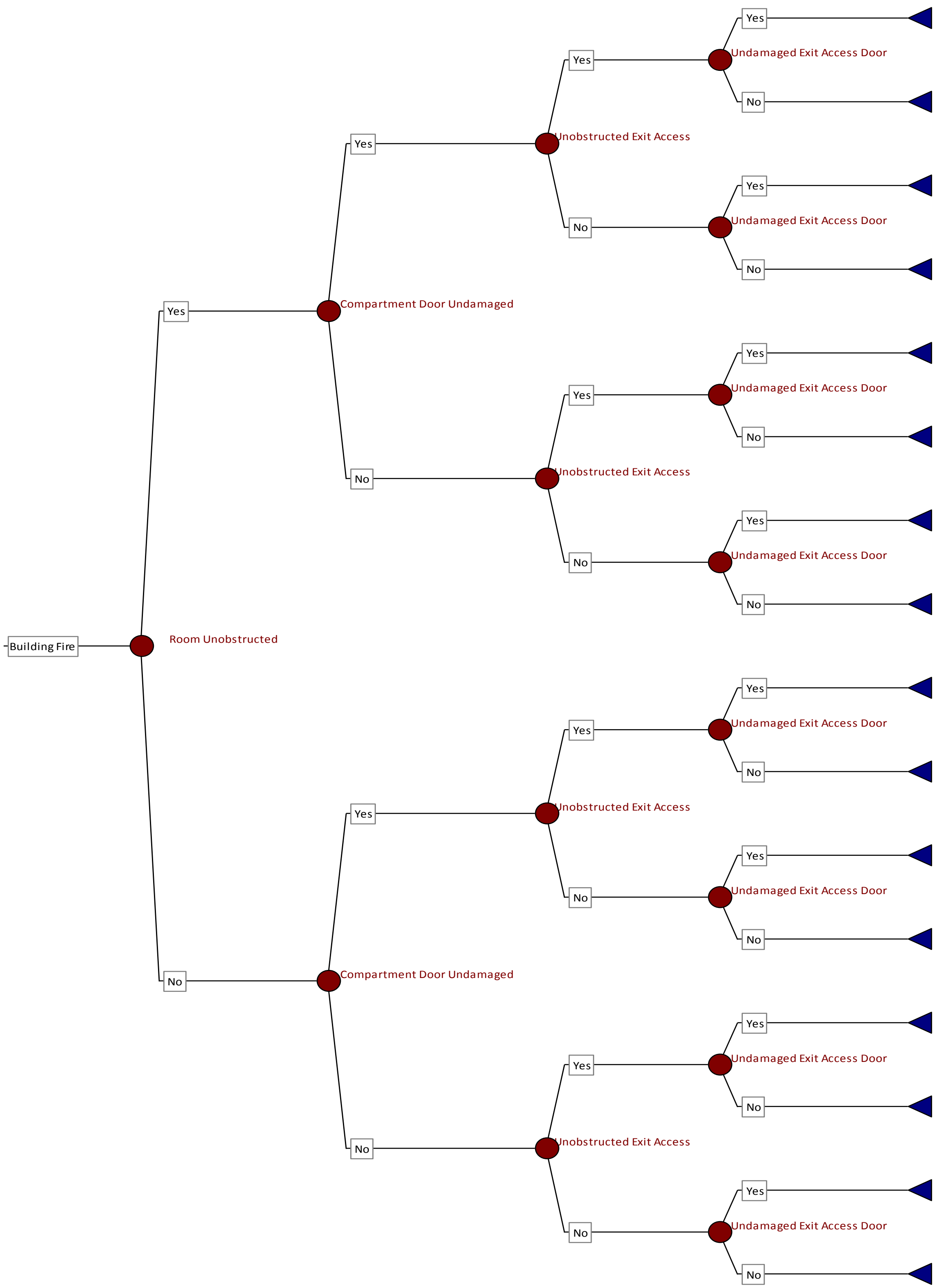


Figure 21. Building fire evacuation event tree

No probability values are included in these trees, as there is a limited data set on which probability values can be drawn upon in a consistent manner. For example, the fragility damage states for some building components in the ATC-58 are not currently developed yet and data from literature do not provide a comprehensive data on all of the building components in a holistic manner. Fault tree analysis is a technique that helps identify factors which contribute to a specific event or a problem. The fault tree is organized by the major event being at the top and the possible causes of this main event are identified at the next lower level. When each contributing factor can produce the major event alone an ‘OR’ gate is used or if all of the contributing factors must combine to cause the major event, an ‘AND’ gate is used. This procedure is followed to the next level.

From the event trees, the mitigating measure of compartment barriers could lack sufficient details to many as there are numerous building components that combine to form a comprehensive compartment barrier. To better identify how specific compartment barrier components perform under seismic loads, a fault tree analysis could be performed to better identify and investigate which of the building components may have an impact on the overall compartmentation of the fire compartment. An example of a fault tree showing compartment barrier broken down into specific components is presented in Figure 22. The selected compartment barrier components for this example are based on observations made during the BNCS project. In general, the fault trees will have probability of occurrences for each of the contributing factors. Such earthquake damage probability values can be derived from experimental results such as the BNCS project, the ATC-58 PACT database, or existing data from literature review. The fault tree factors and probability values will vary depending on the type of building components that are installed and based on the design earthquake motion.

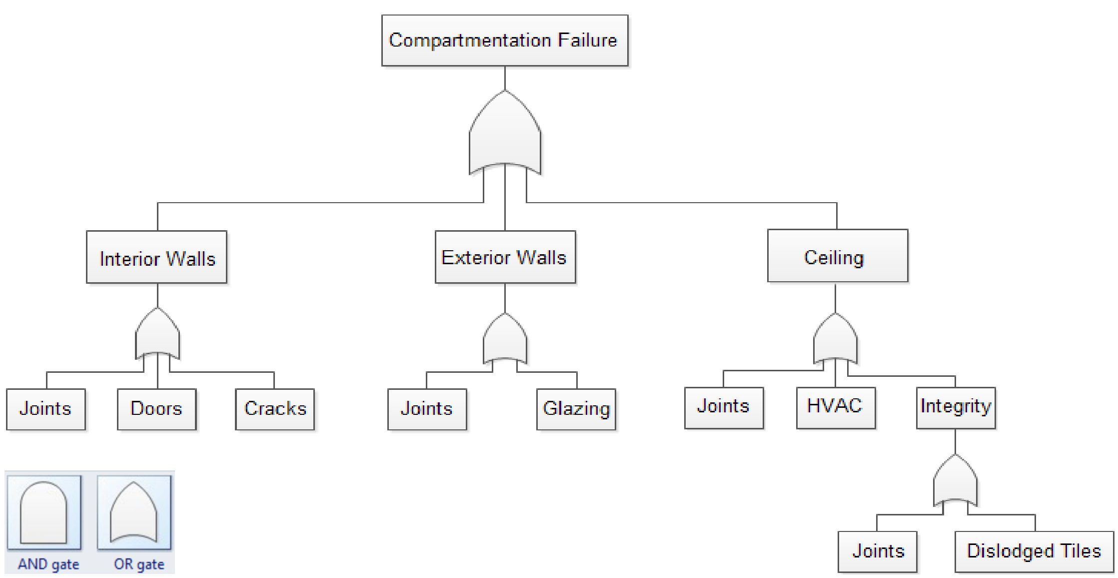


Figure 22. Representative compartment barrier fault tree analysis

The probability values that indicate the performance levels of different fire systems will differ significantly between a normal building fire versus a post-earthquake building fire as earthquakes can leave fire systems damaged and unable to perform as expected. A bar chart shows the performance probabilities of some fire systems under normal and post-earthquake building fire conditions in Figure 23.

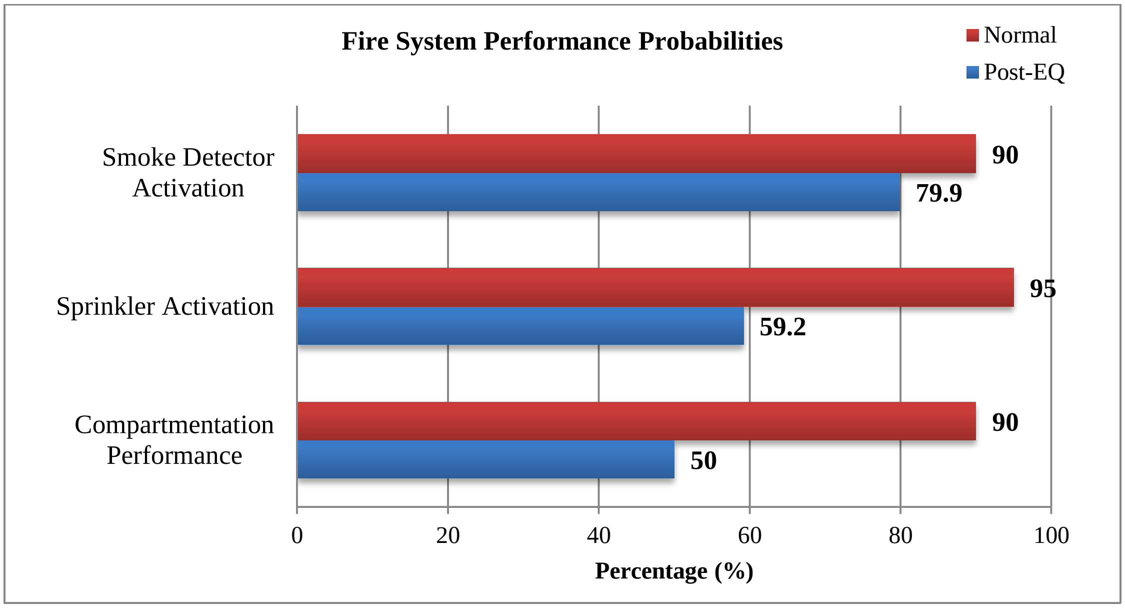


Figure 23. Probabilities of fire system performance levels (Bukowski et al 1999; Collier 2005, Sekizawa et al 2003)

For post-earthquake building fires, although it may be easy setting up and choosing mitigation options to create event trees or fault trees, at current time the most challenging task is populating these analysis tools with the appropriate probability values. Notice how just to create Figure 23, only one source (Bukowski et al, 1999) was required to obtain data on all three components for normal building fire conditions but it required two different sources (Collier, 2005; Sekizawa et al., 2003) to obtain performance probability values for just three different building components under post-earthquake fire conditions. Also, it might not be very feasible mixing data from various sources as building damage clearly varies by the magnitude of the motion and different sources might be from different earthquakes from the past with different intensities and characteristics. For such reasons, the ideal method to populate an event tree would be using data from one source that are resulting data from one seismic event to provide consistency. However, there is no such data available that a FPE can go to and find all the necessary values from one source at this point of time.

Because different earthquake intensities will result in different damage states, a common data set such as ATC-58 might be extremely useful in terms of estimating post-earthquake building conditions accurately. For example, if a FPE was conducting a building design and had identified a specific compartment on floor three of the building as having the greatest fire risk to occupants, the engineer would choose the identified compartment and select a fire scenario accordingly based on the risks assessment. However, if this building was earthquake prone, there might be greater risks presented due to an earthquake that was not considered before. Earthquakes have the potential to change the building, occupant, and fire characteristics. In order to identify these earthquake damage associated risks, a FPE needs to know what kind of building conditions would be presented if an earthquake had damaged the building to get an accurate understanding of the thermal conditions in a post-earthquake fire. If the FPE wanted to know if there would be any damage to the windows and what type of damage could be presented from an earthquake, the seismic engineer would need to inform the FPE of the building response parameter from a specific design earthquake motion and the fragility of the window. If the seismic engineer informs the FPE that the fragility of the window could be characterized as shown in Figure 24, and the building response parameter was 0.04 story drift ratio on floor 3, the FPE could interpret that the highest probability of damage mode occurring would be Damage State 2 with the probability of about 55%. Since Damage State 2 is identified as "glass falls from frame" in the fragility curve, a FPE could model a building with 55% of the windows being broken.

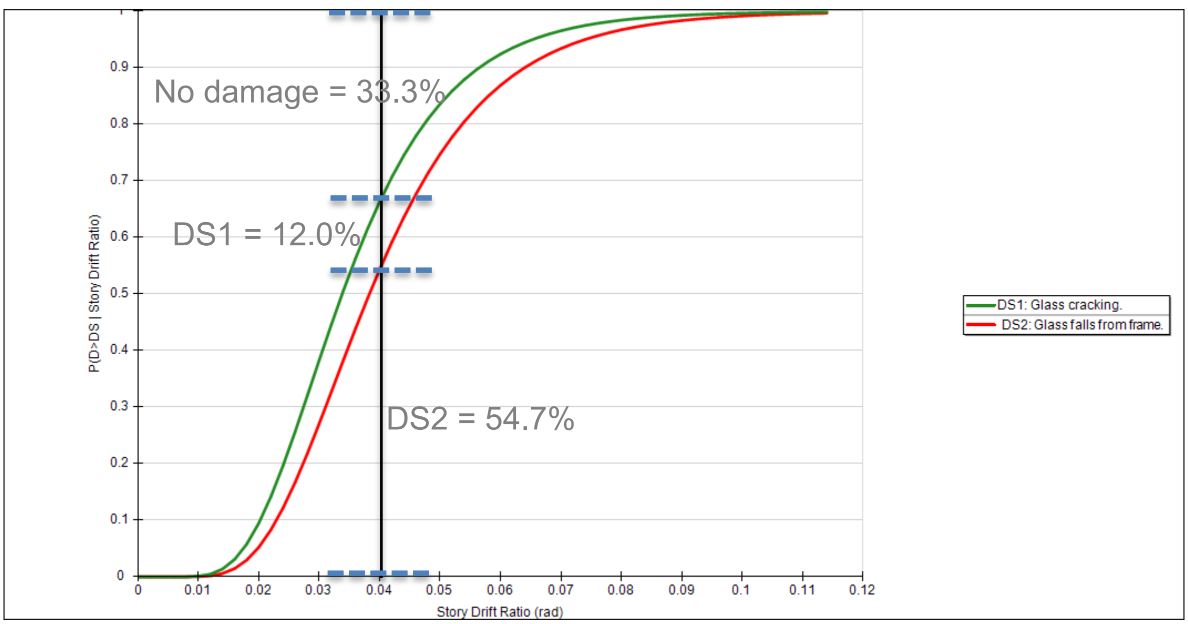


Figure 24. Fragility curve of curtain wall (B2022.001) from ATC-58 electronic database

6.2 Adequacy of Using the ATC-58 Fragilities for Post-Earthquake Building Fire Scenarios

As the commentary on Table 4 explains, not all damage states identified by the seismic engineers in the ATC-58 mean meaningful data to the FPEs as such may have no influence on the building fire safety performance at all. It must be remembered that the ATC-58 methodology provides information on economic loss, building downtime and number of casualties from a resulting earthquake on a building and these are reflected on the fragilities. Post-earthquake building fire conditions are not considered by ATC-58, so it is inevitable that not all damage state data are suitable to use directly as inputs for post-earthquake building fire conditions. The conceptual framework created could be used by the seismic engineers to better understand what type of damage states the FPEs are looking for, and how these damage states could affect the building fire safety performance, which will help bridge the gap between the fire and seismic engineering communities.

7 Summary of Conceptual Framework

In the previous chapters, the BNCS project was introduced and the outcomes were presented which showed that post-earthquake building conditions can be significantly different from what anyone can expect under normal conditions. Details on the PBD guidelines for both fire and seismic engineering disciplines have also been discussed to determine how the two approaches can be integrated to better assess post-earthquake building fire conditions. From these discussions, the type of building damages that are critical to the building fire safety, and the type of information that is needed to be shared between the two engineering disciplines were identified. Based on these information and analysis, a conceptual framework was developed to provide guidance for fire protection engineers to create more accurate delineations of post-earthquake fire scenarios. This chapter summarizes the process of creating post-earthquake building fire design scenarios, the type of information required from each of the fire and seismic engineers and looks at how this approach would fit in to the SFPE PBD guideline, to set up a complete PBD guideline for earthquake prone buildings.

7.1 Developing Post-Earthquake Building Fire Scenario

All of the steps and information required to develop a post-earthquake fire scenario is identified. A step-by-step procedure to create post-earthquake design fire scenarios is laid out in Figure 25. There are two colors in the flow chart with green and red blocks representing the steps that require the expertise of a seismic and fire protection engineers respectively. The following sections go over the steps in general and identify the tasks that need to be performed by both the seismic and fire protection engineers.

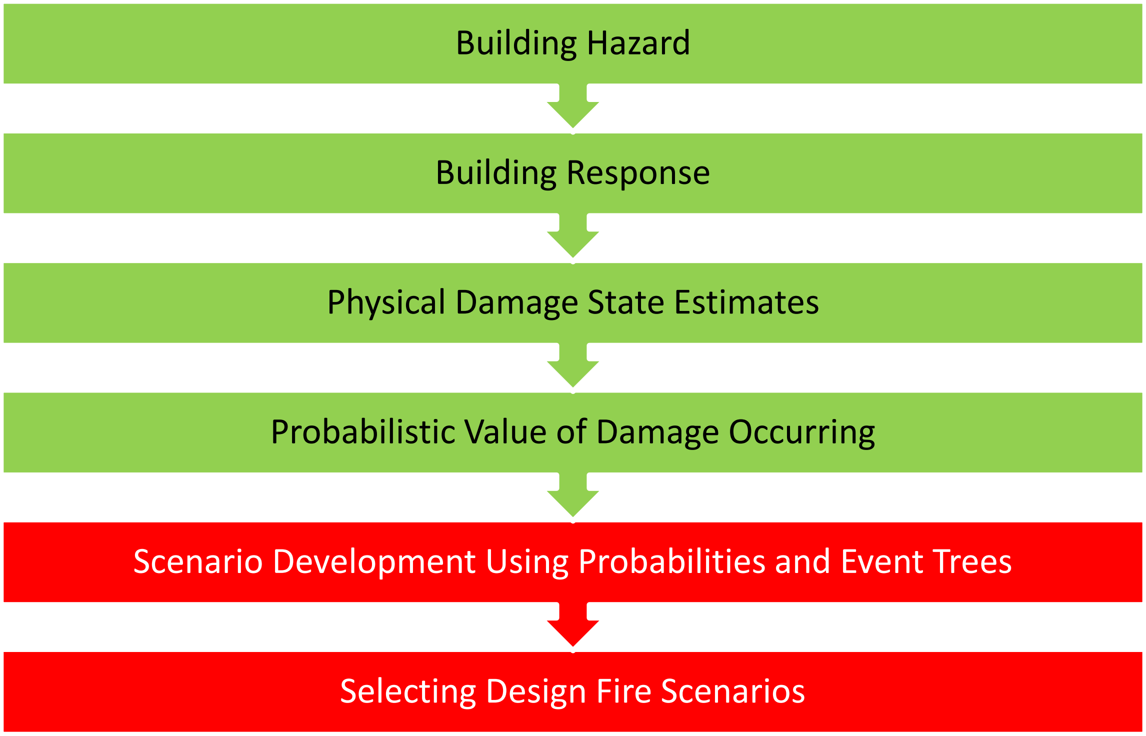


Figure 25. Process for developing post-earthquake building design fire scenarios

7.2 Steps Conducted by Seismic Engineers

Starting the building design process requires identifying all of the building components and contents that may be damaged when subject to seismic loads. Once all of the items have been inventoried, it is assumed that a seismic engineer will select an appropriate design earthquake for the building by taking into consideration the building site and location. Using this design earthquake motion, the seismic engineer will perform analysis using modelling tools to determine how the building will respond to the ground motion. These responses will be translated into meaningful building demand parameter values. All of the data obtained on the building inventory and building response analysis will be used as input values for the ATC-58 PACT software. Using this software and database provided by ATC-58, the damage levels to specific building conditions can be estimated.

7.3 Information Required by FPEs

Once these set of values are obtained a seismic engineer must discuss with the FPE and identify building components that may affect the building fire safety performance when damaged due to the earthquake. The FPE must clearly note the seismic engineer on which floor the most significant fire hazards are presented in the building. This information is crucial because the building response differs by floor level. The seismic engineer needs to pass on building response parameter values of the specific floor and fragility specifications of specific building components of interest to the fire protection engineer.

7.4 Steps Conducted by the FPEs

Using the fragility curves and building response parameters obtained by the seismic engineers, FPEs can determine the probability of damage occurring to a specific building component. Using these probability values, an event tree can be populated with the initiating event being a post-earthquake building fire, and selecting mitigating factors depending on the specific building. Based on the outcomes of the event tree, design fire scenarios can be identified and selected for evaluation. The building damage state conditions identified can be used as input parameters when performing the scenario evaluation.

7.5 Conceptual Framework Integrated with SFPE PBD Guideline

For a typical PB fire protection design analysis, the FPE needs to define the project scope, goals, objectives, and criteria for the building. The building, occupant, and fire characteristics need to be known in order to accurately identify risks and hazards to develop design fire scenarios.

However, if an earthquake impacts a building, it has the potential to damage the building, induce casualties, fear and panic on the occupants, and displace fuel items. Such effects can drastically change the building fire risks and hazards. So when PBD analysis is being performed for an earthquake prone building, the effects of the earthquake on the building must be accounted for. The previous sections discussed what type of information is required by the FPEs to better estimate building conditions and damage states in post-earthquake environment to create accurate representations of post-earthquake design fire scenarios and lays out the required steps. These steps can be successfully integrated into the SFPE PBD guideline. Figure 26 shows the step-by-step process of the SFPE PBD guideline integrated with the conceptual framework or determining earthquake building damage states and the resulting hazards. The processes in red are the steps the fire protection engineers are expected to perform and the processes in green are the steps the seismic engineers are expected to perform.

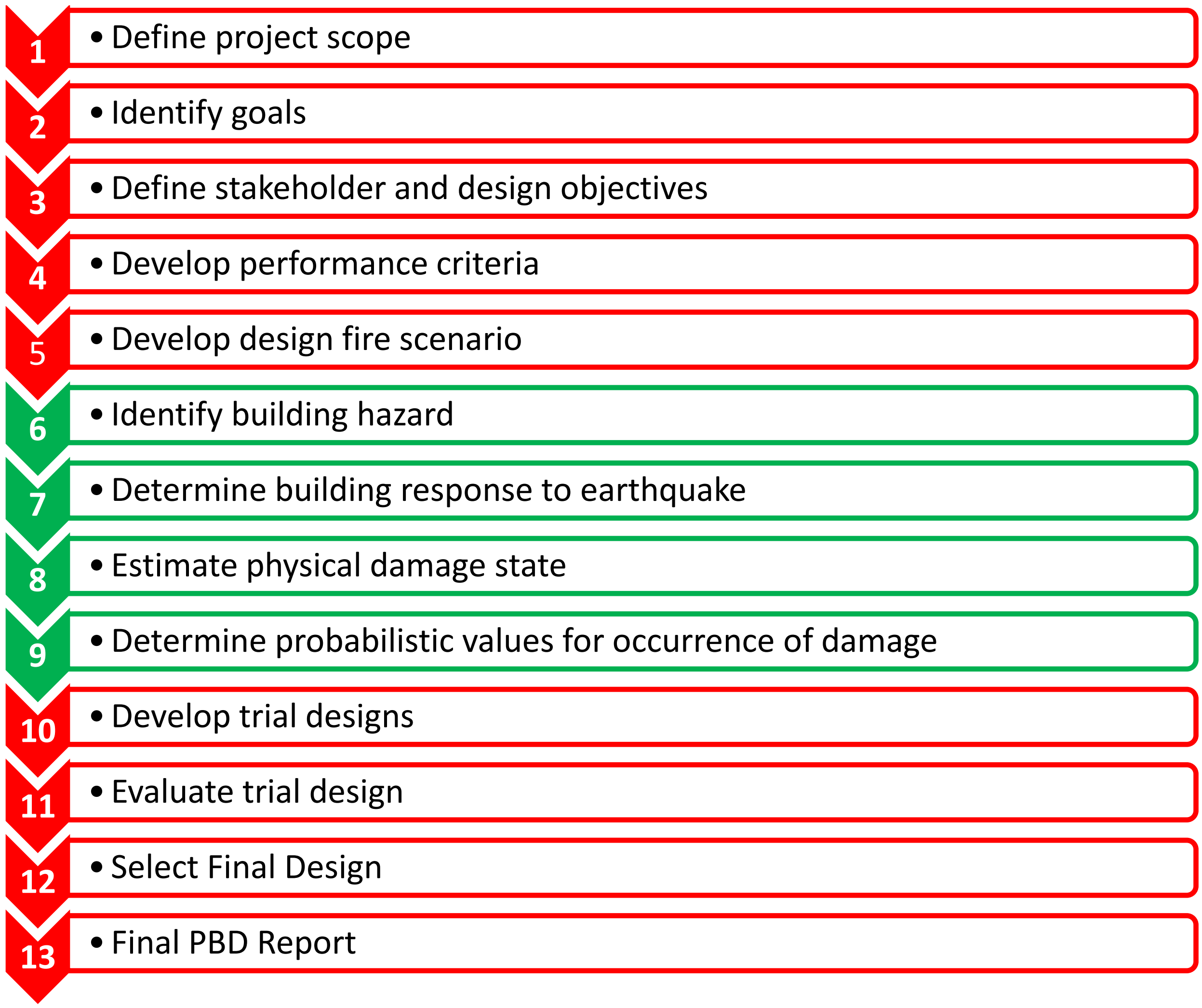


Figure 26. Step-by-step procedure for conducting PBD on earthquake prone buildings

The conceptual framework is inserted after step five of the SFPE PBD guideline. This is because earthquakes will not have any influence the stakeholders, project goals, objectives, and performance criteria. For example, for a normal building, if the fire protection goal was to ensure the life safety of the occupants inside the building during a fire, this will still remain the same even in case of a post-earthquake building fire. The things that can possibly changes in post-earthquake environment are the building, occupant, and fire characteristics. This is the reason earthquake effects need to be investigated when developing design fire scenarios for post-earthquake building fire conditions. The additional steps inserted into the SFPE PBD guideline is intended to help fire protection engineers to better estimate earthquake building damage. The first four steps of the process are steps FPEs must conduct but it is suggested that seismic engineers also participate in these steps as it can provide a better understanding for the seismic engineers to know what kind of goals and criteria the FPE has set and this could lead to seismic engineers being aware of and providing the right type of information the FPE is looking for.

With the project goals, objectives and performance criteria established, the FPE needs to create design fire scenarios based on the risks and hazards presented in the building. This is the critical step for creating accurate post-earthquake building design fire scenarios and requires information and input from seismic engineers. The seismic engineers are expected to identify building components that may be susceptible to damage from earthquakes. Seismic engineers will need to perform analysis on the building to determine the building response in response to the selected design earthquakes. From this they will determine the building response parameters which are used to estimate damage states of specific building components the FPE has selected to have a detrimental effect on the overall building fire safety performance.

Based on the building component damage states due to earthquakes, additional risk assessment needs to be performed to identify if there could be any newly associated fire risks to occupants due to the earthquake building damage. If the building damages are deemed to pose great risks accurate fire scenarios consisting of such damage states should be created. As a result, accurate estimations of earthquake building damage conditions are required to better identify risks and hazards and create accurate delineations of post-earthquake building fire conditions.

The risk analysis should provide better insight on what the probability of such earthquake building damage occurring is or what the most critical building component is in terms of maintaining the building fire safety performance levels to meet the fire protection goals. Based on these evaluations fire scenarios will be selected and evaluated. After analysis of the results, a final design that works can be selected. The following chapter shows an example case of how this process is implemented using a fictional building.

8 Post-Earthquake Design Fire Scenario Modeling Case Study

In this chapter, a fictional building is used as an example to show how the SFPE PBD Guideline integrated with the conceptual framework can be used to perform PB fire protection design analysis on an earthquake prone building. This chapter is laid out in a similar fashion to that of a typical PBD report, introducing the project scope, building, occupant, and fire characteristics.

The impact of an imaginary earthquake impacting the building is taken into consideration in the process of developing design fire scenarios. To account for this, the building components that may be susceptible to earthquake damage and further affect the building fire safety performance are identified and set as the building hazards. These damageable building components are divided into two categories – the first being components which can affect the fire growth, smoke and flame spread, and the second being components which can affect the building evacuation process. It is assumed that a seismic engineer has selected design earthquakes and has also conducted building earthquake analysis on this building. The earthquake analysis results are given to the FPE. Using the results, ATC-58 PACT fragilities are used to determine probability of damage occurring to the selected building components.

Using these values, two event trees are created using the damageable building components, one for the building components that can affect the fire growth, smoke and flame spread and the other for the building components that can affect the building evacuation process. From both event trees, two scenarios are chosen to create a normal building fire scenario where all fire systems are intact without any damage, and a post-earthquake fire scenario with damage to the selected building components. These selected scenarios are modelled using FDS to determine the effect of fire and smoke spread and to determine the available safe egress time (ASET). Pathfinder is used to model the building evacuation to show how damage to egress systems could affect the evacuation for earthquake damaged and normal building conditions and to determine the required safe egress time (RSET). The damage state descriptions and observations made during the BNCS Project are taken into account to translate building component damage into meaningful modelling input parameters for the post-earthquake fire scenario. Based on the modelling outcomes, an ASET/RSET analysis is conducted to show what the effects of earthquake damage can have on the overall building fire safety performance levels.

The primary intent for this modelling exercise is to illustrate how the conceptual framework developed could be used and what type of information is required in the process to create post-earthquake design fire scenario and also show that when even a small number of building components are damaged due to seismic load, these factors could affect the building fire safety performance. Also, this exercise again highlights the problem that currently, there is no one single source where FPEs can turn to obtain earthquake building component performance level to conduct a post-earthquake building fire analysis in a holistic manner. The following sections provide information on the assumptions and limitations for the example, and a detailed explanation on each of the steps of the conceptual framework process.

8.1 Assumptions and Limitations

For this example, several assumptions are made and because of this, there are several sources of uncertainty. For example, the selected damageable building components are based on assumptions, which in reality, might not be damaged to the extent assumed (i.e., there could be mitigation options to protect these building components from being damaged due to earthquake motions). Also the building response parameter values were created simply for the purpose of this example and do not purport to reflect reality. Several assumptions are also made on the occupant characteristics and fire load characteristics (i.e., design fires).

Event trees are created to setup fire scenarios using the fragilities from ATC-58 electronic database. Although data do exist on building component performance during earthquakes, these data are limited to a select few specific building components and are not enough to perform a comprehensive holistic building analysis. For example, the framework by Sekizawa et al. (2003) looks only at certain fire systems such as sprinklers and detectors, and Collier's experimental work (Collier, 2005) only looks at partition wall performances in earthquakes. Also, certain data are obtained from reports of past earthquake events, with damage being a result of a specific earthquake history, building, fuel and occupant condition. This creates uncertainty when analyzing buildings being exposed to a different intensity earthquake.

To try and create a more accurate delineation of building conditions of a specific intensity earthquake event and to perform this analysis in a holistic manner, ATC-58 fragility data is used. As shown in Table 4, however, not all damage states provided in ATC-58 fragility data can be used as direct input for fire modelling purposes as the point of interests differ between seismic and fire engineers. Keeping this in mind only a select few building component fragilities are chosen that could be directly used for creating a post-earthquake design fire scenario. Even so, the ATC-58 PACT fragilities have uncertainties as a lot of the fragilities were created based on expert opinion rather than on data from previous events.

Each of the sources of uncertainty, and the assumptions made, should be addressed more specifically in a real analysis. In such a case, sensitivity analysis might be used to help identify which input parameters have the most influence on design predictions, and more or better data, or specific treatment of uncertainty, might be warranted. However, the main point here is to illustrate that the conceptual model and process described above provides a rational way to approach post-earthquake fire performance assessment, that this model can be used in a qualitative (or even semi-quantitative) way to help identify scenarios for analysis, and that with further research and data development, a more reliable quantitative process can be developed.

8.2 Project Scope

The performance based design approach for this example will determine the smoke and fire effects on the occupants' ability to egress the building during normal and post-earthquake building fire scenarios. A fictional building that is situated in an earthquake zone will be used to show the process to implement the conceptual framework to develop post-earthquake building fire scenario and to also highlight some of the effects the earthquake damage can have in terms of the building fire safety performance. Because the building is located in an earthquake zone, it is important to prepare for earthquakes and assess what kind of fire scenarios could be expected if post-earthquake fire would start in the building.

8.2.1 Building Characteristics

For the modelling purpose, a building called the 'WPI Mall', provided from the Performance-Based Design Based Design course at WPI, is used. The 200m by 60m WPI Mall standing 14.2m in height, consists of a consists of a ground floor and first floor consisting of stores, and a second floor consisting of a food court and food court and kitchen areas. For both the normal and post-earthquake building conditions, store 1.17, a 1.17, a clothing store on the ground floor is picked as the fire origin location. All of the floor plans and plans and elevations are shown in Figure 27 through Figure 30. A key for the floor plans are provided in

Table 5. The building components or building characteristics of the WPI Mall which could have an effect on the overall building fire safety depending on its performance are listed below:

- Automatic fire sprinkler system installed throughout the entire building
- Generic Storefront placed in both side of every store entrances
- Suspended ceiling system installed only on ground floor level
- Prefabricated steel stairs throughout the entire building
- Traction elevators located in the middle of the mall and one on each of the anchor stores
- Internal store walls on ground floor only extend up to ceiling height
- Plenum spaces between shops are open and connected
- Wall mounted beam detector located in the raised roof area
- Mechanically operated double door smoke vents installed in the roof of the building (operated by beam detector activation)

Damage to any of these building components during an earthquake would significantly impact the building fire safety performance levels. It is assumed that the interior store walls consist of storefront glazing. The ground floor interior walls of the stores are partition walls extending to the ceiling height. The ground floor stores consist of suspended ceiling systems with the plenum spaces of the stores being open space between the stores. The walkways and the entire first and second floors do not consist of any ceiling system and is exposed directly to the floor deck or the roof respectively. The WPI Mall egress systems consist of prefabricated steel stairs and elevators.

Table 5. Key for WPI Mall floor plans

Sign	Representation
	Area with ceiling system
	Floor opening area
	Walls extending to floor deck
	Partition wall extending to ceiling system
	Storefront glazing system
⊕	Elevator
⊠	Prefabricated steel stair
,	Door

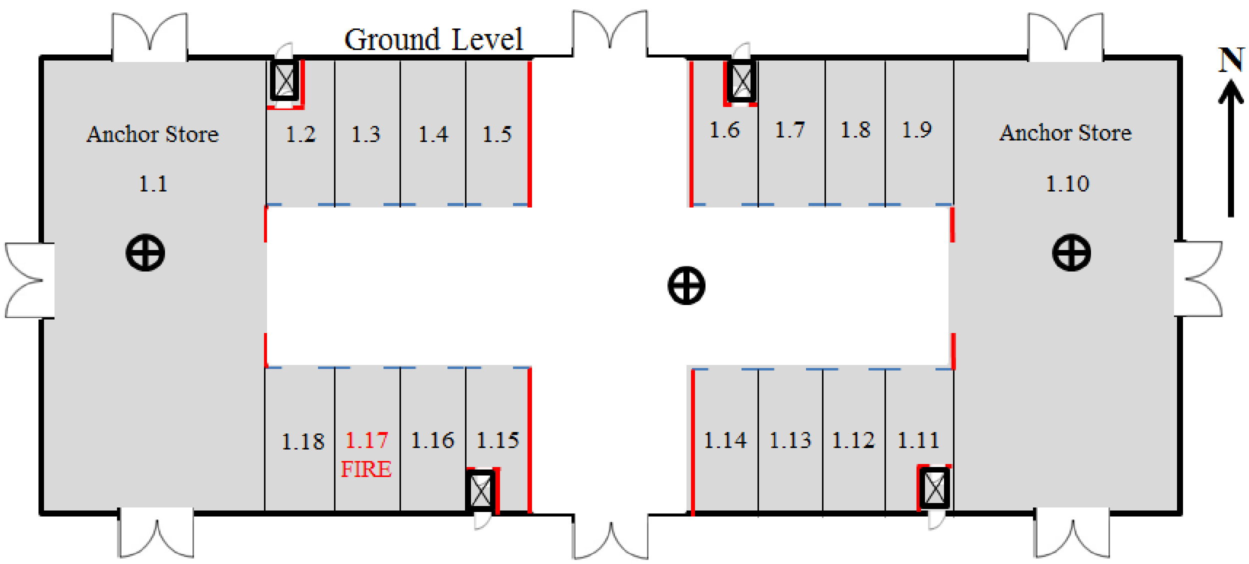


Figure 27. WPI Mall ground floor layout (doors not to scale)

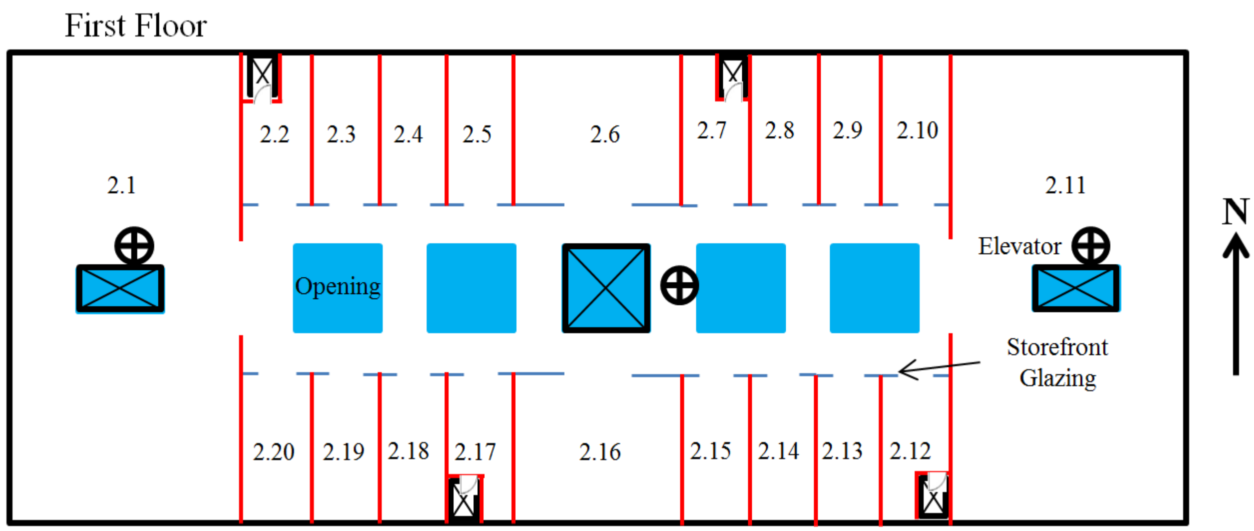


Figure 28. WPI Mall first floor layout

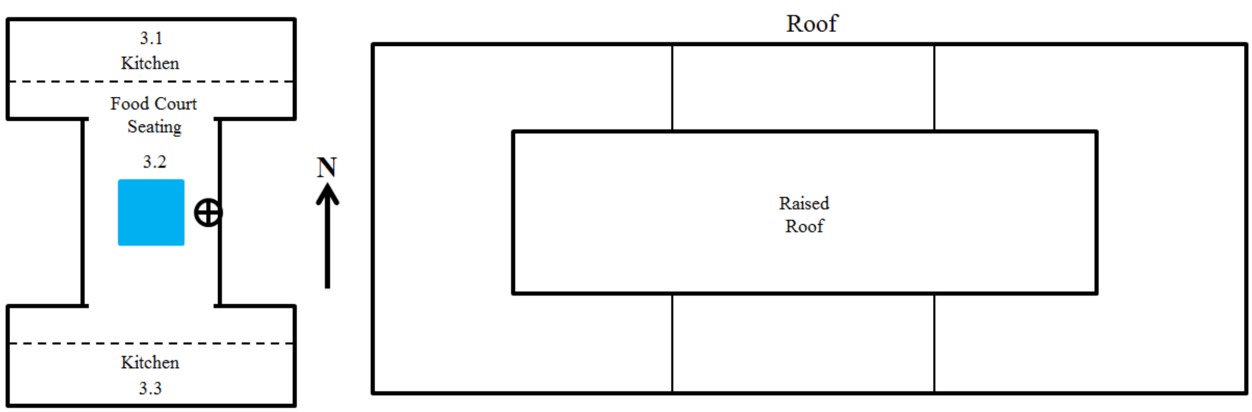


Figure 29. WPI Mall food court and roof layout

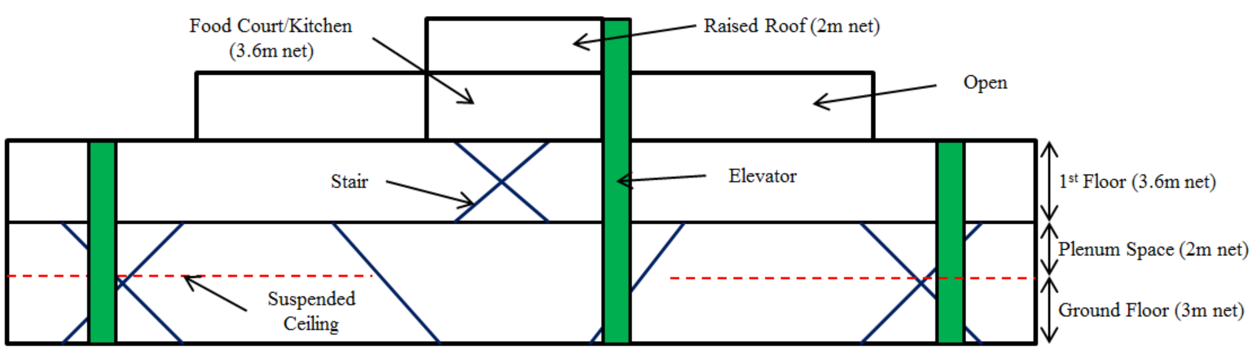


Figure 30. WPI Mall elevation view

Besides the automatic fire sprinkler system, static smoke extraction system is provided in the form of mechanically operated smoke vents. These smoke vents are operated by wall mounted beam detectors located in the raised roof area. The mechanically operated smoke vents are located in the roof and raised roof areas of the WPI Mall as shown in Figure 31. The mechanically operated smoke vents have dimensions of 1.8m by 2.5m. Figure 32 shows the locations of the beam detector transmitter and receiver in the raised roof area.

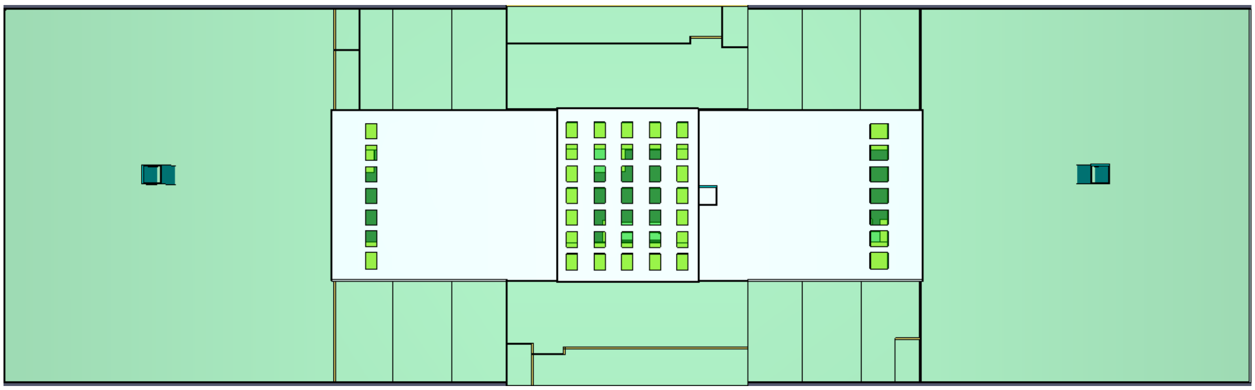


Figure 31. Location of smoke vents in the roof and raised roof area

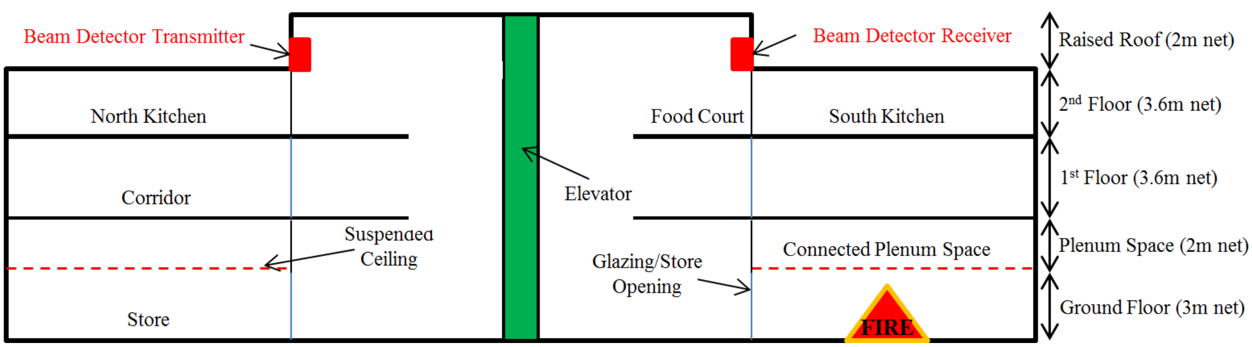


Figure 32. Smoke detectors in the raised roof area

8.2.2 Occupant Characteristics

It is assumed that the fire occurs during the day when the WPI Mall is fully occupied with a 100% occupant load.

Table 6 provides the occupancy load of each of the different areas in the WPI Mall. All of the occupant load and assumptions are kept the same for both the normal and post-earthquake building fire scenarios. Also, for the fire notification, it is assumed that the faster of either the beam detector activation or when the fire reaches 300 kW in size would provide significant fire cues for the occupants and trained WPI Mall staff members to recognize the fire.

Table 6. WPI Mall Occupant Load

Space	Area (sq ft)	Occupancy Load Factor (sq ft/person)	Occupancy Load
Entire Ground Floor	89203.7	31.2	2855
Entire First Floor	95631.2	31.7	3018
Food Court	12565	15	838
Kitchen 1	2050	200	11
Kitchen 2	2013	200	10
		Total occupant load	**6732**

The following assumptions are made regarding the occupants:

- Mobility impairment with cane: 10 % of total occupant
- Mobility impairment with wheelchair: 10 % of total occupant
- Persons between the ages of 65 and 90 years: 20 % of total occupant
- Children and young adults between 10 and 18: 20 % of total occupant
- Children between the ages of 6 months and 9 years: 10 % of total occupant
- Adults between the ages of 18 and 65: 30 % of total occupant
- Family groups: 30 % of total occupant
- Social groups: 30 % of total occupant
- The ground floor walkway/atrium area was not included in the leasable area.
- The notification system is electronic horns (no voice) and strobes.
- ASET time, t = 0 s, begins when the HRR is equal to or greater than 300 kW
- Most occupants will try to leave a building by the same way they entered. As a result, people will try to exit via main entrances on the ground floor using open stairs and escalators. As a result, only the occupants in the food court were allowed to use all exits and stairs including the emergency exits. Occupants on the first and ground floors were only allowed to exit via any of the main exits on the ground floor.
- Family group consists of all occupant classes including disabled people.
- Social group consists of just three occupant classes of persons between the ages of 65 and 90 years (senior club), Children and young adults between 10 and 18 (Boy & Girl Scout), and adults between the ages of 18 and 65 (YMCA & YWCA club).

Based on the assumed occupant load and characteristics, research was conducted to determine appropriate walking speeds for each of the occupant groups. Normally, walking speed is used to differentiate between the various occupant groups. Walking speed values and descriptions are provided as follows:

- Mobility impairment with cane: 0.81 m/s (SFPE HB 4th Ed., Table 3-12.4)
- Mobility impairment with wheelchair: 0.89 m/s (Electric, SFPE HB 4th Ed., Table 3-12.4)
- Persons between 65 and 90: 0.86 m/s (Tubbs & Meacham, 2007, Chapter 7)

- Children and young adults between 10 and 18: 0.88 m/s (Tubbs & Meacham, 2007, Chapter 7)
- Children between 6 months and 9 years: 0.88 m/s (Tubbs & Meacham, 2007, Chapter 7)
- Adults between the ages of 18 and 65: 1.12 m/s (Tubbs & Meacham, 2007, Chapter 7)
- Group behavior: Group sense-making and collective behaviors involve interaction among occupants to collectively develop an understanding of the emergent situation. In new and/or ambiguous situations (Turner and Killian, 1987) and times of urgency (Aguirre, Wenger and Vigo, 1998), occupants are likely to interact with others around them. As reported in several empirical studies of recent accidents, occupants in emergencies make evacuation decision collectively with their group members; they gather information from one another, interpret the emergency cues, and initiate escape actions collectively.
- Family groups: Based on the research of several literatures about the group behavior, it was assumed that the family group member would try to seek their members when they perceive the emergency situation. To represent this behavior in Pathfinder model, initial delay time of 30 seconds was used. Also, since family group members tend to evacuate collectively, all family members will move together at a same walking speed of 0.81 m/s (slowest speed) after the time delay.
- Social groups: Based on the work of Moussa ïd et al. (2010), empirical study shows that the walking speed becomes slower when walking in groups. The mean walking speed of social groups under moderate density is about 0.9 m/s.

Based on the assumptions on the occupant characteristics, the number of the occupants for various groups is calculated. The food court, first floor and ground floor occupant characteristics are summarized in Table 7, Table 8, and Table 9 respectively.

Table 7. Food court occupant characteristics

Food Court		# of Occupant	Group	# of Occupant	Speed (m/s)
Group	**Ratio**				
Cane	10%	84	**None**	59	0.81
			Family	25	15s delay + 0.81
Wheelchair	10%	84	**None**	59	0.89
			Family	25	15s delay + 0.81
65+	20%	168	**None**	33	0.86
			Family	51	15s delay + 0.81
			Social	84	0.9
10~18	20%	168	**None**	33	0.88
			Family	51	15s delay + 0.81
			Social	84	0.9
6~9	20%	84	**None**	59	0.88
			Family	25	15s delay + 0.81
18~65	10%	250	**None**	91	1.12
			Family	75	15s delay + 0.81
			Social	84	0.9
Total Occupant		838		838	

Table 8. First floor occupant characteristics

First Floor		# of Occupant	Group	# of Occupant	Speed (m/s)
Group	**Ratio**				
Cane	10%	302	**None**	211	0.81
			Family	91	15s delay + 0.81
Wheelchair	10%	302	**None**	211	0.89
			Family	91	15s delay + 0.81
65+	20%	604	**None**	121	0.86
			Family	181	15s delay + 0.81
			Social	302	0.9
10~18	20%	604	**None**	121	0.88
			Family	181	15s delay + 0.81
			Social	302	0.9
6~9	20%	302	**None**	211	0.88
			Family	91	15s delay + 0.81
18~65	10%	904	**None**	331	1.12
			Family	271	15s delay + 0.81
			Social	302	0.9
Total Occupant		3018		3018	

Table 9. Ground floor occupant characteristics

Ground Floor		# of Occupant	Group	# of Occupant	Speed (m/s)
Group	**Ratio**				
Cane	10%	286	**None**	201	0.81
			Family	86	15s delay + 0.81
Wheelchair	10%	286	**None**	200	0.89
			Family	86	15s delay + 0.81
65+	20%	571	**None**	114	0.86
			Family	171	15s delay + 0.81
			Social	286	0.9
10~18	20%	571	**None**	114	0.88
			Family	171	15s delay + 0.81
			Social	286	0.9
6~9	20%	286	**None**	200	0.88
			Family	86	15s delay + 0.81
18~65	10%	855	**None**	313	1.12
			Family	256	15s delay + 0.81
			Social	285	0.9
Total Occupant		2855		2855	

8.2.3 Ignition and Fuel Characteristics

According to the national fire protection association (NFPA) statistics, some of the leading causes of building fires in stores and mercantile occupancies in the United States from 2004 to 2008 were:

- Cooking equipment

- Electrical, and lighting equipment
- Heating Equipment
- Intentional
- Smoking Material
- Clothes

For this case study, the source of ignition coming from an electrical or lighting system failure inside a clothing store is assumed.

8.2.4 Stakeholders, Objectives and Goals

The stakeholders involved in the fire protection design of the project include the following:

- WPI Mall Owner – the developer/owner of the building
- Authority having jurisdiction (AHJ) – regulatory agencies
- Fire Protection Engineer – fire protection engineer, code consultant, and fire systems designer
- Insurance Company – primary insurance carrier for the building and responsible for covering property, injury, and business interruption losses
- Construction Company – responsible for constructing the building and make changes per design
- Management Group – contracted to provide maintenance and operations for all of the building features

8.2.5 Fire Protection Project Goals

1. Protect occupants not intimate with the area of ignition from fire-related injuries until evacuated to a safe location
2. Protect fire and rescue service personnel during firefighting and rescue operations
3. Minimize losses due to fire-related damage

8.2.6 Fire Protection Project Design Objectives

1. Prevent flashover in the room of fire origin
2. Maintain tenable conditions for a time period required for all occupants to evacuate the building safely
3. Protect emergency responders from unreasonable risks while carrying out emergency operations
4. Keep the effects of the fire limited to the room of origin

8.2.7 Fire Protection Performance Criteria

A smoke layer height of 1.8m at 93C from the floor level is set as the criterion for measuring the tenability criteria for the ASET/RSET analysis based on data from *NFPA 101*.

8.3 Design Fire Scenario Development Using the Conceptual Framework

All the previous sections reflect steps that follow the SFPE PBD guideline. With the project scope, goals, and objectives all defined, the next step requires creating design fire scenarios. If the WPI Mall was located in place where earthquakes are rare events with low occurrence probability, the FPE can develop fire scenarios alone. If event tree analysis is to be performed for a WPI Mall that has no risk of being exposed to earthquakes, Figure 33 and Figure 34 would represent such conditions with the initiating events being normal building fire rather than post-earthquake building fire. In case of a normal building fire occurring in store 1.17, where only sprinkler is present without detectors, it is expected that sprinkler activation will occur first. As the fire develops and more smoke is produced, the storefront glazing system will reduce the store opening area and act as a barrier to slow the smoke filling rate beyond store 1.17, while the ceiling system will prohibit any smoke intruding the plenum space. As more and more smoke is produced, it is inevitable that the smoke will leave store 1.17 and travel to the upper floors towards the atrium space activating the beam detector. The beam detector activation will automatically lead to the smoke vents activating in the roof areas. Although the smoke vents are not listed separately as they are operated by beam detectors, all of the sequence of events that are expected to occur is laid out in Figure 33.

In terms of building evacuation during a normal WPI Mall fire, since the mall consists of only three floors, it is expected that most occupants will first look to access the stairs, and mostly the impaired or emergency responders will look for the elevator to evacuate or carry out emergency operations respectively as laid out in Figure 34.

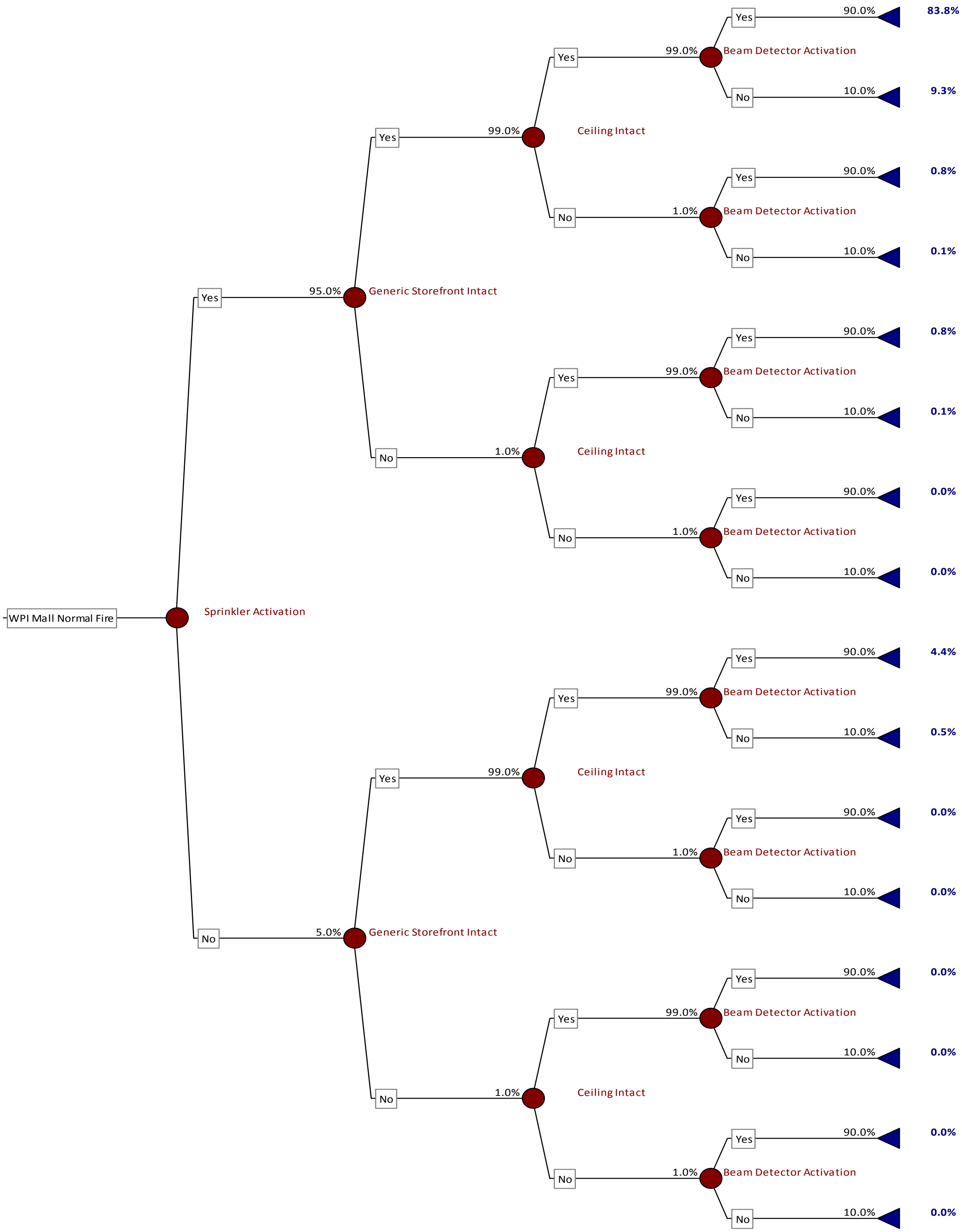


Figure 33. WPI Mall normal fire event tree probabilities

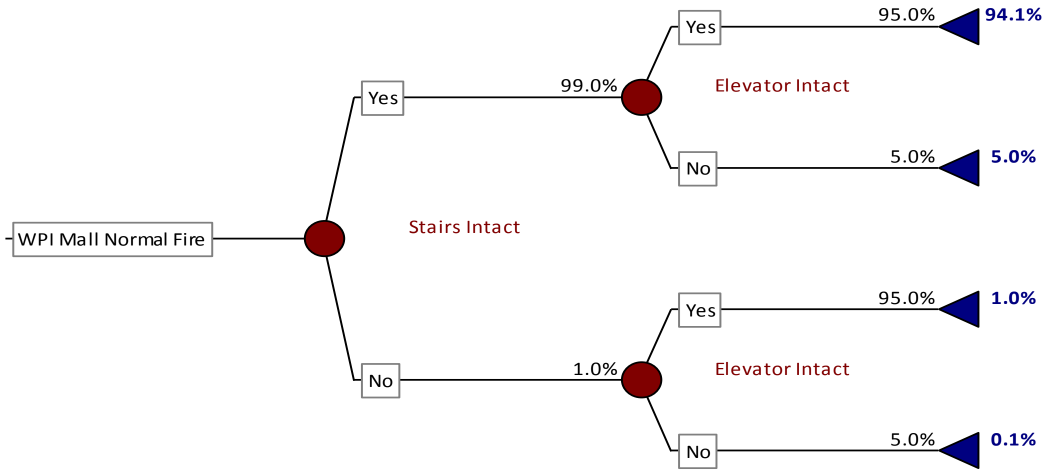


Figure 34. WPI Mall normal evacuation event tree probabilities

Like the event tree probabilities show, there is very little failure probability of any of the fire systems or egress systems under normal conditions. However, because the WPI Mall is located in an earthquake zone, the building is under constant threat from being exposed to earthquakes. The project stakeholders are worried not only about earthquakes but the possibility of post-earthquake fires. Earthquakes have a potential to severely degrade the building fire safety performance than under normal conditions. As a result, the conceptual framework is used in the following sections to develop post-earthquake design fire scenarios as the conceptual framework takes into account the effects of several WPI Mall building components that may be damaged due to an earthquake. For this part of the process, it is essential for FPEs to work together with seismic engineers and obtain the necessary information such as the building response parameters from earthquakes in order to successfully take into account all of the effects that an earthquake could have on the WPI Mall, as effects could change the building, occupant, and fire characteristics.

8.3.1 Building Hazard (Step 1)

The building geometry, building components, and the occupant characteristics of the WPI Mall have been identified. With this data, the first step of the conceptual framework can be conducted by identifying the building hazards. For this example, several building components are selected (assuming that these could be subjected to damage from earthquake) which could have an effect on the fire and smoke spread or the evacuation process.

The building components identified as hazards that can be damaged and affect the fire and smoke spread are the sprinkler system, storefront glazing system, ceiling system, beam detector (smoke vents are operated by the detector activation) and smoke vent. When sprinklers are damaged and does not activate as expected, it can lead to the fire growing fully and lead to potential flame and smoke spread beyond room of origin. The glazing system works as a barrier to limit smoke spread and damage to the storefront glazing can lead to increase in size of the openings. Ceiling system damage can often lead to ceiling tiles being dislodged. This means openings where smoke can travel to the plenum spaces. If the plenum spaces are connected between different compartments, this could lead to smoke infiltrating the other compartments via the plenum space and dislodged ceiling tiles. If the smoke detectors do not activate, the smoke vents will also not activate, which will prohibit smoke extraction from the building.

The building components identified as hazards that can be damaged and affect the building evacuation process are the stairs and elevators. Damage to either system can greatly affect the total evacuation time of the building or in the worst cases even limit certain occupants in certain parts of a building from being able to access any egress systems, leaving them stranded in untenable conditions.

8.3.2 Building Earthquake Response Parameters (Step 2)

As damageable building components have been identified, the next step requires determining what the probability of these building components experiencing damage will be and what the damage states will be. To estimate the probability and damage states, knowing how the building responds to a certain intensity earthquake is required.

For this WPI Mall example, it is assumed that a seismic engineer has already conducted a building response analysis to a specific design earthquake. The building responses are translated into engineering demand parameters per floor level as presented in Table 10. These numbers were randomly created solely for this example to show that this is the type of information that needs to be provided by the seismic engineers to the FPEs.

Table 10. WPI Mall earthquake building response engineering demand parameters

Floor	PFA	IDR
Ground Floor	0.9g	0.6
First Floor	0.7g	0.4
Second Floor	0.4g	0.3

Different floor levels have varying earthquake response values. However, for this example, since the fire origin is assumed to be at ground level, and the highest response values occur on the ground level as well, the response values of ground level are applied to the entire building. This would ensure the worst case scenario is assumed for all floor levels of the WPI Mall building. Usually, seismic engineers use numerous design earthquakes with varying intensities which result in different building response parameters. These response values used for the example are assumed to be results that yielded the highest building response values to evaluate for the worst case scenario. Also, it is assumed that the ground shakes in the east-west direction as the building components under examination (such as glazing systems) are oriented in plane to the east-west direction.

8.3.3 Physical Damage State Estimates and Probabilistic Value of Damage Occurring (Steps 3 and 4)

With the damageable building components selected and the building response parameters determined, this allows for determining what the actual physical damage states will be and what the probability of such damage state occurring will be.

ATC-58 PACT fragilities are used to determine these damage states and probabilities. Figure 35, Figure 36, Figure 37 and Figure 38 shows fragility of selected building components which may affect the building fire conditions and can be used as direct input for FDS while Figure 39 and Figure 40 shows building egress component fragilities affecting the overall safety evacuation of occupants which can be used as direct input for Pathfinder. Figure 35 is a fragility curve of an independent pendant lighting system. The ATC-58 PACT database has no information on smoke detectors so pendant lighting system is selected as a surrogate to estimate beam detector damage, as both systems are similar in installation methods as they are both mounted to the wall or ceiling. The ATC-58 PACT fragilities provide multiple damage states. It is important that a damage state that can have an effect on the overall building fire safety performance is selected so that it is meaningful and provide an actual building hazard.

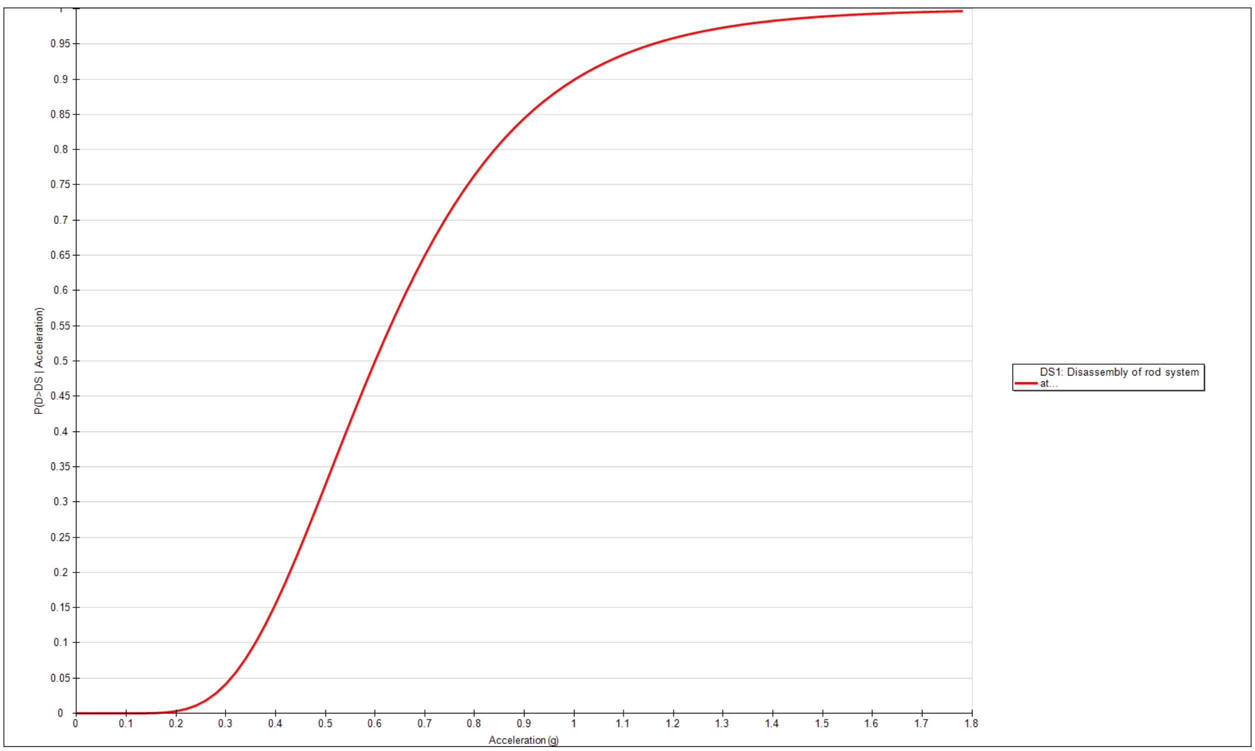


Figure 35. C3034.001-Independent Pendant Lighting (to estimate beam detector damage probability)

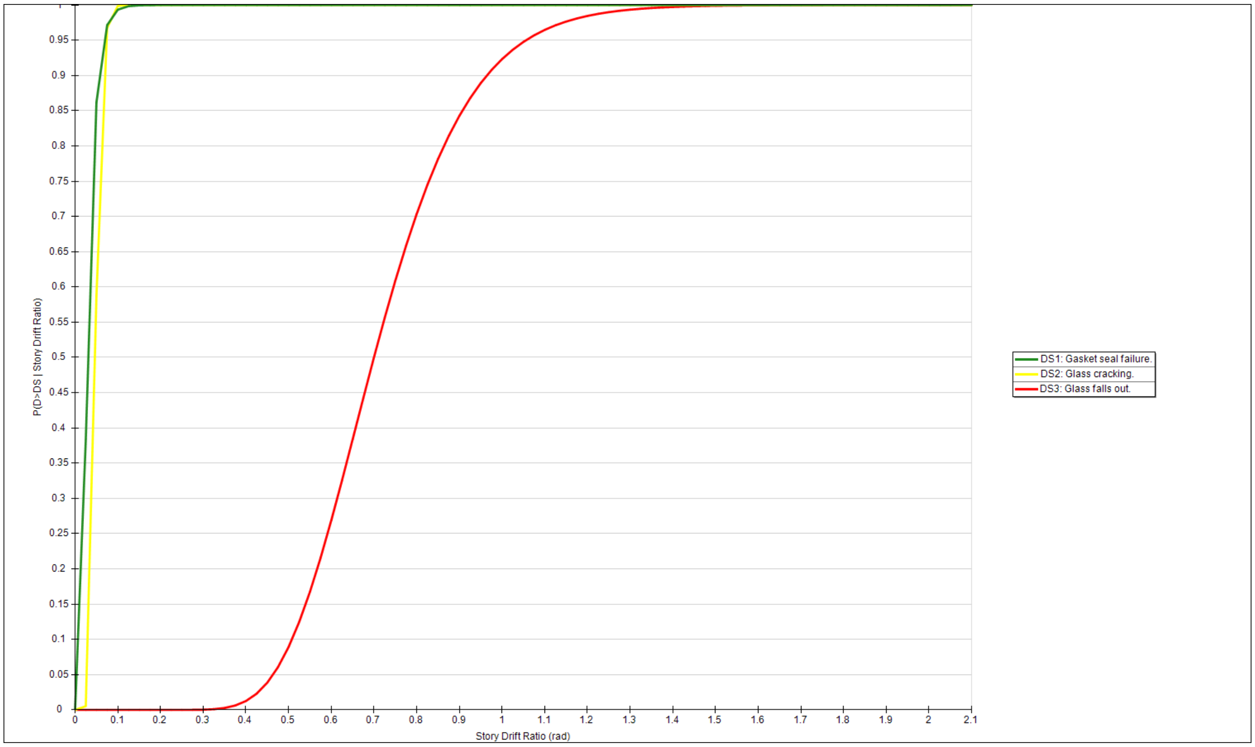


Figure 36. B2023.001-Generic Storefront fragility (ATC-58)

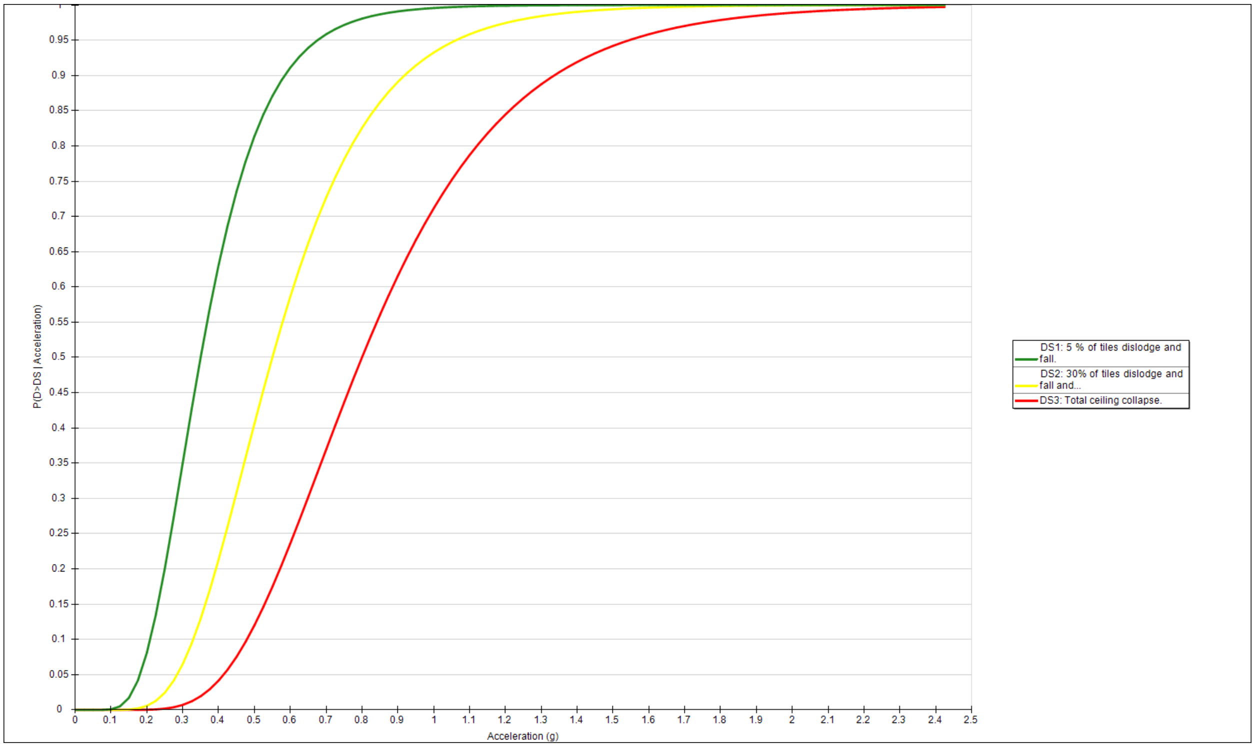


Figure 37. C3032.001c-Suspended Ceiling fragility (ATC-58)

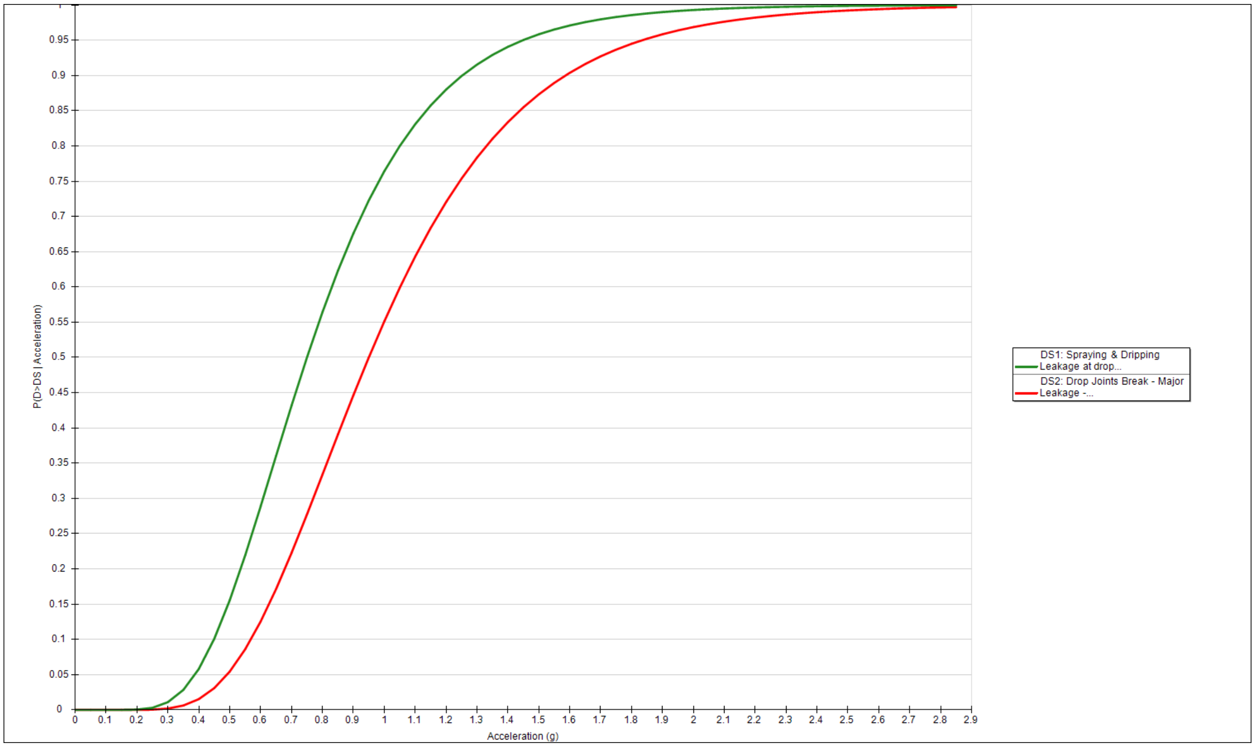


Figure 38. D4011.031a-Fire Sprinkler Drop Standard Threaded Steel fragility (ATC-58)

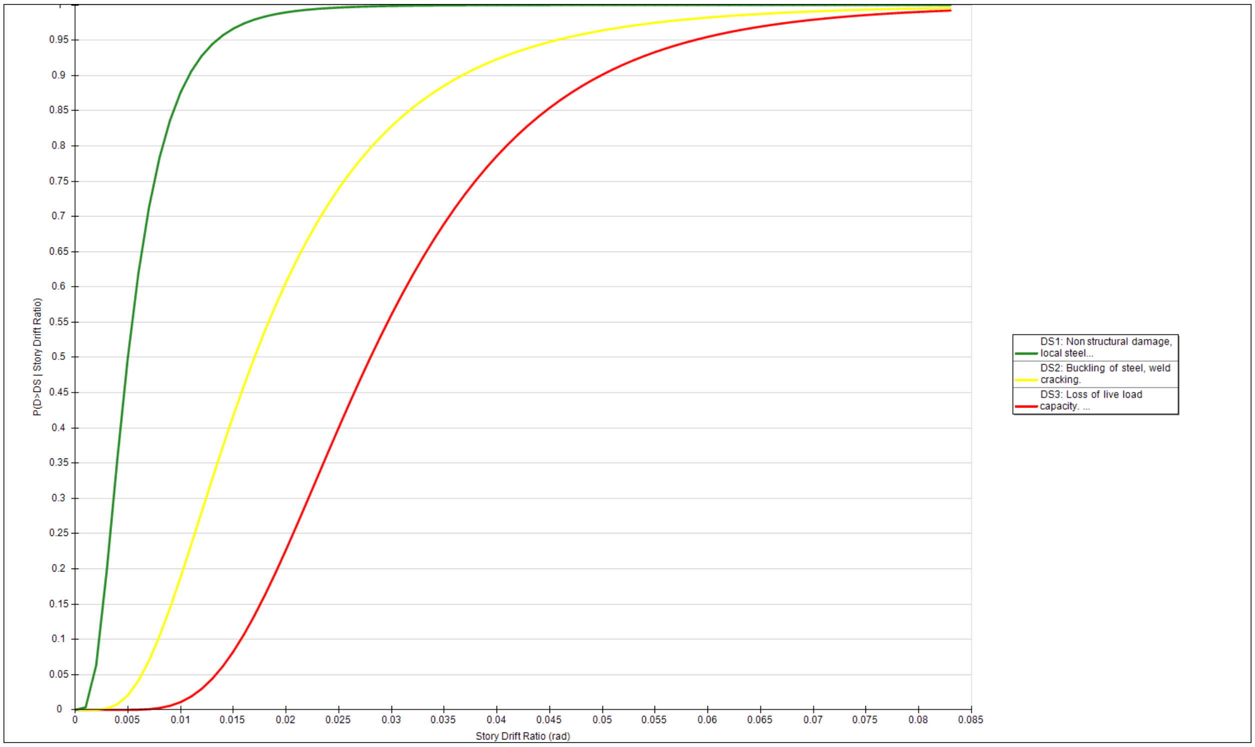


Figure 39. C2011.001b-Prefabricated Steel Stair fragility (ATC-58)

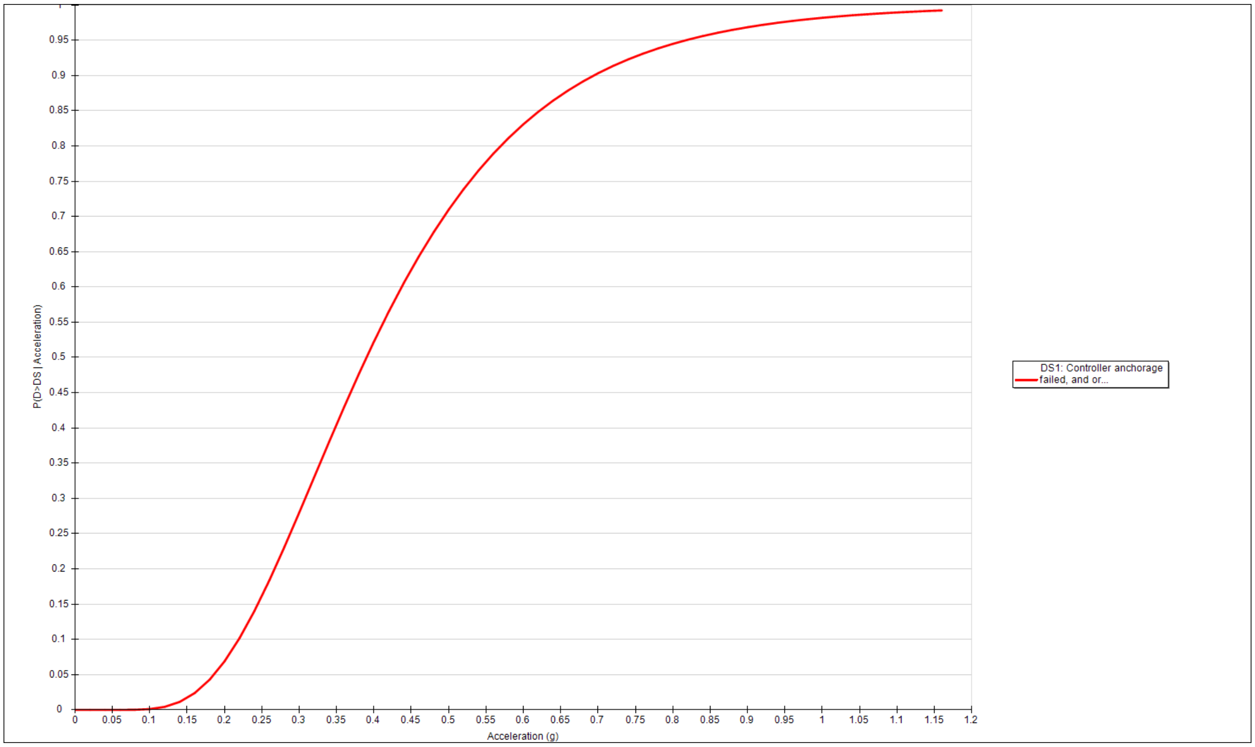


Figure 40. D1014.011-Traction Elevator fragility (ATC-58)

Damage states which would actually have any influence in the fire scenarios and that can be directly used as modelling input parameters are selected and using the building demand parameter values provided at ground level, probability of occurrence of the selected damage states are determined from the fragility curves. These damage states and probability of occurrence are provided in Table 11.

Table 11. Building component damage states and probability of occurrences

Building Component	Selected Damaged State	Probability of Occurrence
C3034.001-Independent Pendent Lighting	DS1: Disassembly of rod system at connections with horizontal light fixture, low cycle fatigue failure of the threaded rod, pullout of rods from ceiling assembly	85%
D4011.031a-Fire Sprinkler	DS1: Spraying & Dripping Leakage at drop joints – 0.01 leaks per drop	35%
B2023.001-Generic Storefront	DS3: Glass falls out	27%
C3032.001c-Suspended Ceiling	DS1: 5% of tiles dislodge and fall	95%

C2011.001b-Prefabricated Steel Stair	DS3: Loss of live load capacity	95%
D1014.011-Traction Elevator	DS1: Controller anchorage failed, and or machine anchorage failed, and or motor generator anchorage failed, and or governor anchorage failed, and or rope guard failures	95%

These probabilities are determined with the aim to perform risk assessment by using event tree analysis. All of these values are based on ATC-58 fragility curves. Some of the damage states selected from the fragilities is validated through the BNCS test observations. Damage states for the suspended ceiling system and prefabricated steel stair was observed during the BNCS project and the extent of the damage increased as the motion intensities increased. Although sprinkler system damage was not observed during the BNCS project and other shake table test data on flexible sprinkler drop devices and suspended ceiling system (Bachman, 2010) concur that if not addressed properly to the seismic demand, sprinkler systems can be subject to damage as seen during the Northridge 1994 and Kobe 1995 earthquakes (Sekizawa et al., 2003).

Although there are no earthquake damage data on beam detectors, it can be argued that if the beam detector transmitter and receiver are not correctly aligned to each other, the beam detector will not function. Typical wall mount beam detectors, as shown in Figure 41, can easily pivot from the wall mount brackets and become misaligned due to seismic motion induced wall movement. As an alternative, a lighting system is selected from the ATC-58 PACT database to estimate beam detector damage as both systems are similarly mounted to a building surface. The ATC-58 independent pendent lighting fragility damage description states there can be disassembly of rod system at connections. Applying this damage logic to beam detectors, the rod system can be considered as equivalent to the wall mount bracket.

Figure 41. Example of beam detector transmitter and receiver (www.pertronic.com.au)

8.3.4 Quantifying Scenarios Using Probabilities from ATC-58 (Step 5)

The previous sections led to identifying key building components that could be building hazards in terms of building fire safety, determining the building response, selecting the physical damage states, and identifying the probabilities of such damage occurring when earthquake hits the WPI Mall. Because of the probability values obtained, these values are used to create and populate event trees to determine what kind of scenarios could exist and what the probability of each scenario occurring is. As the hazardous building components are divided into two categories of which could affect (1) fire and smoke spread, and (2) building evacuation process, to parallel this, two separate event trees are created. For both event trees, the initiating event is set as a post-earthquake fire occurring in WPI Mall store 1.17.

In case of a store 1.17 fire at the WPI Mall, with the assumption that all of the fire systems are intact, the first mitigation option would be sprinkler system activation as there is no detection system in store 1.17. The storefront glazing system should slow down the smoke spread rate out of store 1.17 through the store opening. The ceiling system should protect smoke spread to the plenum space. If there is too much smoke that has left store 1.17, than the beam detector in the raise roof area should activate, which will also activate the smoke vents as well for smoke extraction. If all the egress systems are intact, it is expected that the majority of the occupants (not in the ground floor) will travel towards the nearest stair as the WPI Mall is only three stories high, and the impaired occupants will travel towards the nearest elevator.

Based on these sequential events the event trees are created. For the first event tree, shown in Figure 42, the mitigating factors are the selected building components which could limit the fire and smoke spread. For the second event tree, shown in Figure 43, the mitigating factors are the selected building components which could affect the building evacuation process. Each of the scenario names are labelled in red text following the probabilities of each respective scenario in blue text.

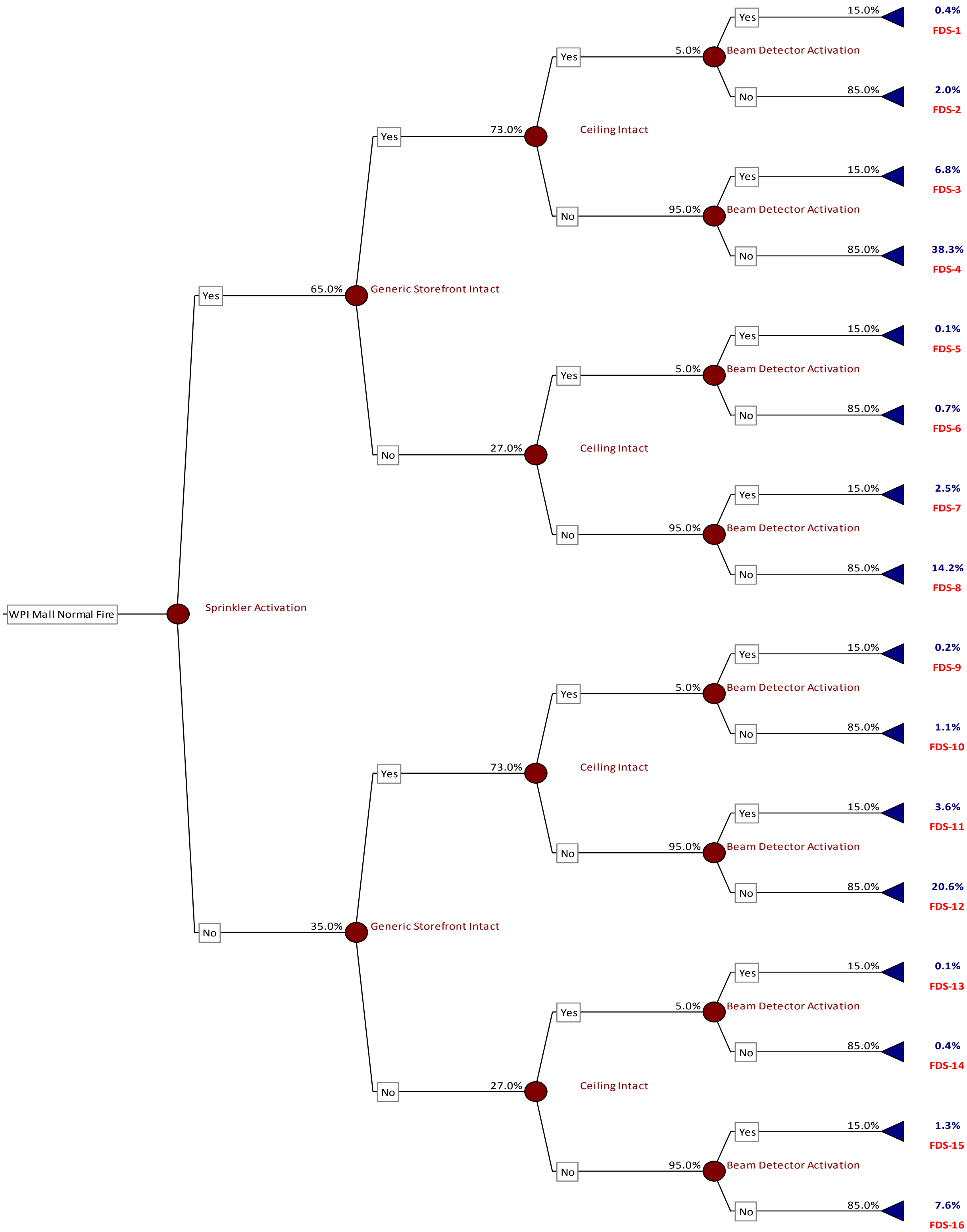


Figure 42. WPI Mall post-earthquake fire event tree for FDS modelling

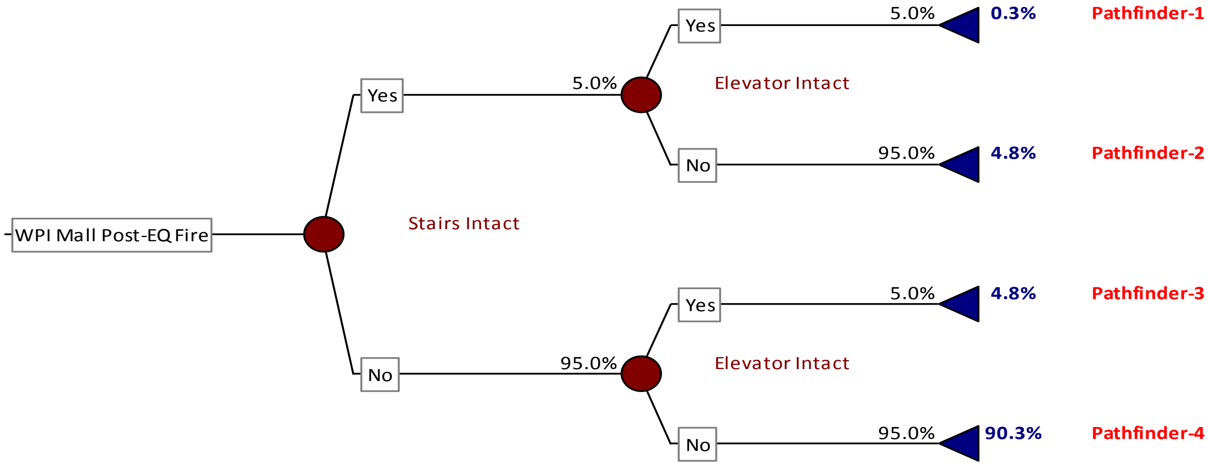


Figure 43. WPI Mall post-EQ fire event tree for Pathfinder modelling

8.3.5 Selecting the Design Fire Scenarios (Step 6)

Usually, in an event tree analysis, the scenarios are selected based on the highest probability of the scenario occurrence. In reality, a FPE will most likely consider scenarios with the highest occurrence probabilities and select scenarios FDS-4 and Parthfinder-4 from Figure 42 and Figure 43 respectively. However, since the purpose of this exercise is to show the effects of earthquake damage to the building fire safety performance levels, the two most extreme scenarios where all the mitigation factors are damaged or all intact are selected. For the FDS oriented design fire scenarios, FDS-1 and FDS-16 are selected and for the Pathfinder oriented design fire scenarios, Pathfinder-1 and Pathfinder-4 are selected. The FDS-1 and Pathfinder-1 scenarios are selected to serve as the base condition where the building is totally intact, representing normal-undamaged conditions, so that the effects of the earthquake damage can be highlighted and assessed. The following sections provide how the selected scenarios are setup in the modelling software and what the outcomes are.

8.4 Common Modelling Input Parameters for FDS

Although two very different fire scenarios are selected to evaluate using FDS, there are some common input parameters these two scenarios share. The following sub-sections list the common input parameters so that information is not duplicated.

8.4.1 FDS Mesh Setup

In FDS the WPI Mall is divided into 5 sections with each being a computational domain itself. Figure 44 provides the setup of the computational domains and the dimensions with the numbers in white text used as labels for each of the computational domain. Table 12 provides details of the computational domain cell sizes and the number of cells in each of the domain.

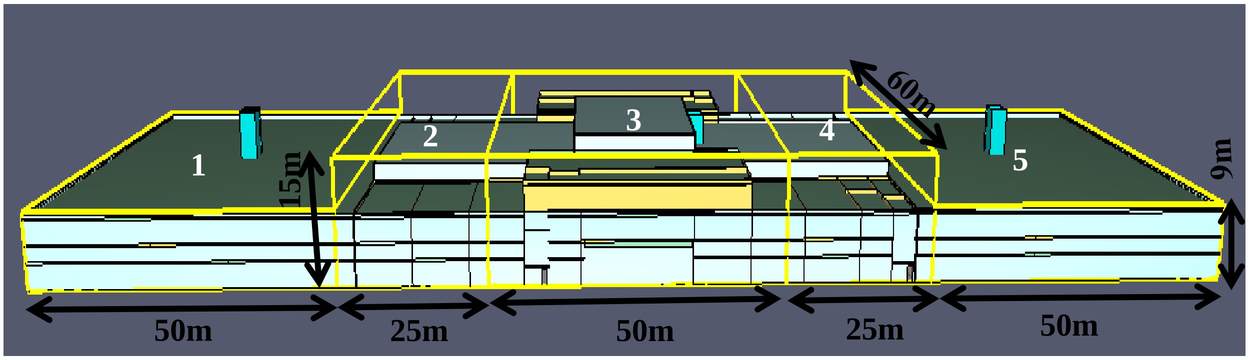


Figure 44. FDS computational domain setup

Table 12. Computational domain cell details

Mesh	# of Cells (x × y × z)	Cell Dimensions (x × y × z)	# of Total Cells in Domain
1	75 × 120 × 18	0.67m × 0.50m × 0.50m	162,000
2	50 × 120 × 30	0.50m × 0.50m × 0.50m	180,000
3	100 × 120 × 30	0.50m × 0.50m × 0.50m	360,000
4	50 × 120 × 30	0.50m × 0.50m × 0.50m	180,000
5	75 × 120 × 18	0.67m × 0.50m × 0.50m	162,000

8.4.2 Clothing Store Design Fire Curve

Although there is a difference in fuel load for the two scenarios, the location of fire origin, store 1.17 is a clothing store, and items that are used as fuel source in both cases are clothes. Research was conducted to find HRR data on clothing fires. To represent a realistic clothing store fire, data from the Zalok et al. (2007) is used as the input design fire. Zalok et al. performed surveys of clothing stores in Canada to determine combustible materials and the total fire load. Based on these surveys, tests representing three different types of clothing stores were conducted to determine the HRR, gas temperatures, heat fluxes and etc, representing fuel load of 1m by 1m area for each of the three different types of clothing store. "Test S", "Test W", and "Test C" represented a small clothing store, a clothing store with mostly wooden interior design, and a clothing store with mostly clothes respectively. Considering the WPI Mall store compartment size and assuming a lot of clothes would be stacked on display and storage 'mostly cloth store', the 'Test C' HRR curve from Figure 45 is selected as the design fire curve. To use this curve as the input design fire curve, 1m by 1m burners representing 1m by 1m clothing materials are placed in store 1.17 and a ramp function is used to represent the HRR curve data in FDS. For the 'Test C' HRR curve, the peak heat release rate of 1528 kW occurs after 5 minutes from ignition and drops to 200 at 12 minutes and slowly starts to decay.

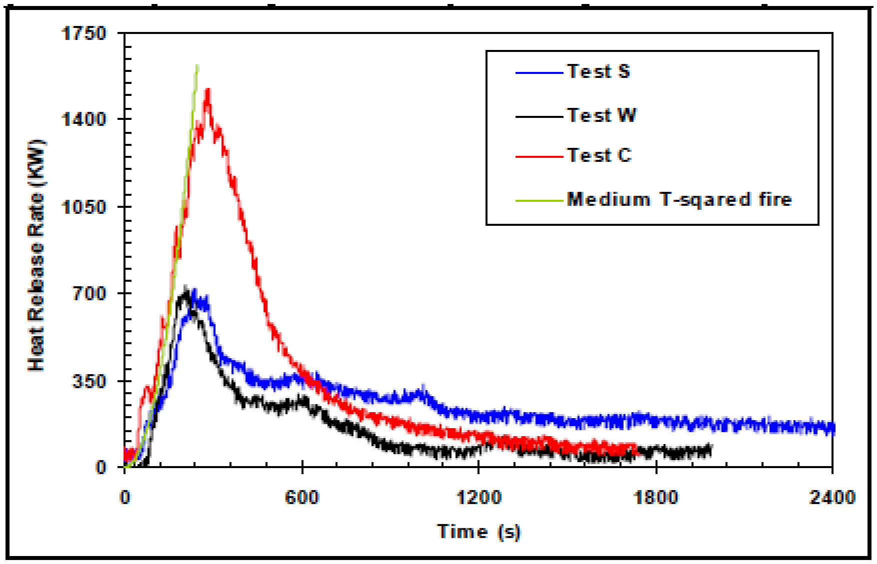


Figure 45. Clothing store design fire HRR curve data (Zalok et al., 2007)

8.4.3 Layer Zoning Devices

Since safe evacuation of all the occupants in the entire mall is the objective and the fire protection goal, the smoke layer height and gas temperatures are measured at various points at all floors of the mall using the 'Layer Zoning Devices' in FDS. A total of seven zoning devices are placed throughout the entire building. These devices are placed in the atrium adjacent to the food court floor slab, north and south sections of the food court, on the first floor at the east and west anchor store, and near the north and south main entrances at the ground floor. Figure 46 shows the locations and names of the zoning devices with blue, red and yellow dots representing food court level, first floor, and ground floor respectively. It is assumed that the critical location would be near the entrance area of the first floor west anchor store as the smoke would travel up through the first floor floor deck opening and enter the west anchor store. There could be a cue near the entrance area for people trying to access the west anchor store stair during emergency.

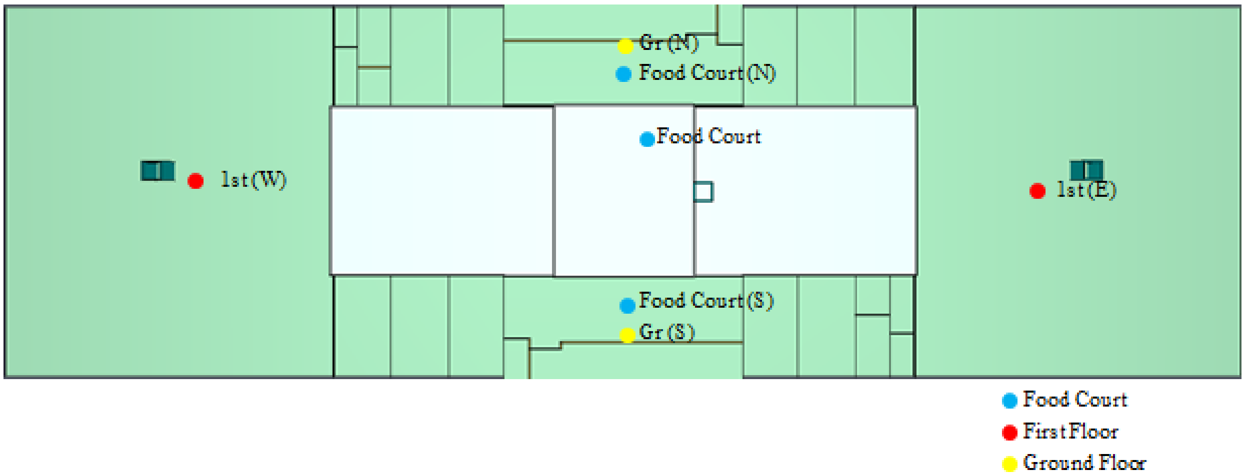


Figure 46. Locations of layer zoning devices

8.4.4 Beam Detector Device

There are no devices representing beam detectors. To represent beam detectors, several spot type detectors are placed in the raised roof area where the beam detector transmitter and receiver would be aligned. In Figure 46, the blue dots represent spot type detectors that are spaced three meters apart for the FDS setup.

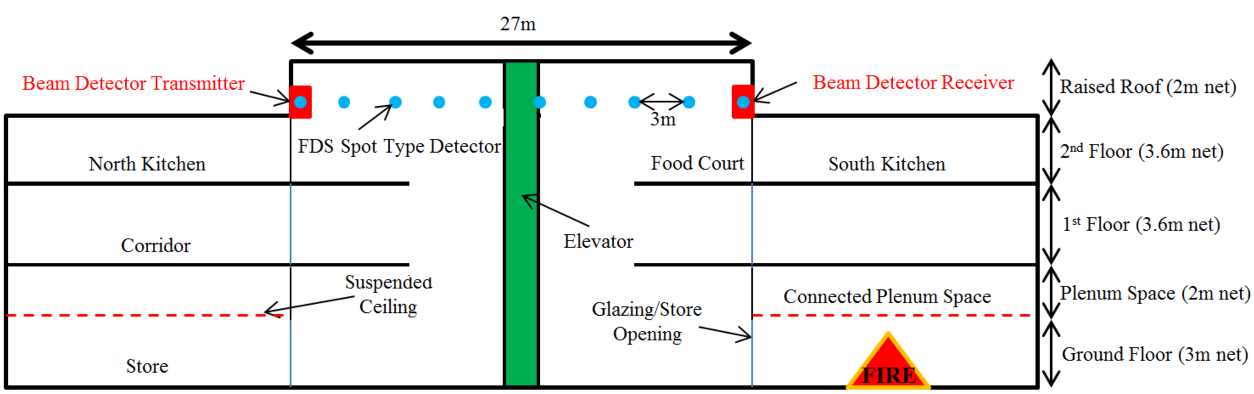


Figure 47. FDS spot type detector location

8.5 Normal Building Fire Scenario Simulation

In a normal building fire scenario, it is assumed that all of the building components would be intact and that the fire systems would work as expected. In the presented event trees, these scenarios would be FDS-1 and Pathfinder-1. Following the sequential events from the event trees, despite experiencing seismic loads, the WPI Mall would have intact sprinkler system, generic storefront system, ceiling systems, beam detectors (which operates the smoke vents), and stair system, elevator system with such probability of occurrences being 0.4% and 0.3% as seen in Figure 42 and Figure 43 respectively. Although the probabilities of having all of the fire systems intact are very small, these scenarios are modelled to show how the effects of the fire would be mitigated when all of the systems perform as expected. As a result, all of the compartment barriers are left intact and the egress components are able to function to their full capacities. The scenario is created so that a fire would occur at a clothing store in store 1.17. The FDS simulation is performed to determine the total ASET.

8.5.1 Normal Building Fire Scenario Setup for FDS

For the FDS simulation of the normal building fire scenario, scenario FDS-1, all of the storefront glazing systems, ceiling system and automatic sprinkler system are left intact. The building geometry is setup exactly to match the floor plans shown in Figure 27 through Figure 29 for the FDS simulation.

8.5.1.1 **Normal Building Fire Scenario Fire Compartment Geometry**

The clothing store (store 1.17) selected for the fire scenario, where it is assumed ignition would occur, had dimensions of 16.5m by 9.5m with a ceiling height of 3m. The opening of the store has dimensions of 9m by 3m. The adjacent spaces next to the store opening are covered with generic storefront glazing system to allow for customers to see inside the store from the corridors. The walls of the store are partition walls extending up to the ceiling height.

8.5.1.2 **Normal Building Fire Scenario Fire Compartment Design Fire**

For this scenario, as the sprinklers are intact, only five burners representing 1m by 1m clothes are used. This amount of fuel is selected because it would provide the required sprinkler activation temperature. Although the sprinkler system activation will control the fire in reality, the HRR of the fire is not affected by the sprinkler activation in FDS. This is another reason only five burners are placed in store 1.17 as there would be a lot more clothes in the clothing store but to show that the sprinkler actually controls the fire once activated and performs as expected. The setup of the burners in store 1.17 is shown in Figure 48. The box labelled as ‘1’ would be the first initial clothes set on fire and the boxes spaced 1m apart are the second clothing items that would ignite. This fire size would be adequate to activate the sprinkler. Due to the store opening, smoke is expected to leave the store and reach the raised roof area through the floor deck openings, where the beam detectors are located. Enough smoke obscuration is expected to result in the smoke detector activation. If any of the ten smoke detectors activate, that would represent beam detector activation. In FDS the smoke vents are set to activate five seconds after any of the ten detectors activate.

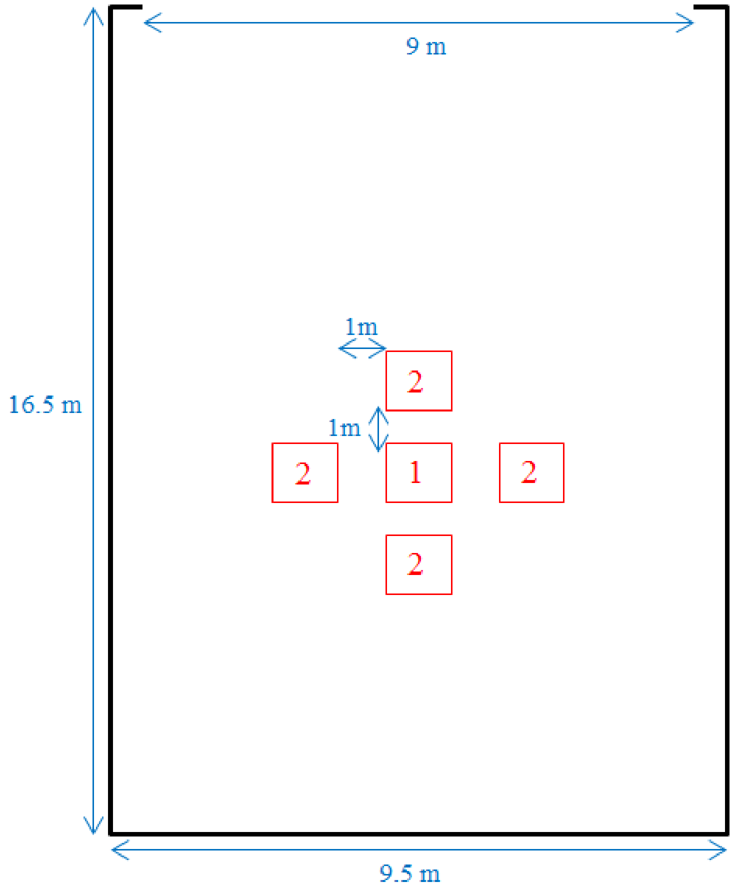


Figure 48. Set up of normal WPI Mall clothing fire in store 1.17

It is assumed that the critical heat flux for ignition of clothes to be 20 kW/m^2. All burners are spaced one meter apart. Based on this setup and assumptions, the maximum distance for pilot ignition is calculated as shown below.

$$\dot{Q}_r = \chi_r Q = 0.3(1528) = 458\ kW$$

$$R_{SD} = \sqrt{\frac{\dot{Q}_r}{4\pi q''_{r,i}}} = \sqrt{\frac{458}{4\pi(20)}} = 1.35m$$

This calculation shows that if the burner is separated more than 1.35m apart it will not ignite. Also the required radiative heat flux for the ignition of burners is determined by the following,

$$\dot{Q}_{r,critical} = \frac{4\pi q''_{r,i} R_{SD}^2}{0.3} = \frac{4\pi(20)(1)^2}{0.3} = 838\ kW$$

From the clothing fire HRR curve data, it is determined that the Test C curve reached 838 kW roughly 150 seconds after ignition. Based on these calculations, the burners are numbered in ascending order to show the sequence of ignition of all the burners as shown in Table 13. The first burner to ignite is labelled as 1 and the second burners to ignite are labelled 2, as shown in Figure 48.

Table 13. Ignition times of burners after initial ignition

Burner #	Time of Ignition (seconds)
1	0
2	150

8.5.1.3 FDS Results for Normal Building Fire Scenario

The WPI Mall as presented in the diagrams in Figure 27 through Figure 30 is modelled in FDS. The WPI Mall looking from above and below in Smokeview is shown in Figure 49 and Figure 50 respectively. The FDS file is setup so the simulation runs for 30 minutes.

Figure 49. WPI Mall looking from above in Smokeview

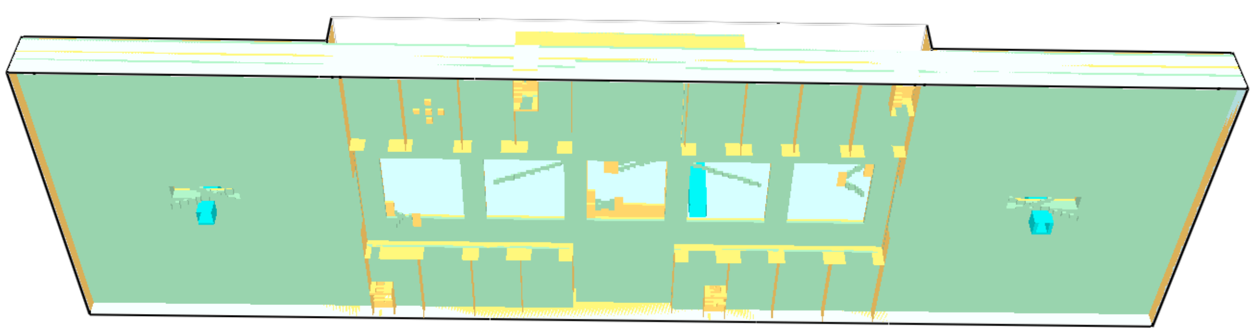


Figure 50. WPI Mall looking from below in Smokeview

With five burners placed in store 1.17, the maximum HRR of about 7100 kW is reached at about 450 seconds as shown in Figure 51. The fire reaches 300 kW at about 59 seconds after ignition, and this time would be the time occupants of the WPI Mall would take notice the fire and start to evacuate.

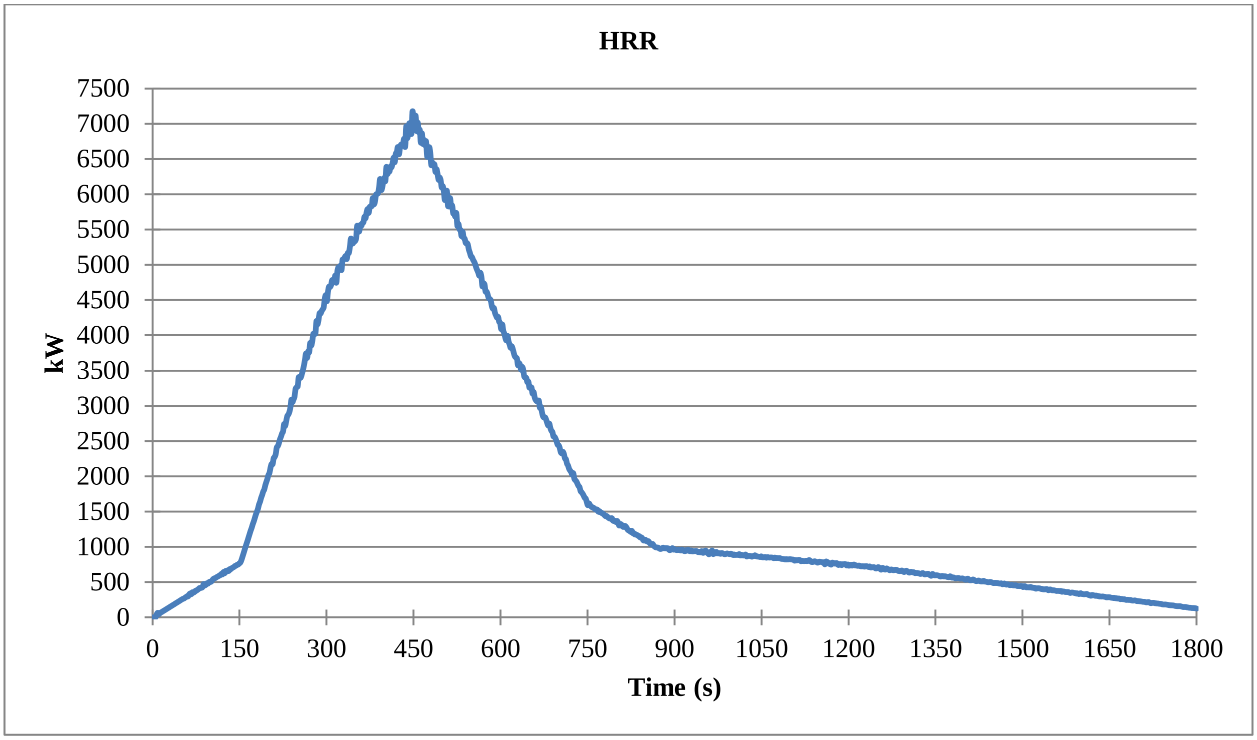


Figure 51. Normal WPI Mall HRR Curve

With an opening in the front of store 1.17, as hot gases are able to exit the fire compartment, the store 1.17 temperature only reaches about 245 °C as shown in Figure 52. With the sprinkler activation temperature being 76 °C the sprinkler activates at 230 seconds. The fastest time a smoke detector activates is at 190 seconds. Because the time it takes the fire to reach 300 kW is faster than the detector activation time, the time for the fire to reach 300 kW, 59 seconds, is selected as the start of the evacuation time.

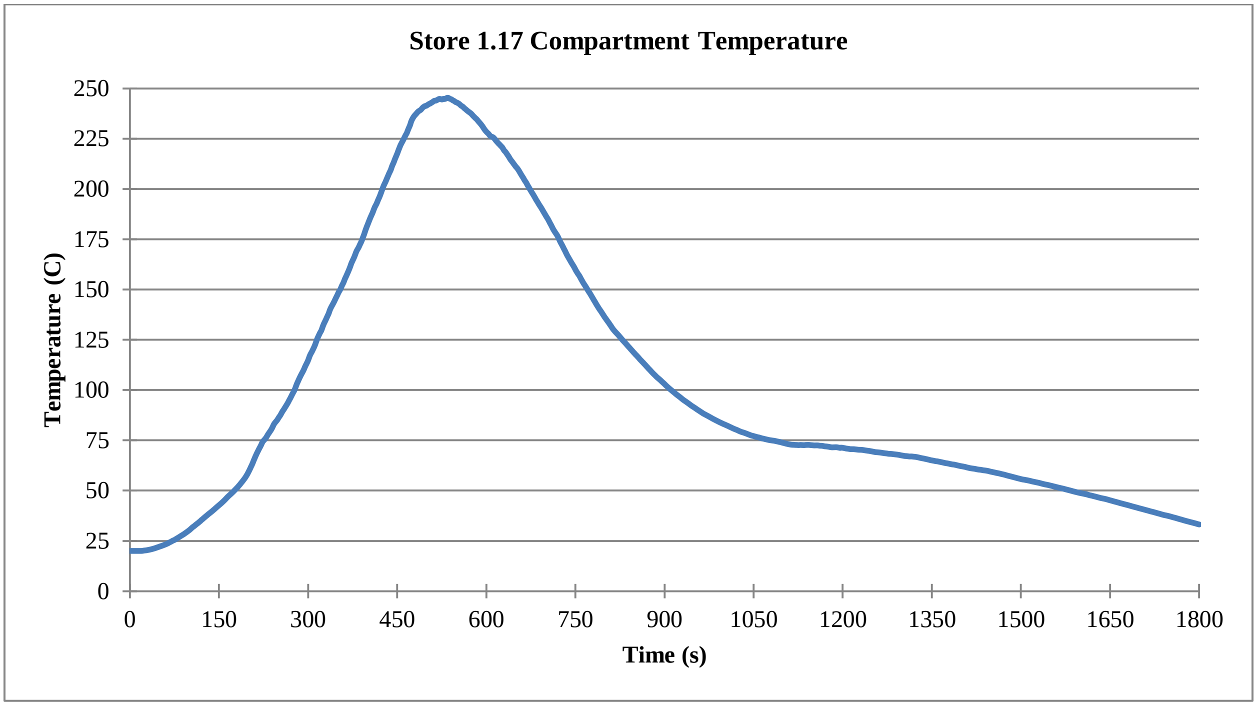


Figure 52. WPI Mall store 1.17 gas temperature at 2.8m height from floor

The smoke vents in the raised roof area activates at 195 seconds, following the smoke detector activation at 190 seconds as shown in Figure 53. The activation of the smoke vents allows for smoke extraction in the WPI Mall and helps maintain tenable conditions during the fire.

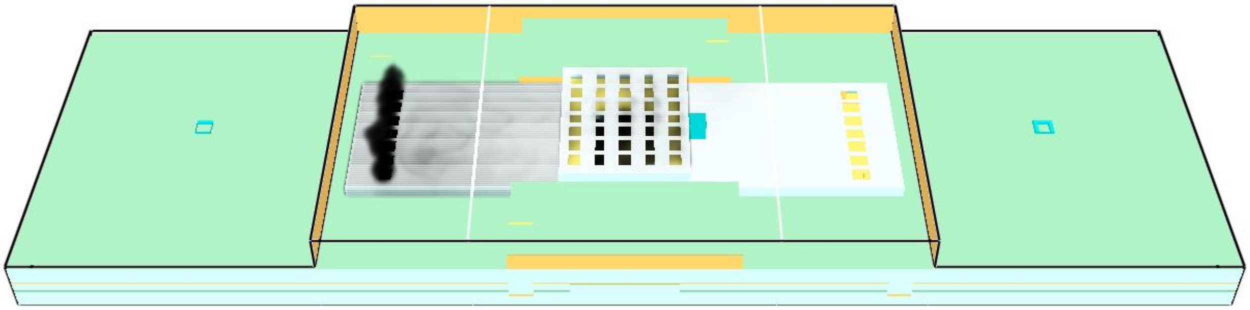


Figure 53. Smoke vent activation in Smokeview

The smoke can be seen to leave store 1.17 through the store opening and travel upward to the roof of the mall through the floor deck openings. Figure 54 is a view from below in Smokeview which shows this smoke movement inside the WPI Mall. Figure 55 and Figure 56 are elevation views showing the smoke travel paths and Figure 57 shows smoke leaving the building as the smoke vents are activated.

Figure 54. WPI Mall view from below in Smokeview

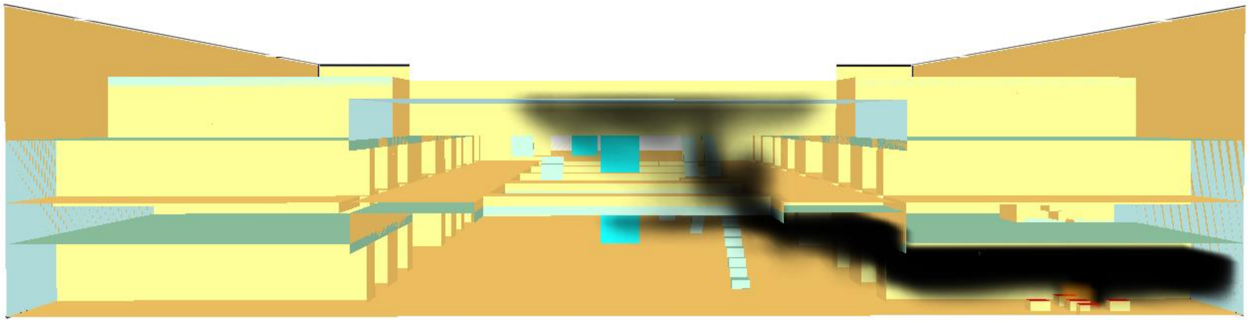


Figure 55. WPI Mall elevation view 1 in Smokeview

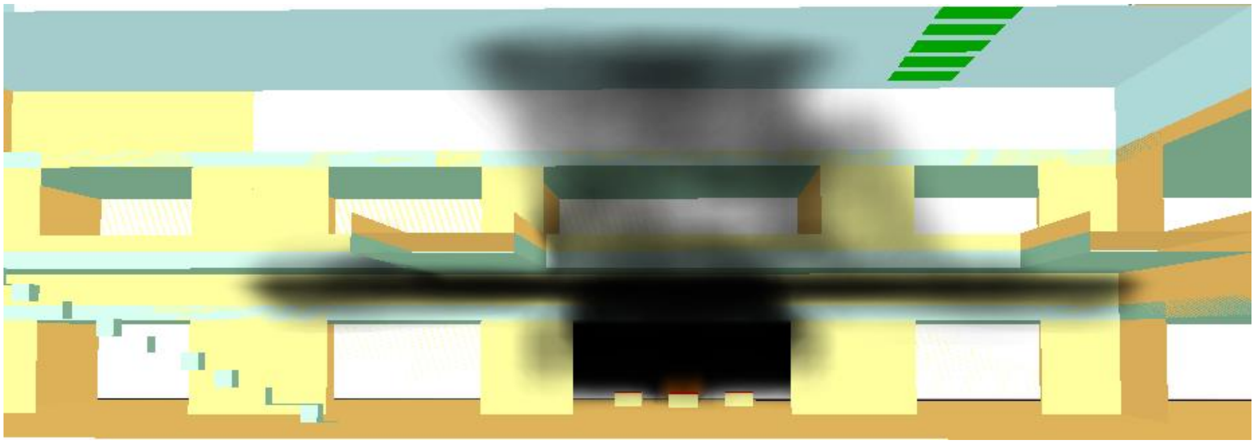


Figure 56. WPI Mall elevation view 2 in Smokeview

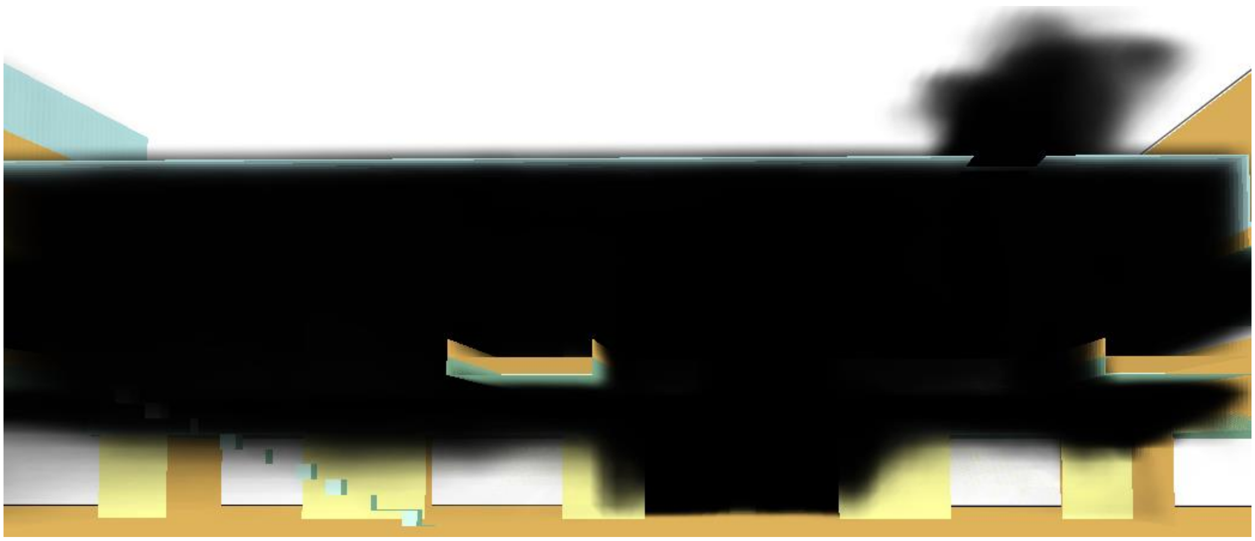


Figure 57. WPI Mall elevation view 2 with smoke vent activation in Smokeview

8.5.1.4 Smoke Movement Observation

After the initial stage of ignition, after the fire grows, it is observed that the smoke exits store 1.17 and due to the buoyancy of the smoke, it travels to the upper floors first through the openings in the first and second floor openings in the floor decks. Most of the other stores in the ground floor have no smoke penetration and only the anchor stores on either side of the building have smoke which penetrates through entrances on for the first floor and through the stair opening from the first floor floor-deck for the ground floor level. This is captured in Smokeview as shown in Figure 58.

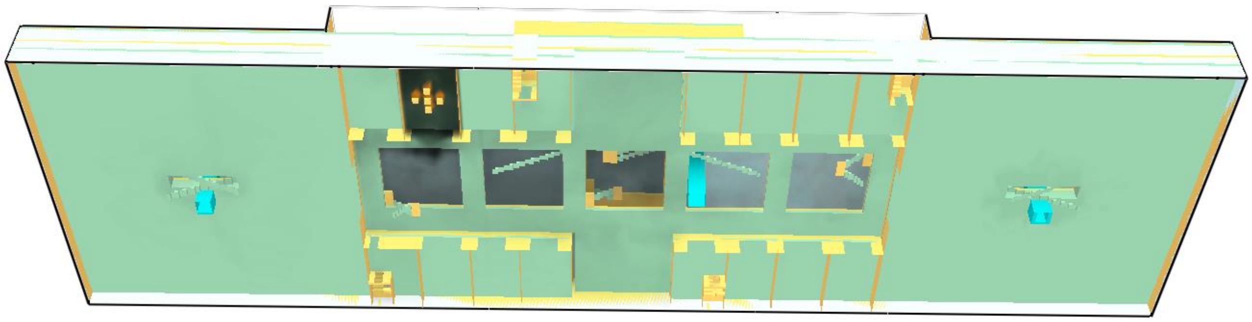


Figure 58. Normal WPI Mall Smokeview at 500 seconds

Despite the observed smoke movement in the initial stages of the fire, once the smoke vents activate, the smoke is extracted through the vents, allowing for tenable conditions to be maintained. The smoke layer heights measured in the ground floor near the South main entrance, the West Anchor shop on the first floor and the North kitchen area are plotted in Figure 59. It can be seen that during the 30 minutes of the FDS simulation, there is no change in the smoke layer height at any of the locations where the smoke layer heights are measured. This means that tenable conditions are maintained throughout the fire and the ASET could be set as 30 minutes or even longer.

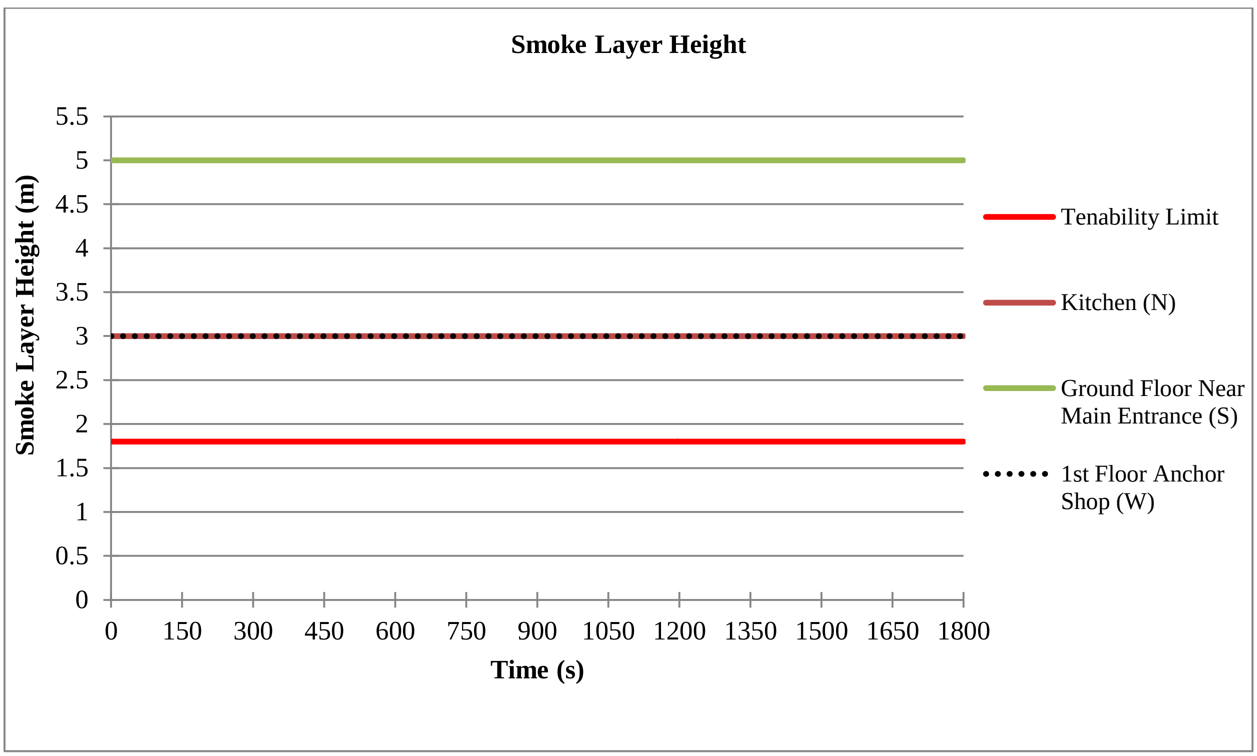


Figure 59. Smoke Layer Heights at various locations for Normal WPI Mall

The temperature measurements, taken in the locations where the smoke layer heights are measured, are plotted in Figure 60. There are no real significant changes in the temperatures of these areas to imply for any untenable conditions.

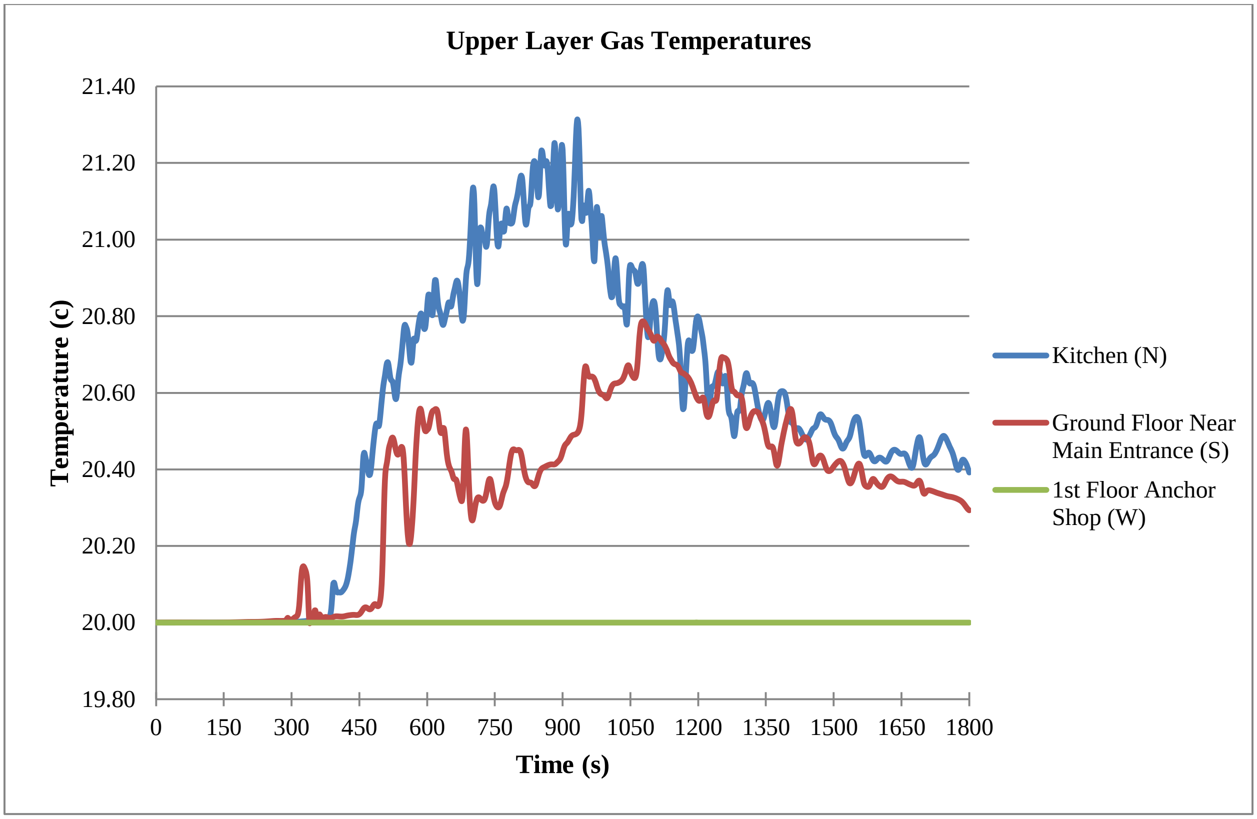


Figure 60. Time duration when smoke layer exceeds the tenability limit during normal fire scenario

The smoke layer height and temperature measurements are used to conclude that the ASET for the FDS-1 fire scenario is 30 minutes or longer.

8.5.2 Normal Building Fire Pathfinder Simulation

For the Pathfinder simulation of the normal building fire scenario, scenario Pathfinder-1 from Figure 61, all of the elevators and stairs are left intact. All of the geometry of the WPI Mall is set up to match Figure 27 through Figure 30. These entire WPI Mall spaces are populated with different occupants with their respective evacuation behavior to match the occupant characteristics presented in Table 7 through Table 9. This setup is shown in Figure 61. The various colored dots populating the WPI Mall on Figure 61 represent people with the color set to distinguish and match characteristics of each of the different occupant groups. The Pathfinder simulation is performed to determine the total RSET. For the evacuation modelling, only people on wheelchairs and canes are allowed to use the elevators to evacuate.

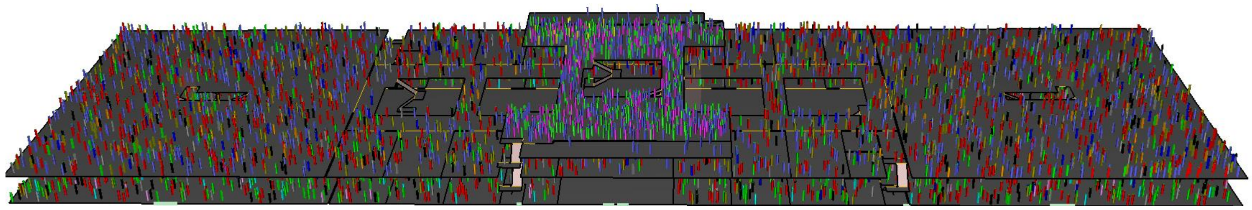


Figure 61. Normal WPI Mall Pathfinder setup

8.5.2.1 Normal Building Fire Pathfinder Results

The RSET is the amount of time (also measured from fire ignition) that required for occupants to evacuate a building or space and reach the building exterior or a protected exit enclosure. RSET consists of 3 elements plus safety factor. Details are as follows:

$$\boldsymbol{RSET = (t_{det} + t_{res} + t_{mov}) * s.f.}$$

Where

$\boldsymbol{t_{det} = detection\ time}$

$\boldsymbol{t_{res} = response\ time = pre - movement\ time}$

$\boldsymbol{t_{mov} = movement\ (travel)\ time}$

$\boldsymbol{s.f. = safety\ factor}$

Detection Time: The fire reaches 300 kW approximately 59 seconds after ignition as mentioned in the previous section.

Pre-movement (Delay) time: Based on the Table 7-5 of Tubbs & Meacham, '*Egress Design Solutions*', the pre-movement time for the mall with nondirective voice messages is 3 minutes.

Movement time: The pathfinder results show that the total evacuation time for the total occupants of 6732 people to safely exit the mall is 850.8 seconds.

The exits are numbered and labelled in Figure 62. The number of occupant usage per exit is graphed in Figure 63. The results show that the north and south main entrances, exit 1 and 7 respectively, are the least used exits. All of the stair exits are heavily used. For both of the anchor stores, the north and south exits are not as heavily used as the side exits in exits 10 and 4. The graph shows that the exit usage is pretty much evenly distributed.

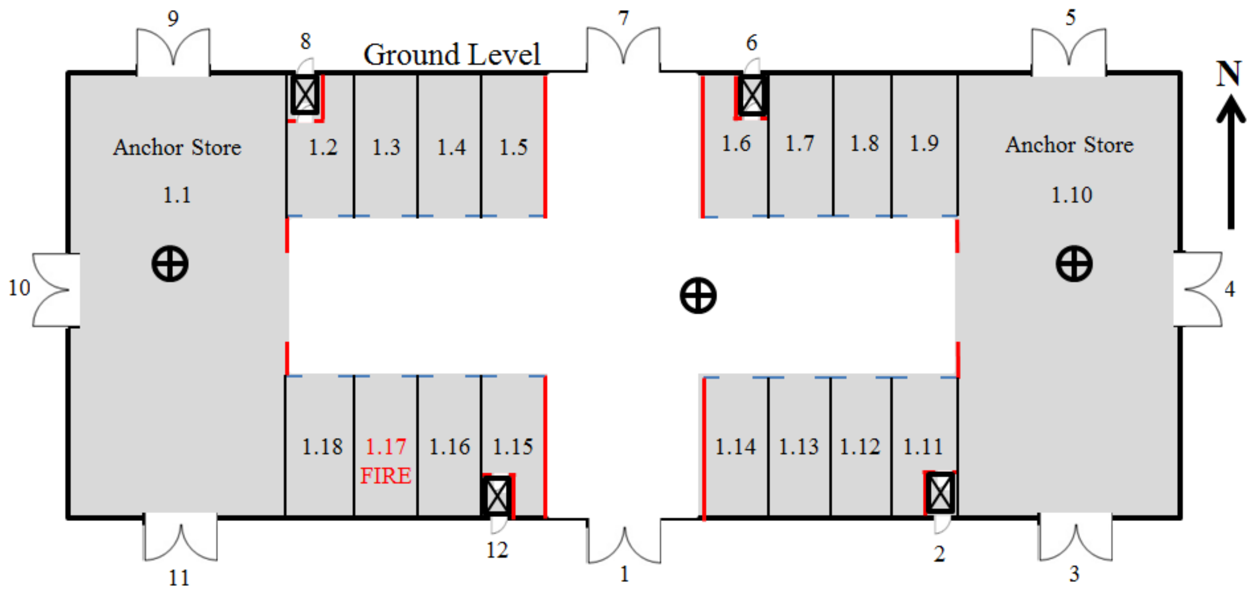


Figure 62. WPI Mall exit number label

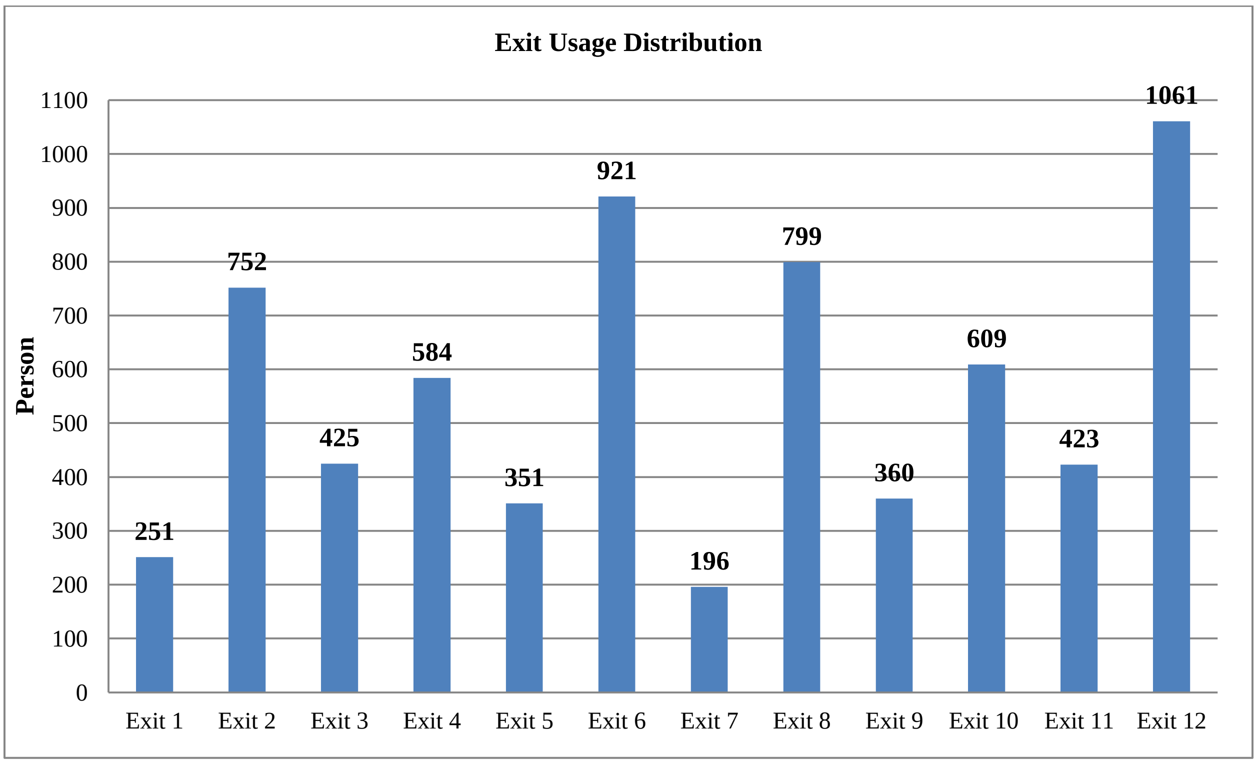


Figure 63. Number of occupant usage per exit

Figure 64 shows a screenshot taken of the WPI Mall ground floor during the Pathfinder simulation. Because all of the stairs and elevators are intact and functioning as expected, the occupants are evenly spread out amongst all the exits.

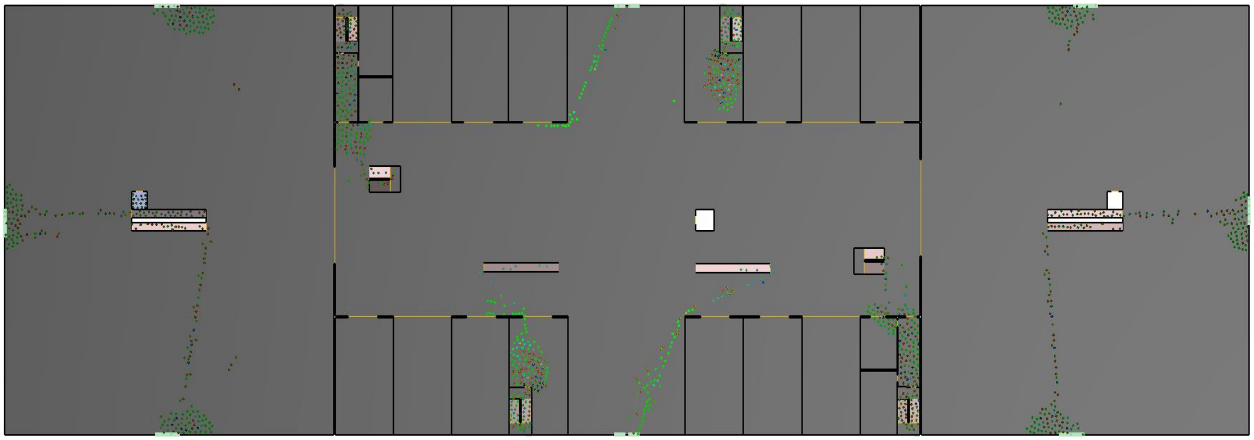


Figure 64. Pathfinder screenshot of ground floor evacuation process

Safety Factor: The value 1.5 is assumed for the safety factor.

Based on the assumptions above and the total evacuation time determined through the Pathfinder simulation, the RSET is calculated as shown below. The calculated RSET is 27.2 minutes for the Pathfinder-1 normal building fire scenario.

$$\boldsymbol{RSET} = (\boldsymbol{t_{det}} + \boldsymbol{t_{res}} + \boldsymbol{t_{mov}}) * \boldsymbol{s.f.} = (\mathbf{59} + \mathbf{180} + \mathbf{850.8}) * \mathbf{1.5} = \mathbf{1634.7}\ \boldsymbol{sec} \cong \mathbf{27.2}\ \boldsymbol{min}$$

8.6 Post-Earthquake Building Fire Scenario

The worst case conditions are selected for the post-earthquake building fire scenario. It is assumed that all of the selected building components would fail as a result of an earthquake. In the presented event trees in Figure 42 and Figure 43, these scenarios are represented in FDS-8 and Pathfinder-4 respectively. Following the sequential events from the event trees, following an earthquake, the WPI Mall would have damaged sprinkler system, generic storefront system, ceiling systems, beam detectors (which also means smoke vents will not activate), and stair system, elevator system with such probability of occurrences being 7.6% and 90.3% for scenarios FDS-16 and Pathfinder-4 respectively. Although the 7.6% probability of sprinkler, storefront glazing, ceiling systems and beam detectors (smoke vents are operated by beam detectors so failure of beam detector leads to smoke vent failure) being all damaged is relatively small, it is higher than the probability of having all the systems intact during an earthquake. As a result, the sprinkler system, generic storefront glazing system, suspended ceiling system, beam detector, smoke vents, prefabricated steel stair system, and the elevator would all be damaged and not perform as expected.

8.6.1 Post-Earthquake Building Fire Scenario Setup for FDS

Based on the event tree analysis, an earthquake damaged WPI Mall scenario selected for this FDS example is the FDS-16 scenario. It can be seen from the event tree that this scenario consists of all the mitigation systems of, sprinkler system, storefront glazing, ceiling system, and beam detector, all being damaged.

The earthquake damaged WPI Mall ground and first floor layouts are shown in Figure 65 through Figure 68 respectively. A key for the diagrams are presented in Table 14. Like the normal WPI Mall scenario, the fire is set to occur at a clothing store, store 1.17. The following sections provide further discussion on how damages are translated into modelling input parameters based on text from the ATC-58 PACT fragility damage states.

Table 14. Key for earthquake damaged WPI Mall floor plans

Sign	Representation
	Area with ceiling system
	Floor opening area
	Opening created by dislodged ceiling tiles
	Walls extending to floor deck
	Partition wall extending to ceiling system
	Storefront glazing system
⊕	Elevator
⊠	Prefabricated steel stair
	Door

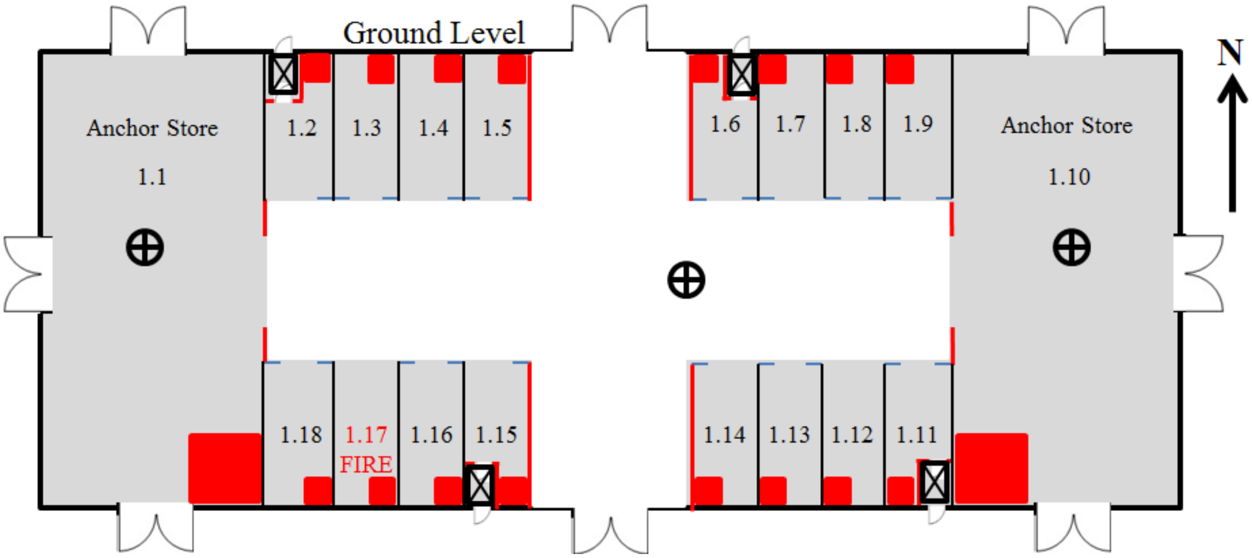


Figure 65. Earthquake damaged WPI Mall ground level layout

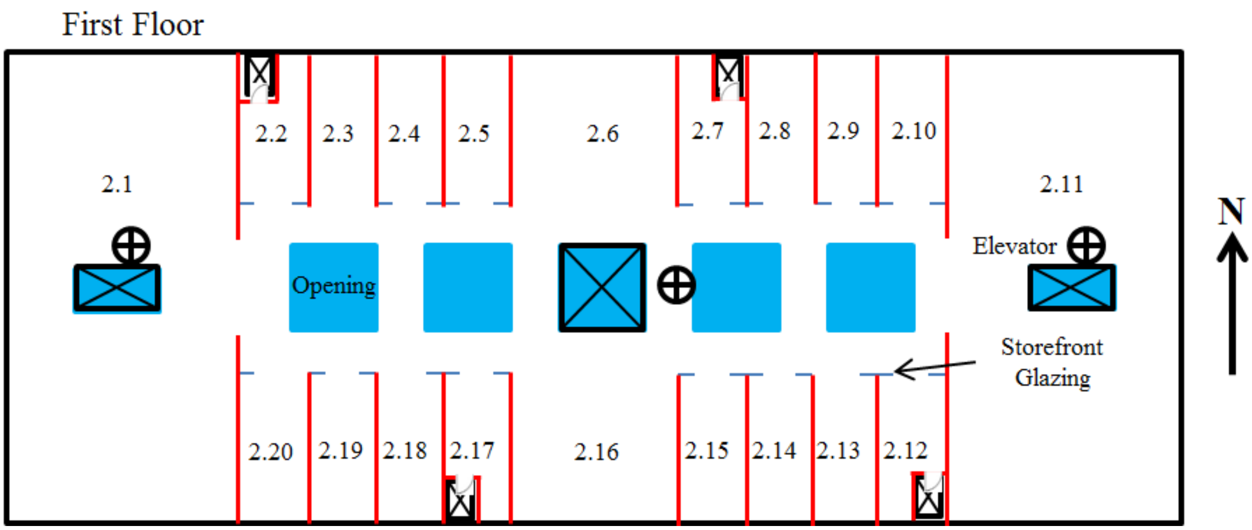


Figure 66. Earthquake damaged WPI Mall first floor layout

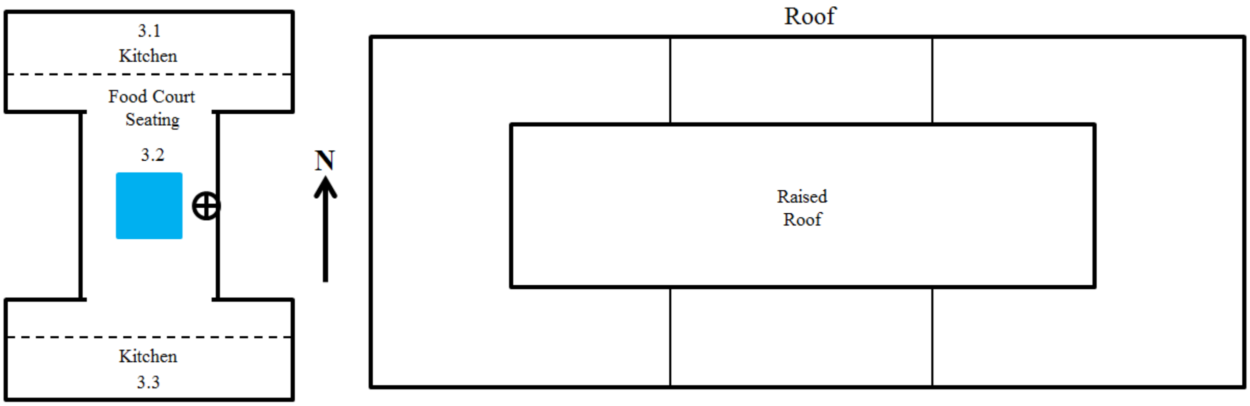


Figure 67. Earthquake damaged WPI Mall food court and roof layout

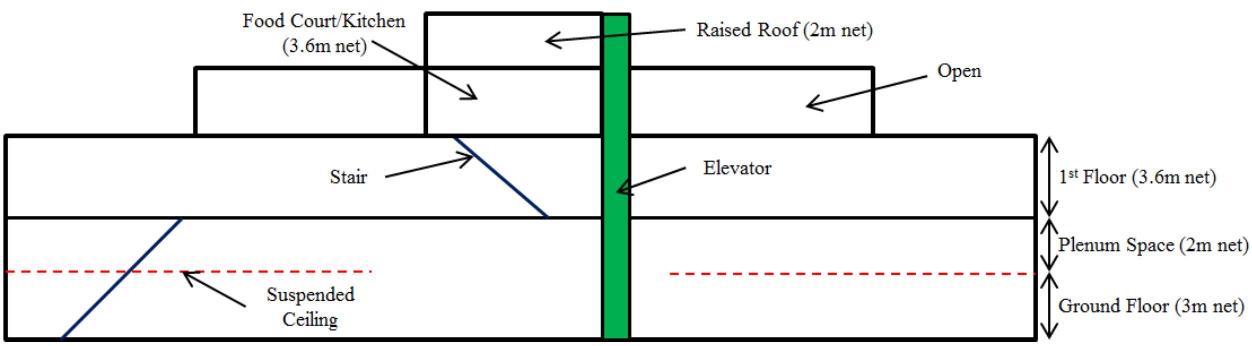


Figure 68. Earthquake damaged WPI Mall elevation view

8.6.1.1 Normal Building Fire Scenario Fire Compartment Geometry

The clothing store selected for the fire scenario where it is assumed ignition would occur, has dimensions of 16.5m by 9.5m with a ceiling height of 3m. The opening of the store has a dimension of 9m by 3m. The adjacent spaces next to the store opening are covered with generic storefront glazing system to allow for customers to see inside the store from the corridors. The walls of the store are partition walls extending up to the ceiling height.

8.6.1.2 Beam Detectors and Smoke Vents

The beam detector earthquake damage mode selected is disassembly of rod system at connections, low cycle fatigue failure of the threaded rod, pullout of rods from ceiling assembly. This is from the ATC-58 PACT fragility data on independent pendant lighting system as there is no fragility data on beam detectors. However, the two systems are similar in that they are both mounted to the wall or ceiling so it is also assumed the damaged mode is similar for this example. Disassembly of rod system can mean the light is displaced. The same logic is applied to the beam detectors. It is assumed that either of the beam detector transmitter or receiver pivots from the wall mount bracket and is misaligned. The beam detectors will not function if the transmitter and the receiver are not aligned together.

Since the smoke vents are operated by beam detector activation, it is assumed the smoke vents will not activate as a result of the detector failure. Also, HVAC duct fire damper actuator failure was observed during the BNCS Project and since these smoke vents in the WPI Mall are mechanically operated, there could be mechanical failure to the smoke vents prohibiting them from activating as expected. All of the spot type detector devices (representing beam detector) and smoke vent openings are deleted from the FDS model to represent this damage mode.

8.6.1.3 **Automatic Sprinkler System and Design Fire**

The automatic sprinkler system earthquake damage mode selected is spraying & dripping leakage at drop joints. Although not with sprinkler system piping, there was a gas pipe disconnection at the joint area observed during the BNCS Project. Such disconnection of any piping system can occur during earthquakes so a similar damage state for the sprinkler system was selected with disconnection at joint area causing water leakage. With leakage of water in the sprinkler pipe system, it is assumed that the sprinkler would have insufficient water and water pressure, and not operate as expected.

To represent the sprinkler damage, and since the failure of sprinkler activation would mean uncontrolled fire, it is assumed that a quarter of the store would be filled with clothes and all ignite. 40 burners are placed in the store with each box representing 1m by 1m stored clothes. The burners are placed 1m apart from each other. Although, in reality, there would be more walking aisles in a normal clothing store, because dislodging of materials were observed during the BNCS Project, the boxes are spaced only 1m apart to represent this observation. The setup of the fire compartment, store 1.17 is shown in Figure 69. The first item to ignite is represented by the burner numbered '1'.

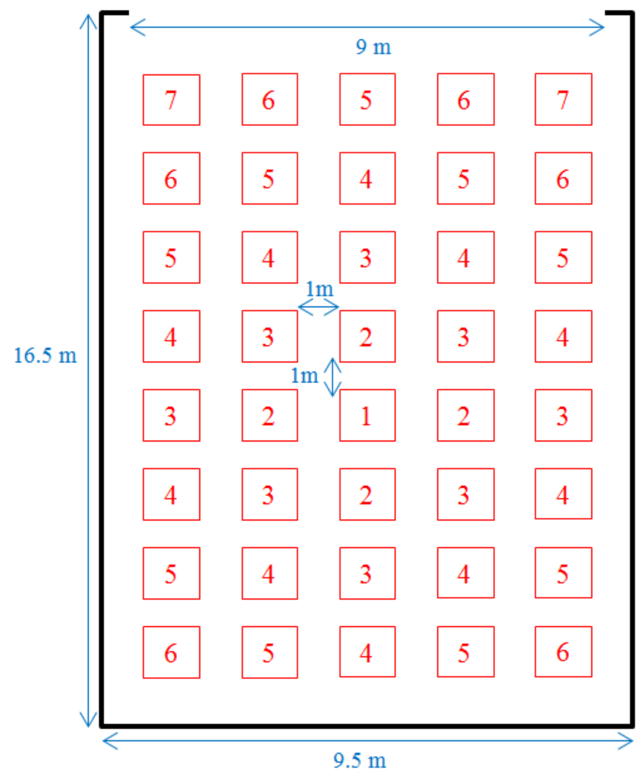


Figure 69. Set up of earthquake damaged WPI Mall clothing fire in store 1.17

Using the same critical radiant heat flux values calculated in Section 8.5.1.2, the time of ignition of all of the other burners are determined. Based on these calculations, the burners are numbered in ascending order to show the sequence of ignition of all the burners and the ignition times are shown in Table 15.

Table 15. Ignition times of burners after initial ignition

Burner #	Time of Ignition (seconds)
1	0
2	150
3	300
4	450
5	600
6	750
7	900

8.6.1.4 **Generic Storefront Glazing System Damage**

The earthquake damage mode selected for the generic storefront glazing system is glass falling out. Although extreme, to represent the worst case conditions, if the storefront glazing system fails, it is assumed that the entire glazing would fall out. The total number of storefront glazing systems (present only on the adjacent sides of the store openings) is counted. A total of 32 and 36 separate storefront glazing systems are located on each of the ground and first floor respectively. From this total number, it is expected that 27% of the storefront systems would fail and be damaged as the probability of failure of these systems are 27%. To represent 27% damage, 9 and 10 storefront glazing systems are removed from the ground and first floors respectively. It is assumed that both the glazing systems of the store opening of the fire compartment would be damaged as this would expedite the process of smoke spread throughout the mall as the opening surface area would increase. Other than these two specific glazing systems, the other storefront systems that would fail are selected randomly and to represent failure mode in FDS, the obstructions representing the glazing system are completely removed to increase the total store opening areas. It is expected that with the removal of the storefront glazing systems, it would expedite the smoke spread rate to the other compartments. As the ground floor stores are filled with smoke, this would also expedite the smoke spread to the upper floors.

8.6.1.5 **Suspended Ceiling System Damage**

The earthquake damage mode selected for the suspended ceiling system is 5% dislodged ceiling tiles. It is assumed that the ceiling tiles are nominal 0.6m by 0.6m ceiling tiles. For damage to ceiling tiles, the entire ceiling surface area is calculated for each store. From the total ceiling area, the number of ceiling tiles required to cover the area is calculated and from that an opening area is calculated that would represent 5% ceiling tile dislodged area. The openings are created at the ceiling area in FDS. The store numbers and the opening area calculated due to earthquake damage for each store are shown in Figure 65 and

Table 16 respectively.

Table 16. Ceiling damage opening area calculation

Room #	Total Ceiling Surface Area (m^2)	Total Ceiling Tiles	# of Ceiling Tiles Dislodged	Area Opening (m^2)
1.1	3000	8333	417	150
1.2	137	381	19	7
1.3	157	436	22	8
1.4	149	414	21	7.5
1.5	157	436	22	8
1.6	137	381	19	7
1.7	165	459	23	8.3
1.8	157	436	22	8
1.9	157	436	22	8
1.10	3000	8333	417	150
1.11	137	381	19	7
1.12	157	436	22	8
1.13	149	414	21	7.5
1.14	165	459	23	8.3
1.15	137	381	19	7
1.16	149	414	21	7.5
1.17	157	436	22	8
1.18	157	436	22	8

With the total ceiling damage calculated, the total area opening for each store is used to represent damage rather than using the number of total 0.6 m by 0.6 m ceiling tiles being dislodged. Holes are created in the shape of a square in the ceiling to represent tiles being dislodged. The total area opening value is square rooted to determine the dimensions of each square. Although 0.6 m by 0.6 m holes each representing a single ceiling tile could be cut out, it is assumed that the dislodged ceiling tiles would be focused in one area rather than being spread out. As a result, one square hole representing the total opening is cut out for each store.

During the BNCS Project, most of the dislodged ceiling tiles were concentrated in the corner areas. This occurred as displacement of the walls during the earthquake had distorted the ceiling grid system and furthermore dislodging ceiling tiles near the corners. To represent this observation, all of the ceiling area openings are placed in the corner areas of the ceiling for each store area.

With the additional openings created in the ceiling system, this would provide another passageway for smoke spread. As a result, this would expedite the time to reach untenable conditions. Although only the ground floor store spaces consisted of ceiling systems, the faster the smoke spread through the areas of the ground level will result in faster smoke spread to the upper floors.

8.6.1.6 **Post-Earthquake Building Fire Scenario FDS Results**

The WPI Mall as presented in the diagrams in Figure 65 through Figure 67 is modelled in FDS. The WPI Mall looking from below in Smokeview is shown in Figure 70. The FDS file is setup to run the simulation for 30 minutes to determine the ASET.

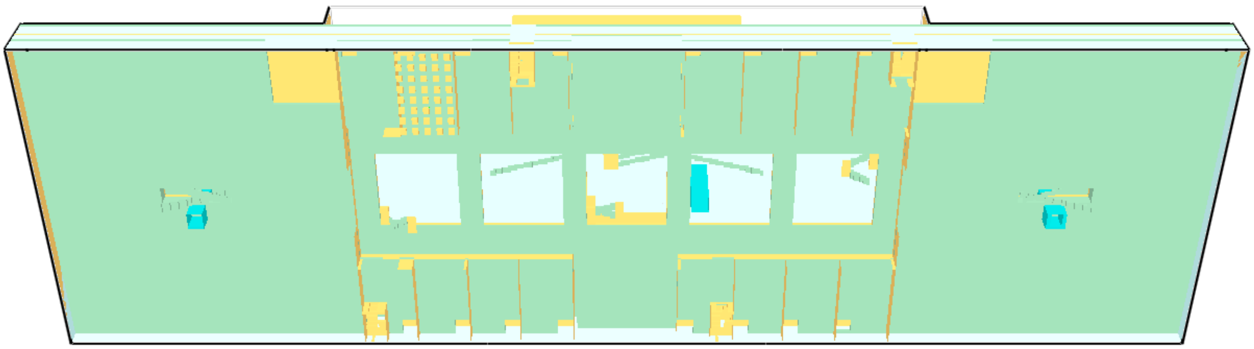


Figure 70. WPI Mall looking from below in Smokeview

With five burners placed in store 1.17, the maximum HRR of 31868 kW occurs at 835 seconds as shown in Figure 71. The fire reaches 300 kW at about 58 seconds after ignition, and this is the time occupants of the WPI Mall would take notice the fire and start to evacuate.

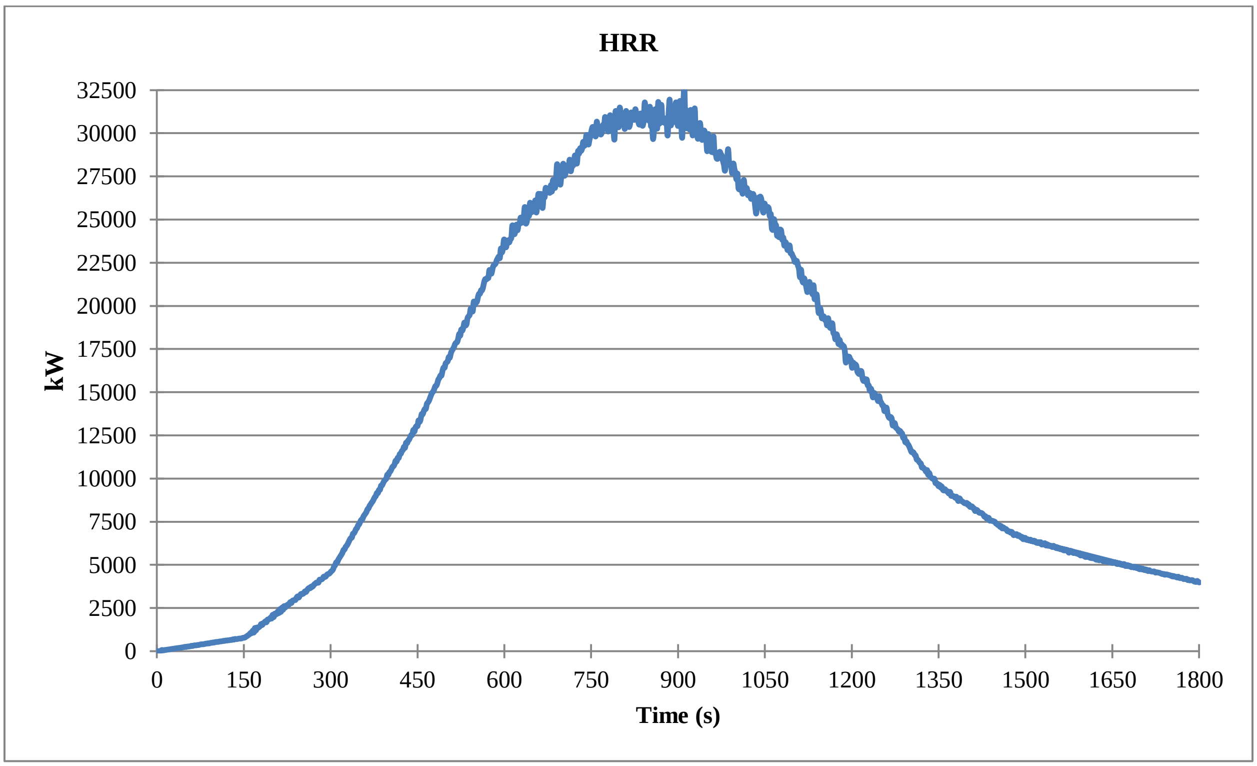


Figure 71. Post-earthquake fire building HRR Curve

With an opening in the front of store 1.17 and opening in the ceiling system representing dislodged ceiling tile damage from an earthquake, although hot gases are able to exit the fire compartment, store 1.17 temperature reached 575 ºC at 648 seconds, as shown in Figure 72, which indicates temperatures high enough for flashover conditions.

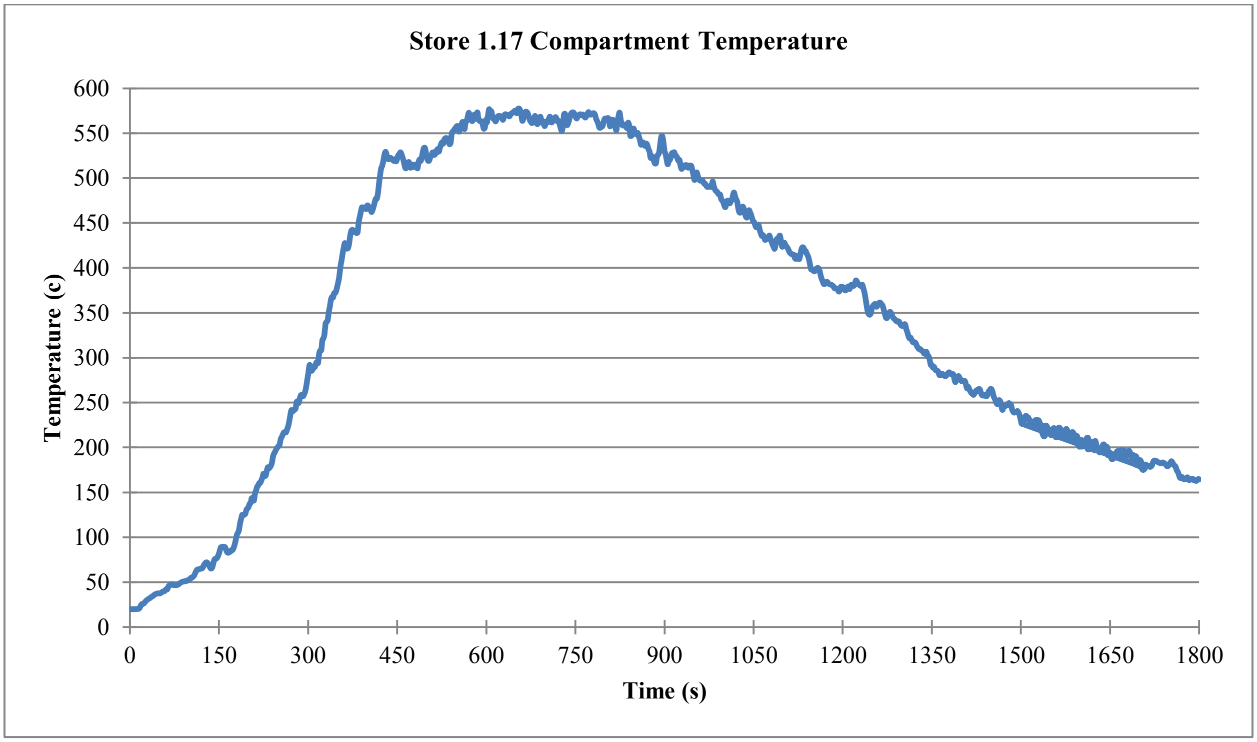


Figure 72. Post-Earthquake building fire store 1.17 gas temperature at 2.8m height from floor

As the opening created in the ceiling system to represent dislodged ceiling tile damage allowed smoke to penetrate the plenum space, extreme high temperatures are observed. The gas temperature measured in the plenum space is plotted in Figure 73. With plenum space temperatures reaching up to almost 550 ºC. this temperature is high enough to bring unprotected and exposed structural members to failure and lose their normal properties as well as load bearing capacities.

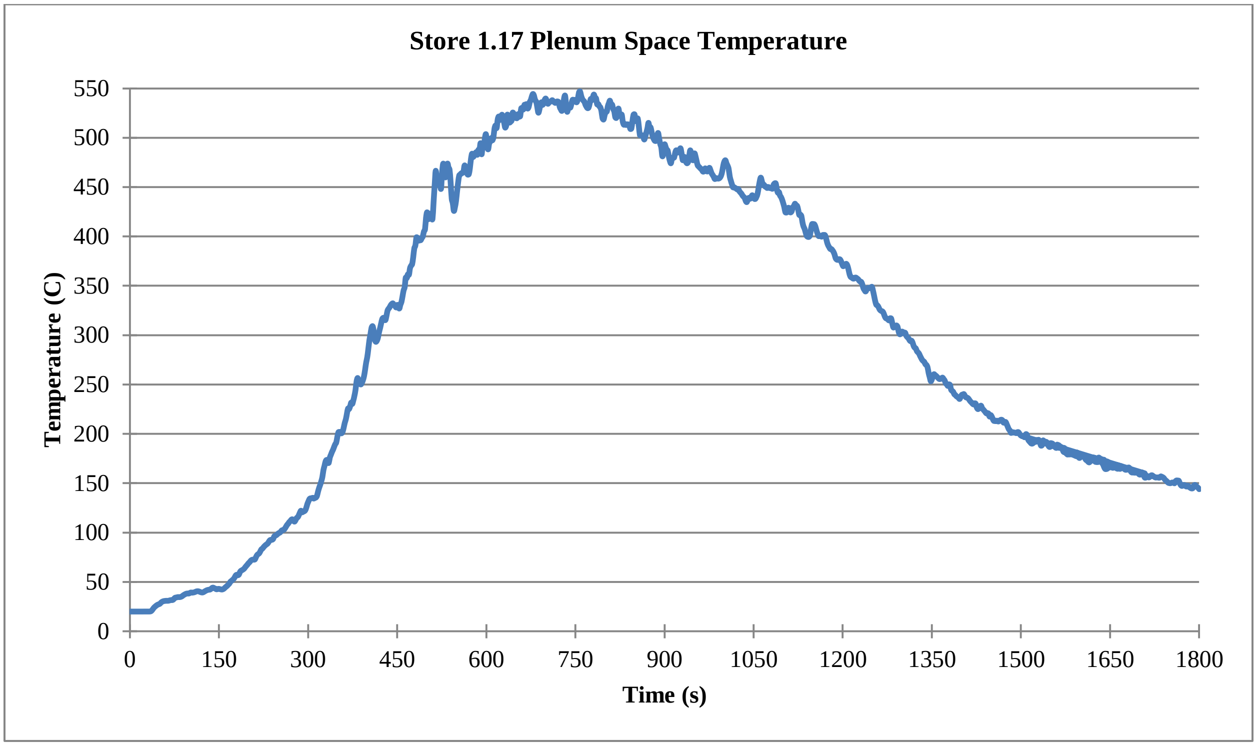


Figure 73. Store 1.17 plenum space gas temperature

8.6.1.7 **Smoke Movement Observation**

After the initial stages of ignition, after the fire grows, it is observed that the smoke travels through the plenum space via the gaps that are formed as the ceiling tiles are dislodged, and enters adjacent compartments through ceiling holes. At the same time, smoke also exits store 1.17 through the store opening, and due to the buoyancy of the smoke, it travels to the upper floors through the openings in the first and second floor openings in the floor deck. Figure 74 is nn elevation view of the WPI Mall from Smokeview taken in the initial growth stage of the fire which shows smoke entering the plenum space through the opening of the dislodged ceiling tiles and leaving the store through the store opening. Despite the smoke travelling to the upper floors through the natural openings in the floor deck, because of the multiple ceiling openings and the damaged storefront glazing openings, smoke spread in the ground floor occurs rapidly. This is captured in Smokeview as shown in Figure 75.

Figure 74. WPI Mall elevation view in Smokeview in the initial growth stage of the fire

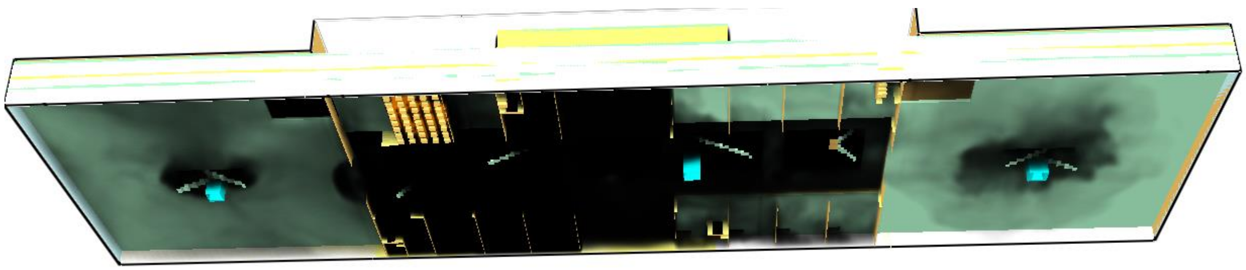


Figure 75. WPI Mall view from below in Smokeview in the fully developed stage of the fire

The smoke layer heights measured substantiates this observation seen in Smokeview. The smoke layer heights measured in the ground floor near the South main entrance, the West Anchor shop on the first floor and the North kitchen area are plotted in Figure 76. It can be seen that during the 30 minutes of the FDS simulation, smoke layer has descended greatly in the ground floor and reaches about 2.5m from the floor. In the West Anchor Store on the first floor, the smoke layer reaches 1.8m at 617 seconds and constantly keeps on descending to reach 0.5m. In the North Kitchen area, the smoke layer initially descends below 1.8m at 553 seconds but there is a lot of fluctuation in the smoke layer. However, the smoke layer remains constantly below 1.8m starting from 632 seconds and remains below 1.8m until 1364 seconds.

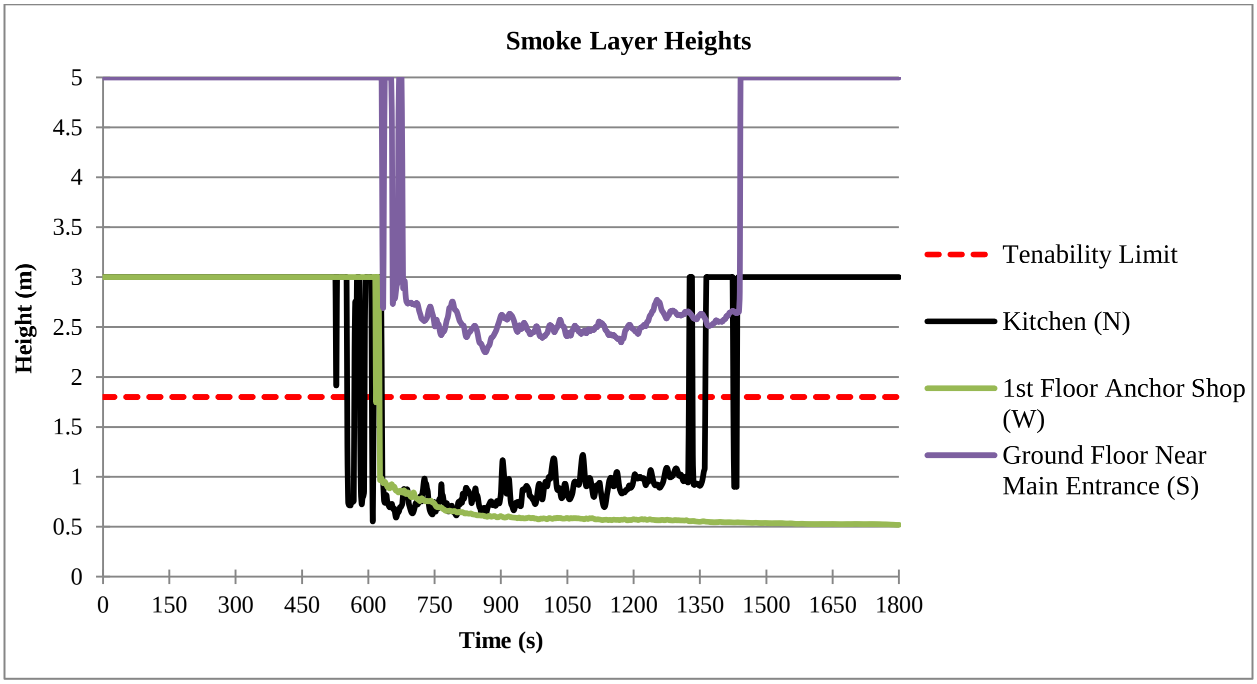


Figure 76. Post-earthquake fire Smoke Layer Heights at various locations

To investigate and look closely at the times when the smoke layer descends below 1.8m, a plot of the smoke layer heights from 500 seconds to 1150 seconds is shown in Figure 77. For the North kitchen area, there are four spikes where the smoke layer descends below 1.8m but quickly returns back to 3m. However, after these initial spikes, the smoke layer stays constantly below 1.8m from 632 seconds to 1362 seconds. In the first floor west anchor shop, the smoke layer descends below 1.8m and reaches 1m at 625 seconds and the smoke layer keeps descending to 0.5m until the end of the fire simulation.

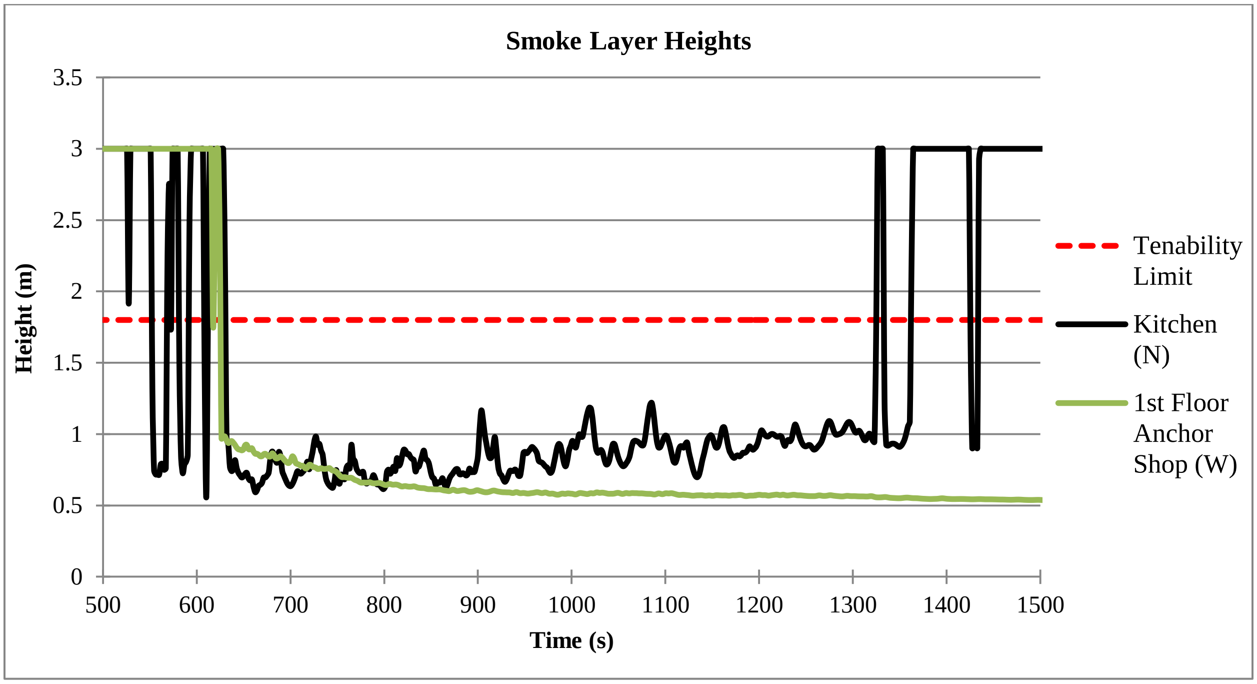


Figure 77. Time duration when smoke layer exceeds the tenability limit during post-earthquake fire scenario

Gas temperature measurements are taken at the same locations the smoke layer heights are measured. These temperature curves are shown in Figure 78. Although there is smoke penetration into various areas throughout the mall, there are no significant increases in the gas temperatures. The maximum temperature recorded is in the North Kitchen area which is about 48C. Based on the smoke layer height and temperature measurements, the ASET for the post-earthquake WPI Mall fire scenario is determined to be, 625 seconds minus the 58 seconds it takes for the occupants to recognize the fire cue, 567 seconds or 9.5 minutes.

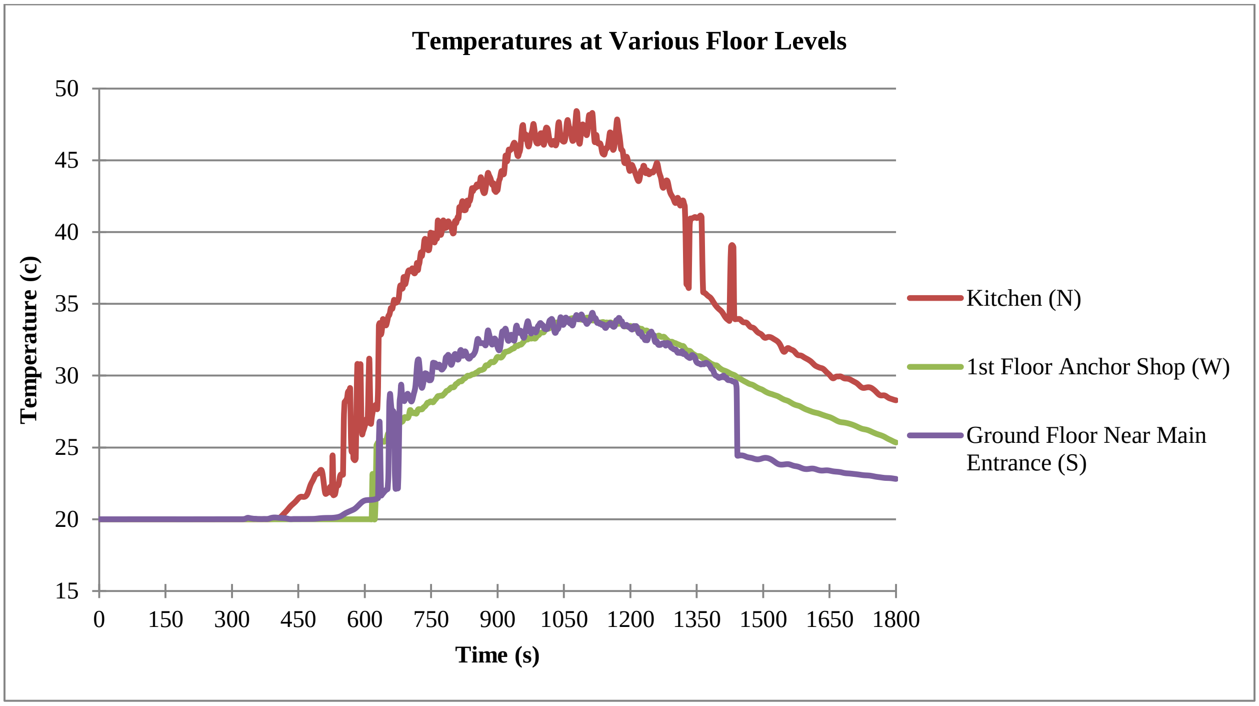


Figure 78. Post-earthquake fire upper layer gas temperatures at various locations

8.6.2 Post-Earthquake Fire Pathfinder Simulation

For the Pathfinder simulation of the post-earthquake building fire scenario, scenario Pathfinder-4 from Figure 43 is selected. For this scenario, there would be damage to stairs and the elevators. All of the geometry of the WPI Mall is set up to match Figure 68. The entire WPI Mall spaces are populated with different occupants with their respective evacuation behavior to match the occupant characteristics presented in Table 7 through Table 9. The Pathfinder simulation is performed to determine the total RSET. For the evacuation process, only people on wheelchairs and canes are allowed to use the elevators to evacuate. The damage states for stairs and elevators, and how these damage states are translated into the Pathfinder modelling are presented in the following sections.

8.6.2.1 **Prefabricated Steel Stair Damage Selection and Representation**

The selected failure mode for prefabricated steel stairs following an earthquake is loss of live load capacity. This could be translated as stairs not having the full capacity to support live loads. This would mean that the stairs are unusable for the occupants during evacuation. For the selected design earthquake motion and the resulting building response values, the likelihood of stairs experiencing this damage mode is identified to be 95%. There are a total of 10 stairs connecting the ground floor with the first floor and a total of four stairs connecting the first floor to the food court and kitchen area. To represent 95% damage and failure probability to the stairs, all but one stair is selected to be damaged and unusable for each of the connecting floors. Because the occupants from the food court would land in the middle of the first floor, all of the stairs located in the middle of the ground floor are selected to be damaged and the only intact stair selected on the ground floor is the one located in the West wing of the WPI Mall as shown in Figure 79. There is only one stair left intact in the first floor of the building connecting the food court and kitchen floor as shown in Figure 80. These stairs are selected to be damaged as it would represent the worst case scenario as it would increase the travel distance of occupants traveling from the food court to the first floor as well as occupants that are located in the East Anchor store on the first floor of the WPI Mall as they would have to travel to the other side of the building to access an egress system. To represent this damage mode in the Pathfinder model, the stairs that are damaged are simply just removed from the model. The various colored dots populating the WPI Mall on Figure 79 and Figure 80 represent people with the color set to distinguish and match characteristics of each of the different occupant groups.

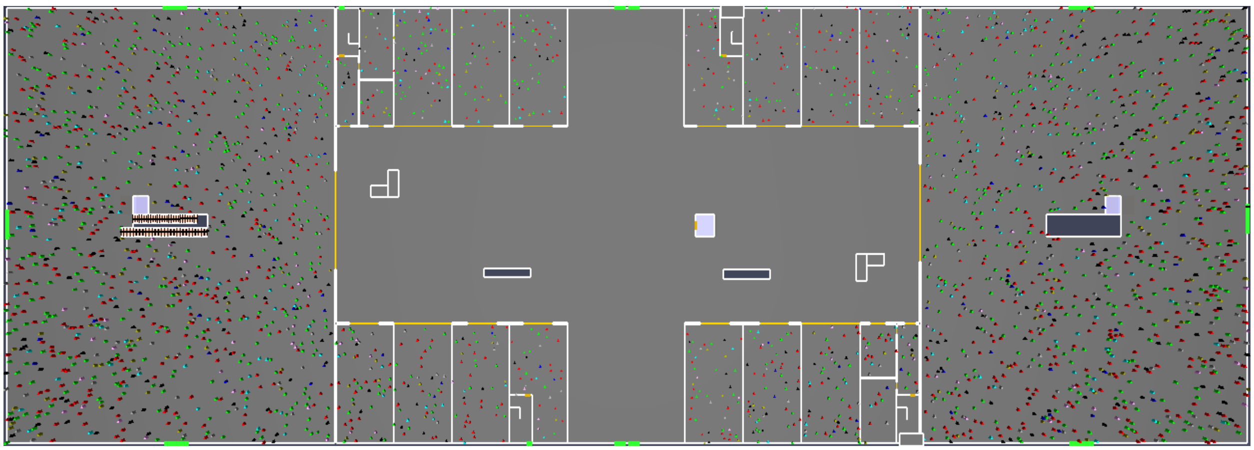


Figure 79. Post-earthquake damaged ground floor of WPI Mall

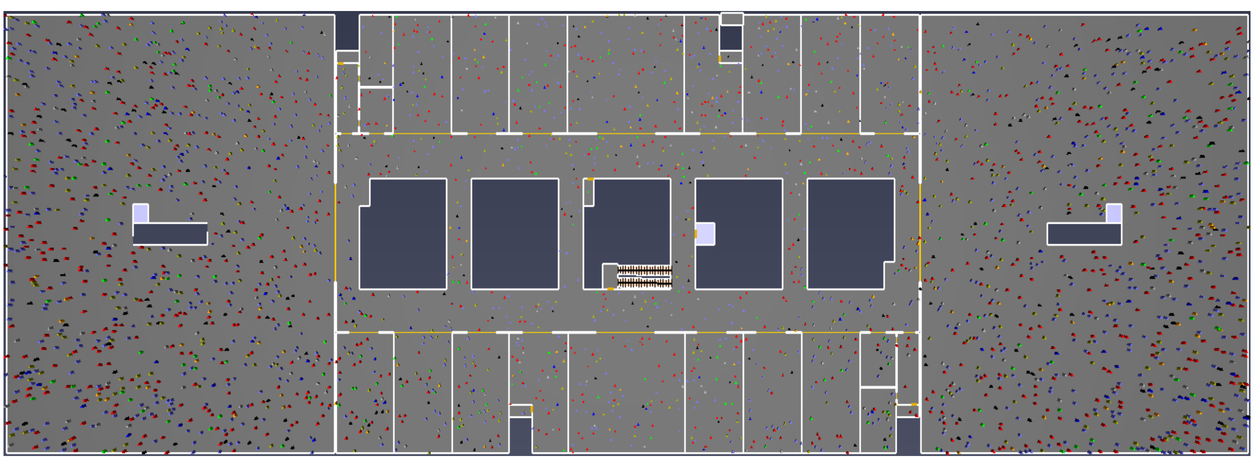


Figure 80. Post-earthquake damaged first floor of WPI Mall

8.6.2.2 Elevator System Damage Selection and Representation

The selected failure mode for the elevator system following an earthquake is controller anchorage failure, and or machine anchorage failure, and or motor generator anchorage failure, and or governor anchorage failure, and or rope guard failure. This could be translated as elevator cab malfunction and simply mean failure of the elevator operation during the evacuation process. For the selected design earthquake motion and the resulting building response values, the likelihood of elevators experiencing this damage mode is identified to be 95%. To represent the 95% probability of failure, all of the elevators except for the one located in the middle atrium space of the WPI Mall, as shown in Figure 68, are selected to be damaged and inoperable. The middle elevator is selected to be operable because this is the only elevator to travel all the way up to the food court and kitchen floor. Because all of the occupants on canes and wheelchairs are set to use the elevators for evacuation, it is required that there is at least one elevator that travels to all floors of the building. To represent the elevator damage, the elevators are simply disabled for the Pathfinder simulation.

8.6.2.3 Post-Earthquake Building Fire Pathfinder Results

The RSET is the amount of time (also measured from fire ignition) that required for occupants to evacuate a building or space and reach the building exterior or a protected exit enclosure. RSET consists of 3 elements plus safety factor. Details are as follows:

$$\boldsymbol{RSET = (t_{det} + t_{res} + t_{mov}) * s.f.}$$

Where

$\boldsymbol{t_{det} = detection\ time}$

$\boldsymbol{t_{res} = response\ time = pre - movement\ time}$

$\boldsymbol{t_{mov} = movement\ (travel)\ time}$

$\boldsymbol{s.f. = safety\ factor}$

Detection Time: The post-earthquake fire reaches 300 kW approximately 58 seconds after ignition as shown in Figure 71.

Pre-movement (Delay) time: Based on the Table 7-5 of Tubbs & Meacham, '*Egress Design Solutions*', the pre-movement time for the mall with nondirective voice messages is 3 minutes.

Movement time: The pathfinder results showed that the total evacuation time for the total occupants of 6732 people to safely exit the mall is 1734.8 seconds.

The exits are numbered and labelled in Figure 81. The number of occupant usage per exit is graphed in Figure 82. The results show that the more than half of the entire WPI Mall occupants exited the building through Exits 10 and 11, which are located in the west anchor store.

This occurred as the only stair connecting the first floor to the ground floor is the stair located in the west anchor store. The least used exits are the stairway exits, exits 2, 6, 8 and 12, as these stairs are removed to represent earthquake damage.

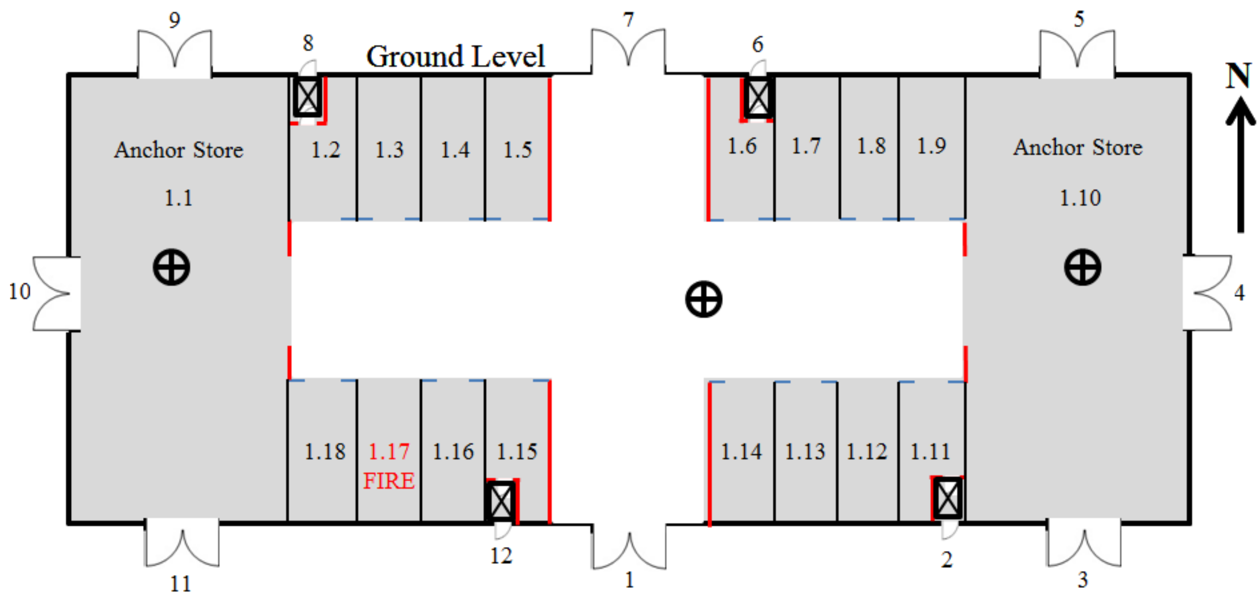


Figure 81. WPI Mall exit number label

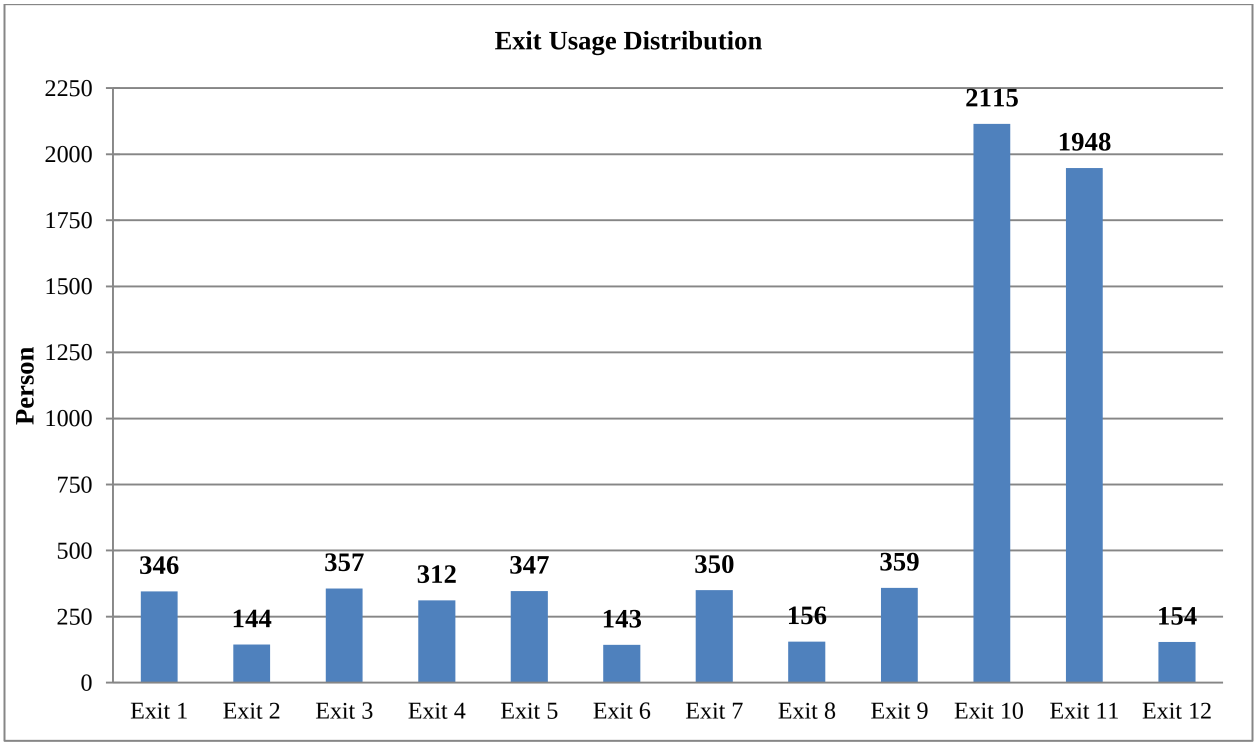


Figure 82. Number of occupant usage per exit

Safety Factor: The value 1.5 is assumed for the safety factor.

Based on the assumptions above and the total evacuation time determined through the Pathfinder simulation, the RSET is calculated as shown below. The calculated RSET is 46.6 minutes for Pathfinder-4, post-earthquake building fire scenario.

$$\boldsymbol{RSET = (t_{det} + t_{res} + t_{mov}) * s.f. = (59 + 180 + 1734.8) * 1.5 = 2960.7\ sec \cong 46.6\ min}$$

8.6.2.4 Post-Earthquake Fire Pathfinder Result Observations

From the Pathfinder simulation of the post-earthquake building fire scenario, it is seen that all of the occupants from the food court and kitchen floor and the first floor has to travel to the West Anchor store of the WPI Mall as the only stair connecting the first floor to the ground floor is located in the middle of the West Anchor shop. However, because the occupants on the wheelchair and canes have to access the elevator to evacuate, they have to travel through the opposite direction from most of the other occupants to try to get to the middle of the floor where the elevator is located. Besides the damaged stairs and elevators missing, this is another reason that for the long evacuation time. Figure 83 is taken from the Pathfinder simulation which shows all the occupants gathered around the west anchor store stair or the elevator to access the only egress systems that are intact and fully functioning.

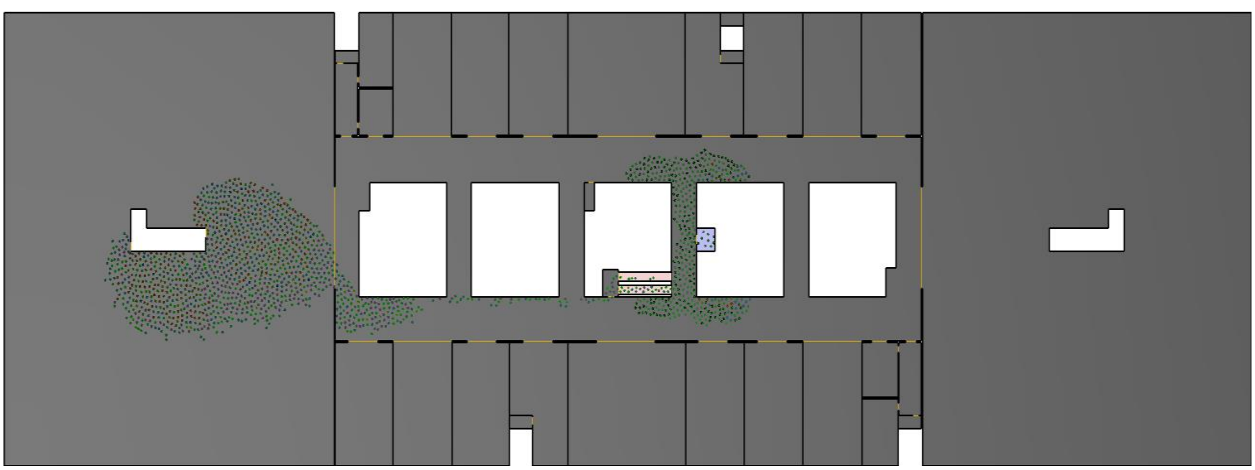


Figure 83. WPI Mall first floor from the Pathfinder simulation showing occupant evacuation route

9 Results

In Chapter 8, two different design fire scenarios, a normal-undamaged and a post-earthquake fire, are created and simulated through FDS and Pathfinder. With the smoke layer height of 1.8m from the floor level selected as the performance criteria, the smoke layer heights are measured in several locations in the WPI Mall building to determine the ASET through FDS. The WPI Mall is fully populated with occupants and with the specific occupant characteristics assumed the RSET is determined through Pathfinder. The ASET/RSET times for each of the normal and post-earthquake WPI Mall fire scenarios are shown in Figure 84.

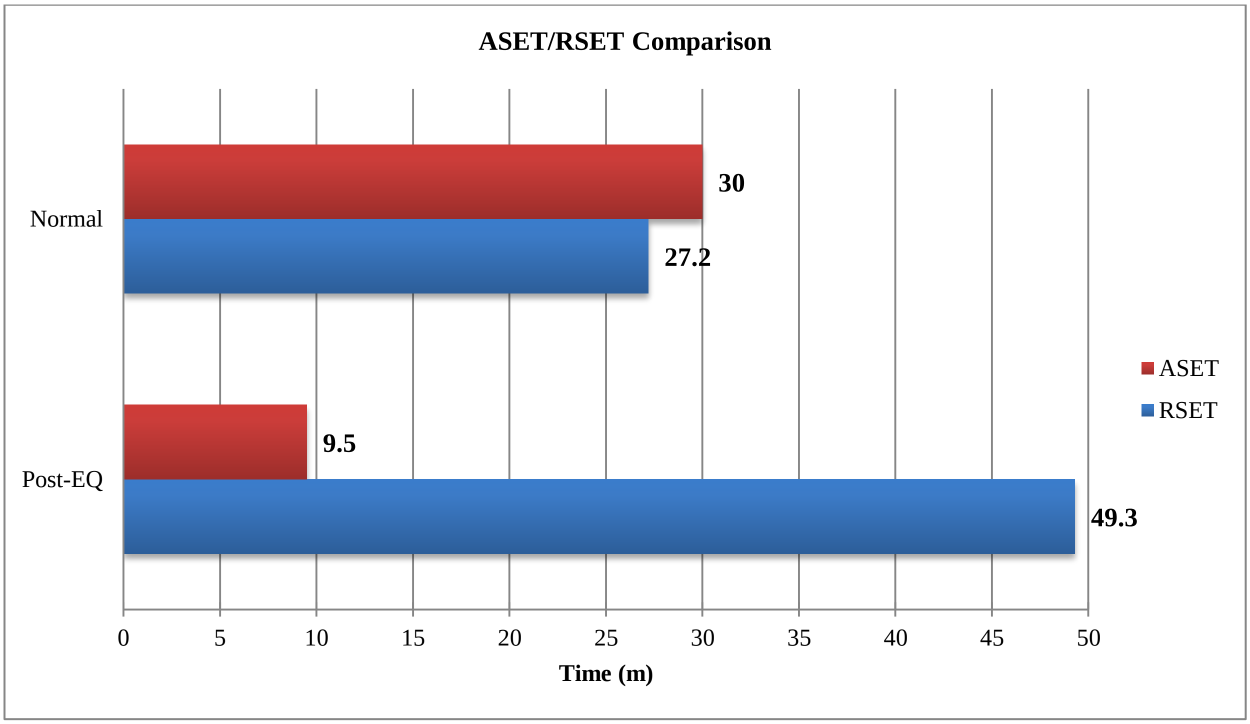


Figure 84. WPI Mall fire scenarios ASET/RSET comparison

The bar chart shows a significant difference between the ASET/RSET values for the two scenarios. The ASET is greater than the RSET for the normal fire scenario proving the design of the WPI Mall is safe under a clothing store fire in store 1.17. The results also show that when a building is damaged from an earthquake, this can severely affect the building fire safety performance as the RSET is about five times greater than the ASET. The effect of the damages to the building components from earthquake is easily visible as the post-earthquake fire scenario results show that the ASET is reduced by 20 minutes and the RSET is increased by about 20 minutes when compared to the results of the normal fire scenario.

9.1 ASET Results Comparison

The ASET is determined by investigating the time when untenable condition is reached. This untenable condition was identified as when the smoke layer height reaches or descends below 1.8m height from the floor level. With the fire originating from one of the clothing store in the ground floor, the smoke leaves the store via the store opening and travels to the upper floors through the openings provided in the first floor floor-deck. As a result, it is the food court and kitchen areas which the smoke reached first. The smoke layer heights measured for both fire scenarios in the North Kitchen area is shown in Figure 85. The results show that there is not enough smoke to fill up the kitchen room for the normal fire scenario as the sprinkler system controls the size of the fire and the smoke vents extract smoke out of the building. In the post-earthquake fire scenario, the fire is allowed to grow and produces large amounts of smoke. For the post-earthquake fire scenario, there is absolutely no change in the smoke layer height. But during the post-earthquake fire scenario the smoke layer is constantly below 1.8m for a long duration of time.

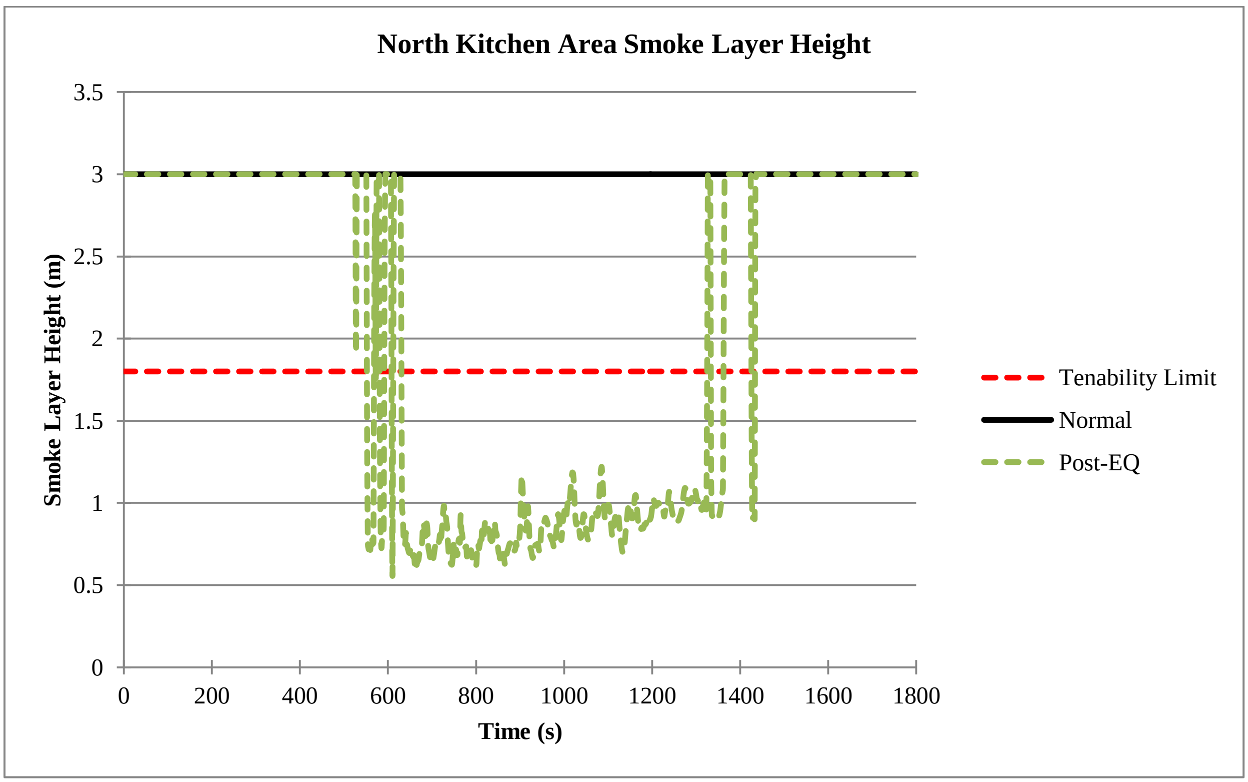


Figure 85. Smoke layer height comparison in North kitchen area

This same trend is observed in the first floor west anchor store as well. The smoke layer height measurement taken at the first floor west anchor shop, in Figure 86, shows that again, there is no change in the smoke layer height for the normal fire scenario, but a significant drop in the smoke layer height for the post-earthquake fire scenario. The smoke layer height reaches almost 0.5m in the first floor west anchor shop in the post-earthquake fire scenario. This location where the smoke layer height is measured is deemed the most critical location as the smoke would leave store 1.17 and travel up through the floor deck openings and enter into the first floor west anchor shop. This is a location where a lot of the occupants could be cueing up to access the west anchor store stair.

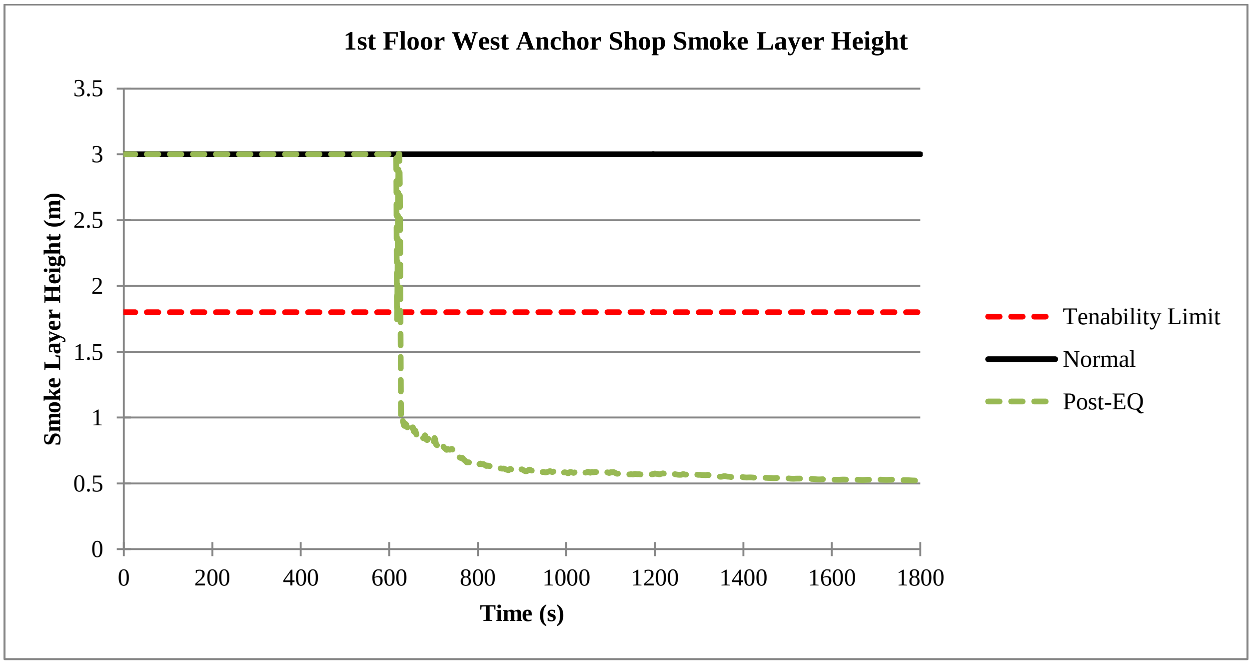


Figure 86. Smoke layer height comparison in the 1st floor west anchor shop

Because of the additional openings that are created in the post-earthquake fire scenario due to dislodged ceiling tiles in the ground floor ceiling system, this exacerbates the smoke spread in the ground floor. Figure 87 shows that there is no change in smoke layer height in the ground floor near the south main entrance for the normal fire scenario. However, the smoke layer height descends greatly in the post-earthquake fire scenario to reach below 2.5m but does not reach below the performance criteria of 1.8m.

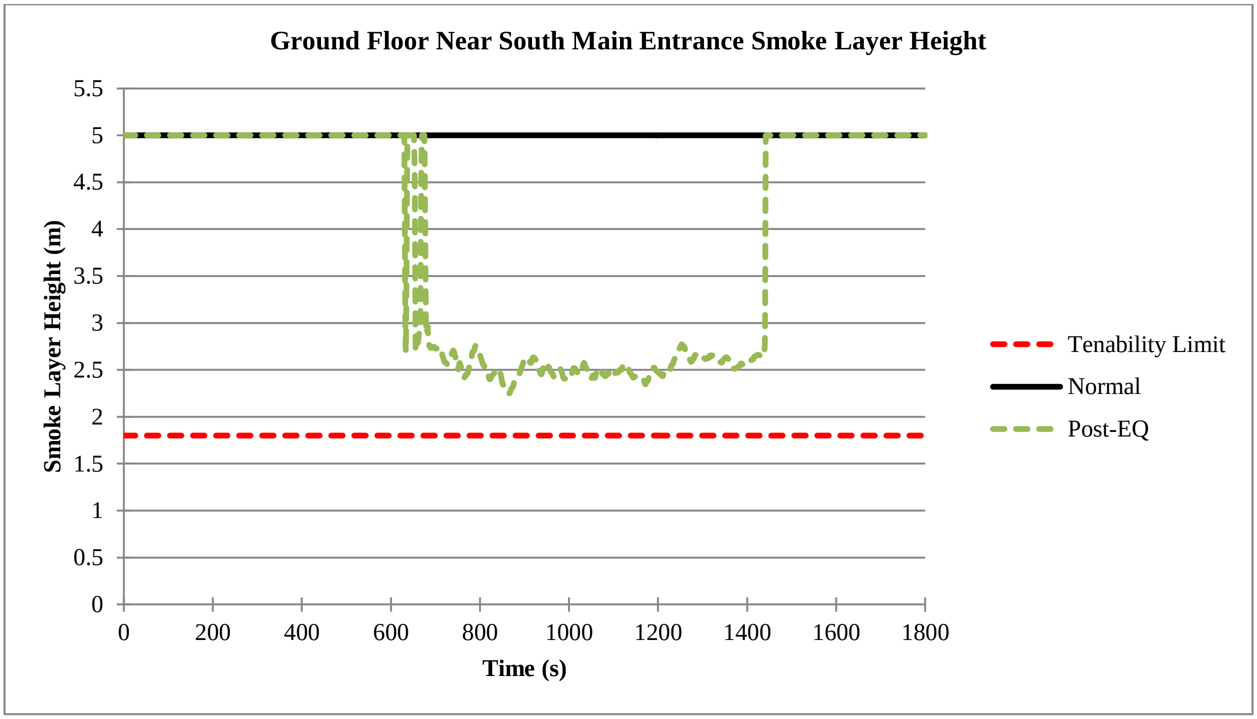


Figure 87. Smoke layer height comparison near the ground floor south main entrance

The smoke layer height data shows that controlling the fire size through sprinkler activation and extracting smoke through smoke vents work to maintain tenable conditions for the normal fire scenario. The post-earthquake fire scenario results show that failure of sprinkler system and smoke vents allows for smoke to fill up the WPI Mall quickly. Also, the additional openings created and changes in geometry can affect the smoke spread direction. For the post-earthquake damaged building, the openings representing dislodged ceiling tiles and the broken storefront glazing system expedites the smoke spread in the other ground floor areas. This shows that additional openings in a building compartment as a result of an earthquake can significantly affect the smoke spread to other unexpected and critical areas that would not be expected in normal fire conditions.

9.2 RSET Results Comparison

The RSET for both fire scenarios are determined by using Pathfinder. With the specified occupant characteristics and assumptions, the total movement time is determined through this evacuation modelling exercise. Based on this time, the assumed response time, and the identified detection time through FDS, the total RSET time is calculated. Figure 84 shows that there is a great disparity in the RSET between the normal and post-earthquake fire scenarios. More detailed travel times of occupants to evacuate each floor level is shown in Figure 88.

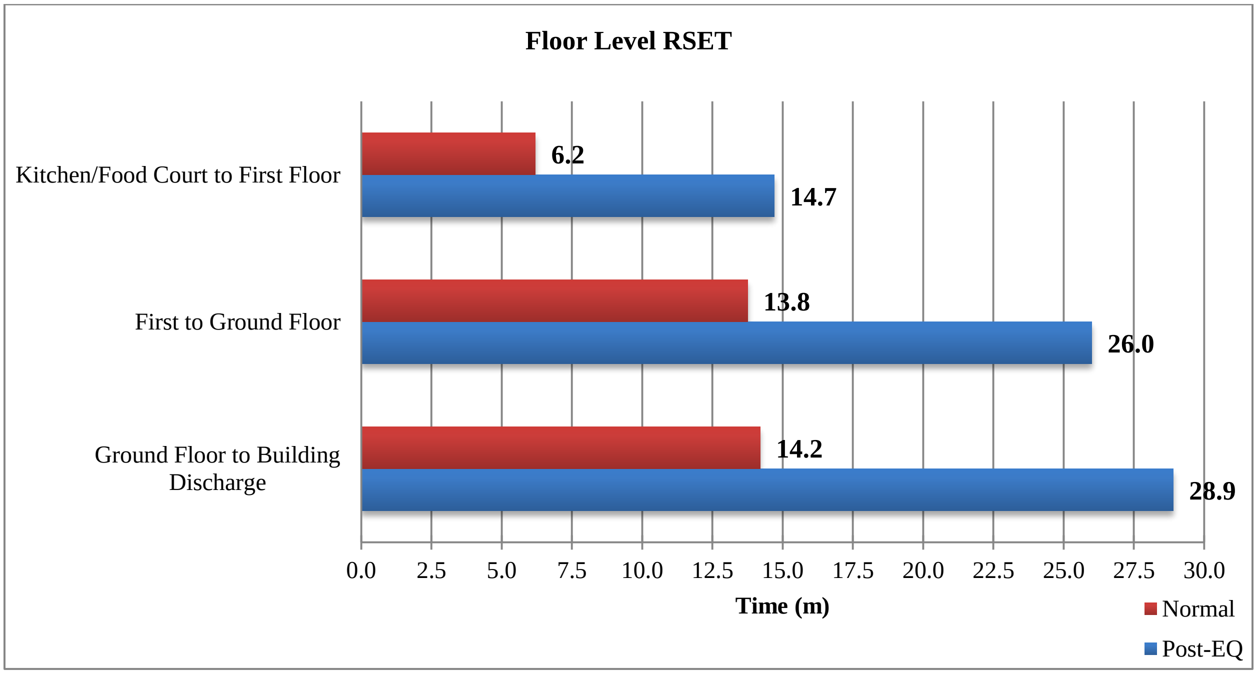


Figure 88. Floor by floor occupant evacuation time

The difference in the floor to floor evacuation time between the scenarios increases when the kitchen and food court occupants land in the first floor of the WPI Mall. For the normal fire scenario, it takes 6.2 minutes for the occupants in the kitchen and food court area to move to the first floor and it takes another 13.8 minutes for all the occupants in the first to evacuate to the ground floor. However, due to the missing stairs and elevators in the post-earthquake fire scenario, it takes 14.7 minutes for the occupants in the kitchen and food court area to move to the first floor and it takes 26 minutes for all of the occupants in the first floor to evacuate to the ground floor. This shows that there is a great delay in the first floor evacuation process as none of the anchor store elevators are functioning and the only stair accessible is in the west anchor stairs, forcing occupants in the east side of the building to travel across the entire building before any egress system can be accessed. Also with only the west anchor store stair intact and people moving in the west direction, because the only elevator to function is in the middle, the occupants in wheelchairs or using canes in the west of the first floor trying to access the middle elevator are travelling in the opposite direction to the majority of the occupants travelling in the west direction to access the west anchor store stair, causing more delay and reducing the travel width. Also it can be noted that if the one elevator selected to be intact is the one on the either side of the building rather than the one in the middle, there would be no elevator access for any occupant located in the kitchen and food court area.

9.3 Comments on Uncertainty and Sensitivity Analysis

Section 8.1 lists several of the assumptions made to conduct the case study, and states sources of uncertainty that may be associated by these assumptions and variances in data. For the post-earthquake fire scenario modelled in Pathfinder, despite the change in building geometry representing earthquake damage, the occupant characteristics are not changed and kept the same as the occupant characteristics of the normal-undamaged fire scenario, which does not take into consideration earthquake building damage factors affecting the occupant characteristics such as displaced contents hindering the occupant travel speed.

Also, to determine the RSET, a pre-movement time of 180 seconds as well as the fire detection time is applied for the post-earthquake fire scenario. However, in post-earthquake building fire scenarios, it can be argued that pre-movement and detection times are not required as people would already be alert and ready to evacuate as a result of the initial earthquake event itself.

Taking into consideration the factors mentioned above, another post-earthquake fire scenario is simulated using Pathfinder, to perform a sensitivity analysis. For this additional simulation, the earthquake damaged building conditions are the same as the post-earthquake building geometry modelled in Chapter 8. The occupant characteristics are altered as in post-earthquake fire conditions, research by Hokugo et al. (2011) revealed that the total evacuation time was longer with obstructed pathways than without, becoming longer as the size of obstructions increase and the effective egress width and travel speed decrease. Based on the occupant walking speed data in Table 17, a walking speed of 0.27 m/s in severely damaged building condition is selected.

Table 17. Occupant walking speed in post-earthquake building fire conditions (Hokugo et al. 2011)

Earthquake Building Damage	Occupant Walking Speed
No damage	1.0 m/s
Light damage	0.55 m/s
Medium damage	0.38 m/s
Heavy damage	0.32 m/s
Severe damage	0.27 m/s

For the post-earthquake fire scenario Pathfinder setup in Chapter 8, even the impaired occupants with canes or on wheelchairs had faster walking speed than 0.27 m/s. Just as the most extreme scenarios were selected for evaluation in the previous chapter, again the slowest waking speed is selected and applied to all of the occupant groups to represent worst case conditions. Also, all of the initial delay times are removed and set as 0 seconds as all the occupants would already be ready to or have started evacuating during the earthquake. With these modifications, the Pathfinder model is re-simulated to determine the required travel time.

Again, using the same equation below, the RSET is calculated. Details are as follows:

$$\boldsymbol{RSET = (t_{det} + t_{res} + t_{mov}) * s.f.}$$

Where
$\boldsymbol{t_{det} = detection\ time}$
$\boldsymbol{t_{res} = response\ time = pre - movement\ time}$
$\boldsymbol{t_{mov} = movement\ (travel)\ time}$
$\boldsymbol{s.f. = safety\ factor}$

Detection Time: 0 seconds as occupants are already alert and aware of danger due to the initial earthquake motion prior to the post-earthquake building fire.

Pre-movement (Delay) time: 0 seconds as the earthquake motion will alert all occupants and prepare them to evacuate the WPI Mall as soon as possible.

Movement time: The Pathfinder results showed that the total evacuation time for the total occupants of 6732 people to safely exit the mall is 3315 seconds.

Based on the assumptions above and the total evacuation time determined through the Pathfinder simulation, the RSET is calculated as shown below. The calculated RSET is 46.6 minutes for the modified Pathfinder-4, post-earthquake building fire scenario.

$$\boldsymbol{RSET = (t_{det} + t_{res} + t_{mov}) * s.f. = (0 + 0 + 3315) * 1.5 = 4973\ sec \cong 82.9\ min}$$

With ‘Post-EQ-1’ representing the Pathfinder-4 post-earthquake building fire scenario results from Chapter 8, and ‘Post-EQ-2’ representing the occupant characteristics modified Pathfinder-4 post-earthquake building fire scenario results from above, both results are shown in Figure 89 as a comparison to the normal-undamaged building fire scenario results. It can be seen that changing the building geometry more than doubles the travel time and almost doubles the RSET from the normal fire scenario. However, changing both the building geometry and occupant characteristics increases the evacuation time by almost four times and the RSET by three times from the normal fire scenario results. Another Pathfinder model can be simulated with the building geometry being the same as the conditions in the normal fire scenario but just changing the occupant characteristics and the detection and pre-movement times. This can provide FPEs the means to identify what the most essential input parameter is in determining the RSET.

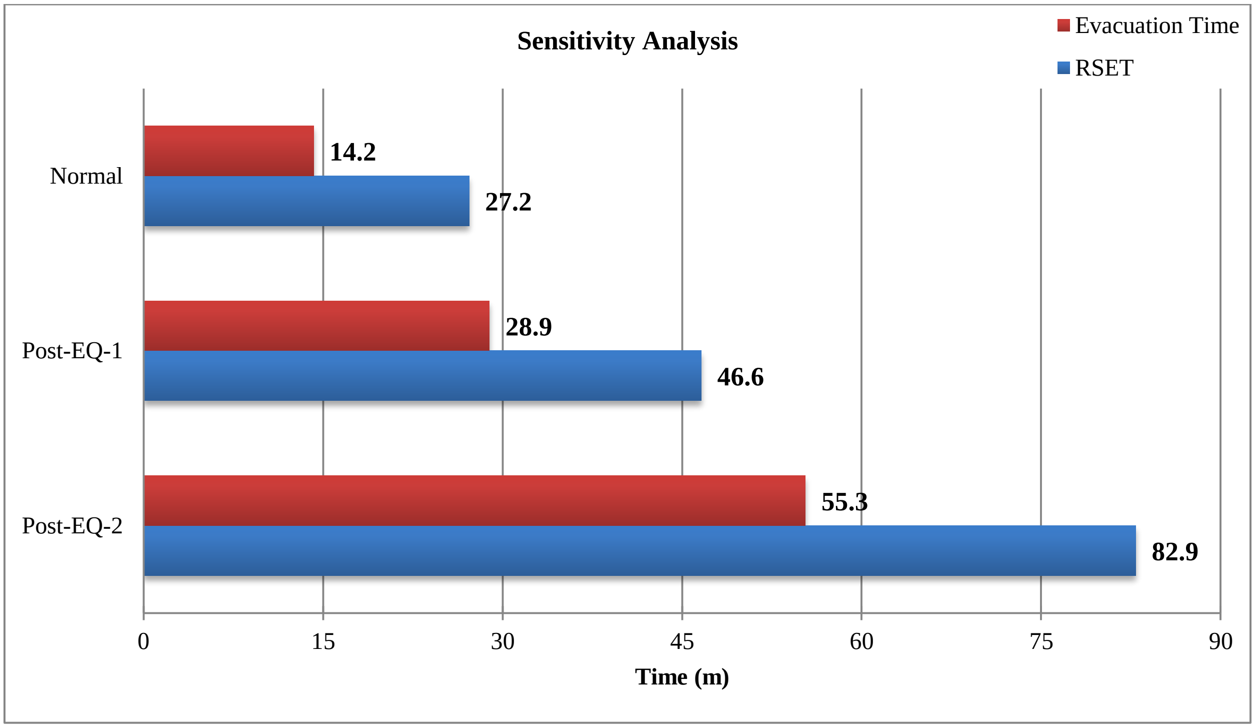


Figure 89. Travel time and RSET comparison

The above is an illustration of how sensitivity analysis – even very generalized – can be used to identify parameters of importance for more detailed consideration. In reality, a much more comprehensive and structure sensitivity analysis would be warranted as appropriate to the overall fire safety assessment. It is highly recommended that such analysis is undertaken for any real project.

9.4 Uncertainties and Risk Analysis

All building fires are unique and distinguished from other fires. The reasons can vary as all buildings have different geometry, ignition sources, fuel items, ventilation configurations and etc. After all, doing all that is necessary to prevent the exact same fire incident from occurring again might render fruitless results as there is a high probability that the next fire incident will not be exactly the same. This is also true about building earthquake damage. Each earthquake has different intensities and durations, which will also vary depending on the distance of a building from the earthquake and the quality of the building as well. To reduce and mitigate potential risks from all potential events, it is highly recommended that risk analysis is performed. Many of the nonstructural building component fragilities in the ATC-58 PACT database, which is used in the case study example, were created based on expert judgment rather than on empirical data. Although the fact that these data set are published and available to the general public might suggest there is a high confidence level on these fragilities, the uncertainties still cannot be ignored.

In the previous section, a simple sensitivity analysis is conducted by changing just the occupant characteristics. Although sensitivity analysis is not performed in the case study example as the best and worst case scenarios are selected for evaluation, in reality, such sensitivity analysis should be performed to account for the uncertainties and variability in the current data set available, and to determine the most critical model input parameter that has the greatest influence on the building fire safety performance level.

For this case study example there is uncertainty associated with each of the building earthquake damage estimated. To determine which type of damage can be the most detrimental to the building fire safety performance, there are numerous post-earthquake fire scenarios that could be setup for sensitivity analysis. A typical method would be to setup each scenario with only one building component being damaged. For example, a post-earthquake WPI Mall fire scenario with just the sprinkler system damaged would allow a FPE to determine if having an uncontrolled fire due to the failure of sprinkler activation would have a big enough impact that supersedes the mitigation effects of all of the other fire systems intact. It is also important to clearly identify what the design objectives are prior to performing the sensitivity analysis. Ceiling tiles dislodging and creating a hole in the ceiling system exposing the plenum space is one of the damage states selected in the case study example. To a FPE that is trying to look at the smoke spread effects on the occupant evacuation process, the ceiling system damage may not be much of a significant importance, and may perhaps even slow down the smoke filling rate in occupied areas as there are additional cavity spaces that the smoke can travel to. However, to a FPE that is trying to assess the structural integrity during the fire, the ceiling system damage may be crucial as the smoke intruding the plenum space could induce high enough temperatures in the plenum space to bring unprotected structural members to failure.

As suggested above, performing sensitivity analysis be creating numerous different scenarios and evaluating them can help prioritize and identify the greatest risks. These results also can also be useful in highlighting the wide range of impact and consequences that can occur in the event of a post-earthquake building fire.

There are guidelines provided in various sources that a FPE can refer to for performing uncertainty analysis. The SFPE PBD guideline provides discussion on how to determine uncertainty, how to treat various types of uncertainties, and various tools that can be used to conduct uncertainty analysis. The SFPE Handbook of Fire Protection Engineering has a chapter dedicated to uncertainty which provides discussion on the nature, sources and different types of uncertainty, terms of uncertainty used in probability and statistics, and the uncertainties that exist in various steps of the SFPE PBD guideline procedures. These are just examples of some of the resources that can used to get a better understanding of how to determine and treat uncertainties.

9.5 Further Discussion on Use of Conceptual Model

As mentioned previously, there is currently not enough earthquake building damage data, in terms of both quantity and quality wise, that a FPE can use to perform very detailed, in-depth post-earthquake building fire analysis with a high degree of confidence. Nonetheless, this should not detract the value of the conceptual framework, and the fact that as more data become available, the confidence in predictive capability will increase.

The conceptual framework is developed with the aim to make FPEs and seismic engineers be more aware of the potential interactions and connections between fire and seismic engineering, hazards that could be presented in post-earthquake building fire conditions, types of information required, and ultimately provide details on the necessary procedure and steps that are required to conduct PB analysis on an earthquake prone building. In the future, it is anticipated that data will become available to more robustly populate a quantitative approach – either as suggested here, or by Sekizawa et al. (2003). As a first step, however, this approach clearly illustrates the benefit of a more integrated approach, and presents a roadmap for the type and quality of data that are needed to refine the process.

10 Conclusion

History has shown that post-earthquake fires can be more destructive than the earthquake itself. Earthquakes have the potential to cause significant damages to building structural and nonstructural systems. These damages can occur to critical building components that can have a negative effect on the building fire safety performance. Such damages have been validated through the BNCS Project where a five-story reinforced concrete test building built on top of a shake table, fully outfitted with various nonstructural components, was subjected to numerous motion and post-earthquake fire conditions.

To better understand building performance as a result of earthquake and fire events, PB approaches have been identified by both the seismic and fire engineering communities to make up for the shortcomings of the prescriptive approach. As a result, a lot of research and planning has led to the development of PBD approach guidelines for both engineering disciplines. However, due largely to the lack of a shared perspectives, the guidelines have been written separately by the fire and seismic engineers. As a result, despite sharing a common goal to contribute to the design of safe buildings under different events in fires and earthquakes, current analysis and design processes are being conducted separately without consideration of potential interaction. Despite the well-known threats of post-earthquake building fires, there is no framework or approach which characterizes both fire and seismic hazards and their effects on buildings in a consistent compatible manner.

FPEs have great problems when it comes to dealing with post-earthquake building fires as there is no framework which guides them how to analyze and predict post-earthquake building conditions. Literature review on PB seismic engineering guidelines revealed seismic engineers estimate building damage conditions in order to translate those damages into repair or replacement cost, building down time and casualties. One of the most recent PB seismic engineering guideline in ATC-58 provides an electronic database which provides the probabilities of 700 different building components incurring their respective damage states under certain intensity seismic motions. Although such damage occurring probability values and damage state descriptions are the type of information FPEs require to accurately analyze post-earthquake building conditions, because of the lack of perspectives shared between the fire and seismic engineering disciplines, not all of the damage states seismic engineers describe will be meaningful in terms of fire analysis.

To achieve the goal of developing an integrated performance-based approach for earthquake and fire analysis, a conceptual framework is developed. The conceptual framework diagram, in Figure 90, shows given the building hazards of the separate events in earthquake and fire, represented in left and right of the diagram respectively, the building characteristics, what the potential resulting consequences are and the links and connections between these factors. The consequences are further linked to provide the resulting potential post-earthquake building fire conditions.

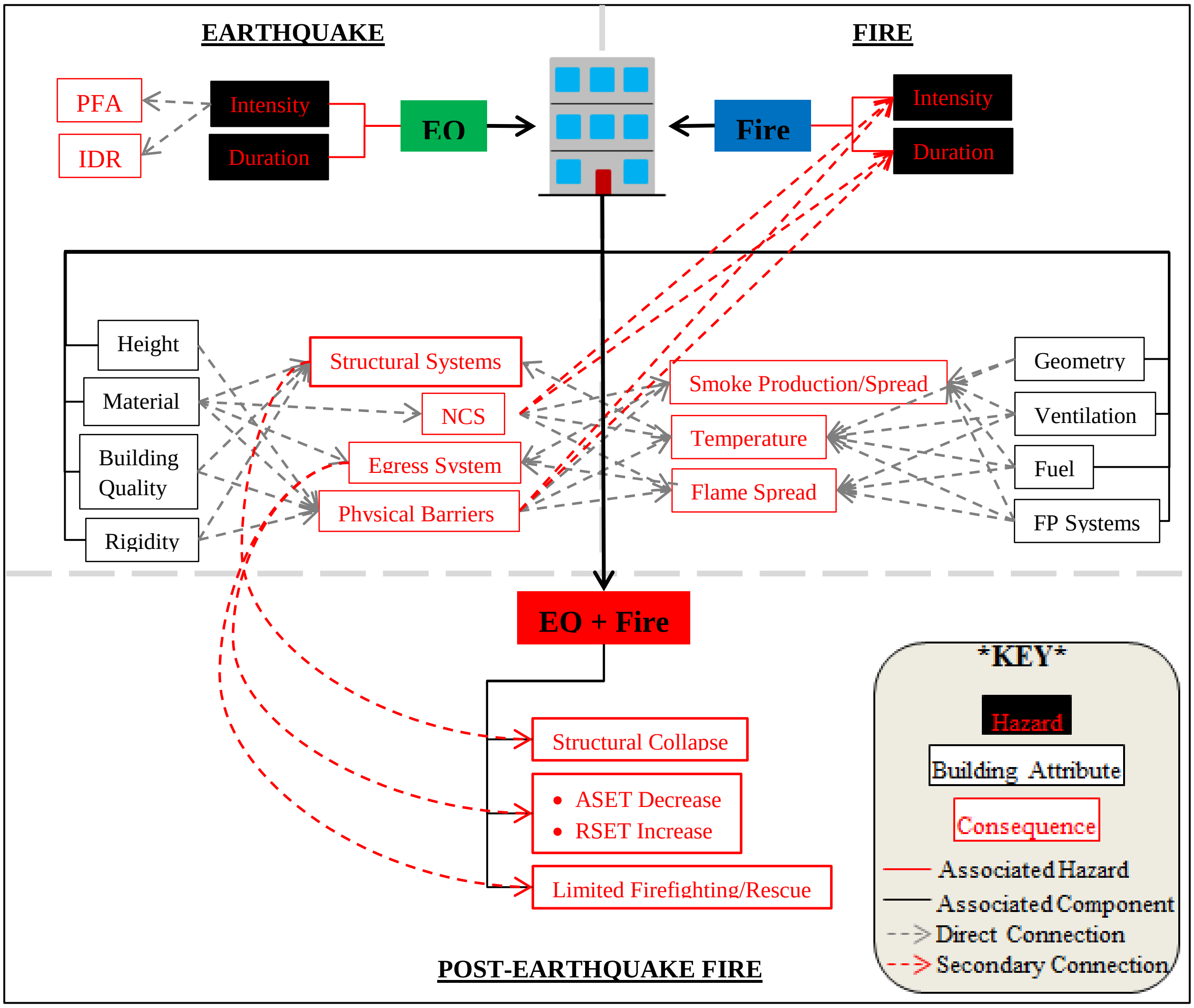


Figure 90. Conceptual framework

Essentially, this conceptual framework is expected to help fire and seismic engineers identify how certain building components can affect the building fire safety performance levels to provide connecting links between earthquakes and fires. Based on this, the types of information and procedures FPEs and seismic engineers need to perform post-earthquake building fire analysis and design are identified. These steps are integrated into the SFPE PBD guideline procedures as shown in Figure 91, where the procedures in red and green are steps fire and seismic engineers must perform respectively. It is suggested that the FPE must have the help of a seismic engineer to perform building earthquake analysis and determine how the building responds and what type of building damage conditions can be expected and what the probability of occurrences are. This will greatly help FPEs better understand how the building, occupant and fire characteristics have been altered in post-earthquake building fire conditions.

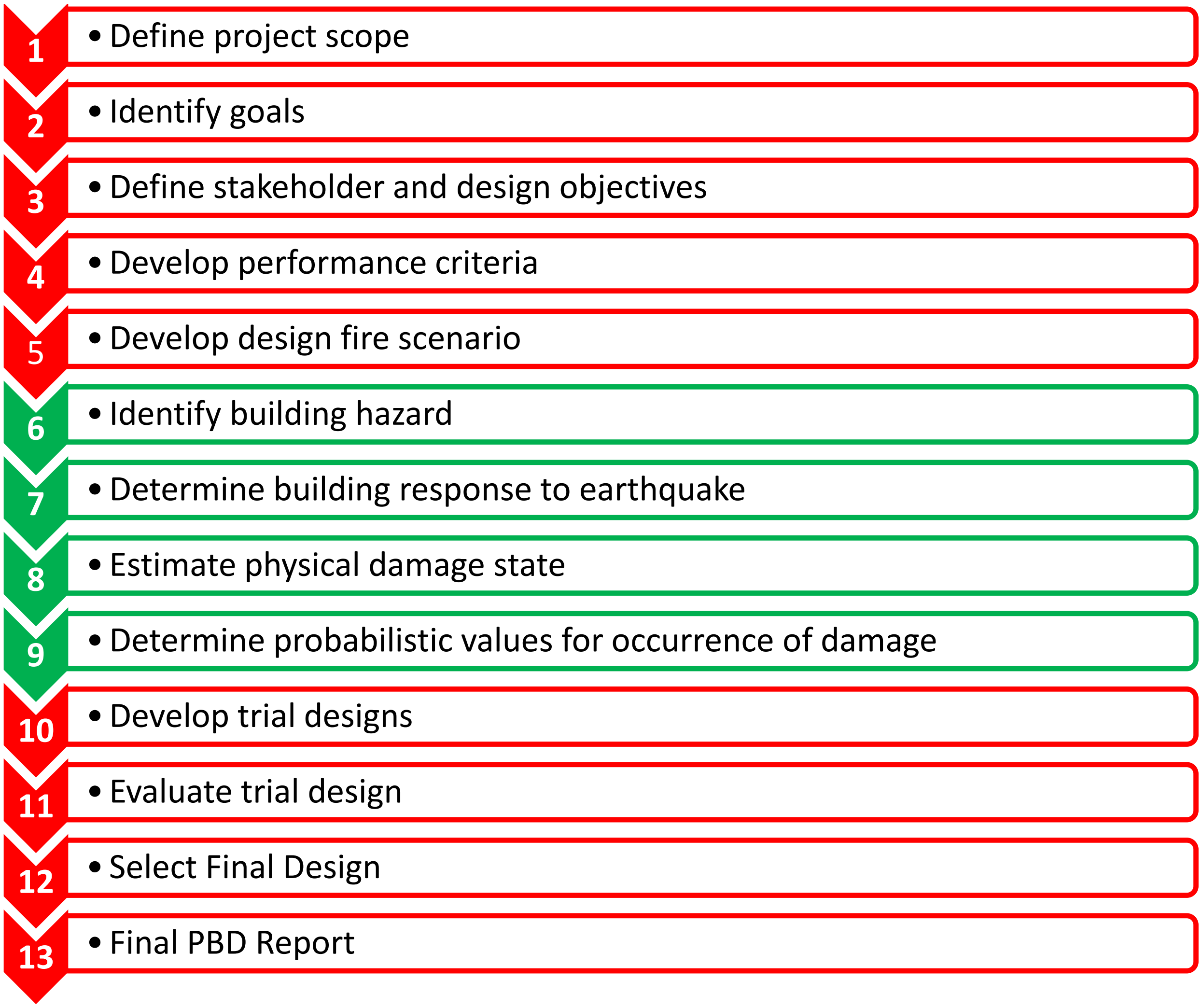


Figure 91. Step-by-step procedure for conducting PBD on earthquake prone buildings

The conceptual framework is implemented for a case study example, to perform a post-earthquake building fire analysis on a fictional WPI Mall building. Post-earthquake fire scenarios of WPI Mall are created with various building components being damaged. This entire step is laid out in a step-by-step manner to show how the conceptual framework can be applied in practice. The post-earthquake fire scenario, along with normal building fire scenario, where the WPI Mall is perfectly intact, is assessed through FDS and Pathfinder. The modelling results, shown in Figure 92, indicate that in the case of the post-earthquake building fire condition, buildings can be exposed to untenable conditions leading to significantly decreased ASET and increased RSET.

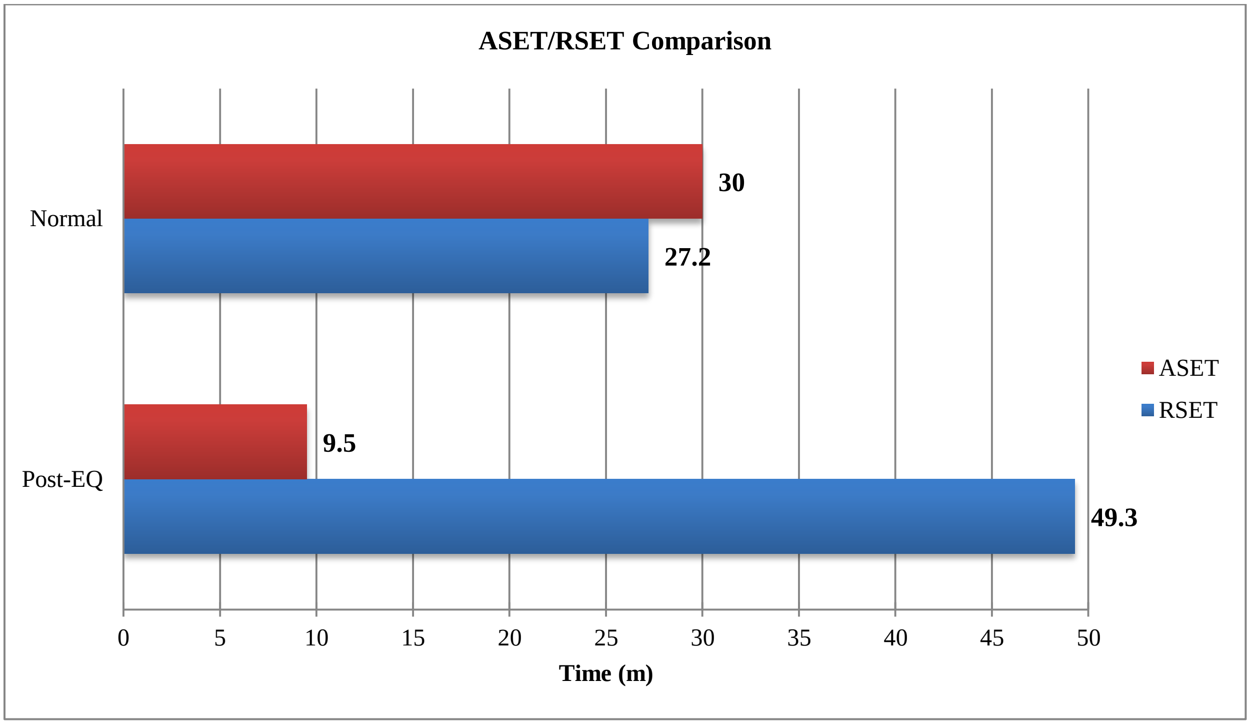


Figure 92. WPI Mall fire scenarios ASET/RSET comparison

Although numerous assumptions are made for creating the post-earthquake building fire condition for the case study example, the process alone itself should help refine the development of scenario analysis and more appropriate design mitigation options for post-earthquake fires.

11 Future Work

Despite the post-earthquake fire hazards presented in history through previous post-earthquake fire events, the lack of interaction and differing points of interest between the seismic and fire engineers have led to building damage data set that are hard to translate into meaningful design parameters for the FPEs. And although there is some data on building component performance under seismic loads, much more data is required to perform detailed accurate analysis and design on earthquake prone buildings. Different resources can be utilized to find such data but using data from one resource is recommended as various resources may be data collected from different earthquake events and might not match performance levels under differing seismic loads, adding to the uncertainties and data variability levels. Also, the fact that several of the damage estimates are being made by seismic engineering experts based on their judgment and experiences adds to the uncertainty as well, and again shows for the lack of data available currently.

More interaction between the fire and seismic engineering communities is encouraged in attempts to better understand each other’s perspectives and to find the connecting links between the two events in fire and earthquake. This interaction should (1) help seismic engineers better understand how different building components can affect building fire safety performance, and (2) help FPEs better understand building component performance under seismic loads to better identify post-earthquake building fire hazards.

Without enough quality building earthquake damage data available, the conceptual framework can only mostly be used as a tool to provide general steps and procedures required to conduct post-earthquake building fire analysis, identify connections that link building earthquake and fire events, and instill awareness of post-earthquake fire hazards to seismic and fire engineers. To maximize the potential of using the conceptual framework, more interaction between the seismic and fire engineers, building earthquake damage data, and experimental tests are required.

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Appendices

Appendix A

"Fire Performance of a Full-Scale Building Subjected to Earthquake Motions: Test Specimen, Seismic Motions and performance of Fire Protection Systems" published in the proceedings of the 11th International Symposium on Fire Safety Science.

Fire Performance of a Full-Scale Building Subjected to Earthquake Motions: Test Specimen, Seismic Motions and Performance of Fire Protection Systems

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ABSTRACT

A full-scale, five-story building specimen was erected on the Large Outdoor High Performance Shake Table (LHPOST) at the University of California, San Diego, outfitted with various nonstructural components and systems (NCSs), and subjected to a series of earthquake motion tests and compartment scale fire tests. The aim of these tests was to increase knowledge on the performance of NCS and contents during earthquakes and post-earthquake fire events. An overview of the building specimen, earthquake motions and performance of NCS critical to building fire safety are presented. Outcomes illustrate the extent of damage to compartment barriers, façade systems, egress systems and fire protection systems that could occur given different levels of ground motion, and how such damage could impact occupant life safety and emergency response during fires in earthquake-damaged buildings. Details of the post-earthquake fire tests and fire performance observations are presented in an associated paper [1].

KEYWORDS: post-earthquake fire, structural response, compartmentation, and evacuation

INTRODUCTION

While developments in seismic analysis and design methods, building code provisions and mitigation technologies has significantly reduced the potential for structural collapse and associated loss of life as a result of earthquakes, damage to and losses associated with nonstructural components and systems (NCS) remains a concern. This is surprising given the loss potential associated with NCS. In the United States, it has been reported that the structural components of a commercial building account for approximately 15-25% of the original construction cost, while the nonstructural (mechanical, electrical, plumbing, and architectural) components account for the remaining 75-85% of the cost [2]. Significant NCS-associated losses have occurred due to earthquakes. In the 1994 Northridge earthquake, NCS damage was reported to have accounted for 50% of the $18.5 billion loss associated with building damage [3]. Similarly, NCS damage was reported to account for the majority of the total losses in the 2010 Maule earthquake in Chile [4]. In addition to losses associated with earthquakes alone, the performance of NCS are also important in terms of post-earthquake fire performance, since all active and most passive fire protection systems are considered NCS. The impact of damage to fire protection NCS has been observed in numerous earthquakes, including the 1994 Northridge and 1995 Kobe earthquakes, where damage to fire sprinkler systems and fire doors was reported to be over 40% and 30% respectively [5]. While building codes and standards have addressed seismic performance of some fire protection systems as a result of these events, such as improved requirements for sprinkler hangars and bracing, there has not been much focus on other areas, such as seismic performance of compartment barriers, doors and stairways, which form important parts of egress systems. The implications of such omissions have also been observed in earthquake events. In the 2010 and 2011 Christchurch earthquakes, for example, interior stairs collapsed and impeded safe evacuation [6]. Such failures not only impact the ability of occupants to escape, but impact the ability of first responders to enter buildings and conduct rescue and firefighting operations. As evident from these events and others, damage to fire protection NCS can result in occupants and first responders being placed at risk in case of post-earthquake fires. Data such as these clearly show that more work is needed to improve the seismic performance of NCS: not only those which can result in high direct and indirect monetary losses, but those which can impact safety to occupants and first responders [7].

To better understand, characterize and predict the potential damage to NCS during earthquakes and post-earthquake fires, a full-scale five-story building specimen was constructed, equipped with various NCS and contents, and subjected to a series of earthquake motion tests and post-earthquake fire tests. Referred to as the BNCS Project, this unique collaboration between academia, government, and industry was developed with the aim to expand on the knowledge of the performance of the NCS during earthquakes and post-earthquake fires [8]. Details on the program and partners can be found at the project website (http://bncs.ucsd.edu/index.html). The test facility, building specimen, earthquake motions and earthquake performance of the fire protection NCS are described below. The fire test program and results are presented in a corresponding paper [1]. Full documentation of the test program, preliminary data and summaries of the test program and preliminary data are available [8-13].

EXPERIMENTAL FACILITIES

Experiments were performed on the large high performance outdoor shake table (LHPOST) at the Englekirk Structural Engineering Center of the University of California, San Diego. The LHPOST, shown in Fig. 1, measures 7.6 m by 12.2 m and is able to reach a peak acceleration of 4.2 g and a peak velocity of 1.8 m/s (unloaded) in the East/West direction. Addition details can be found at (http://nees.ucsd.edu).

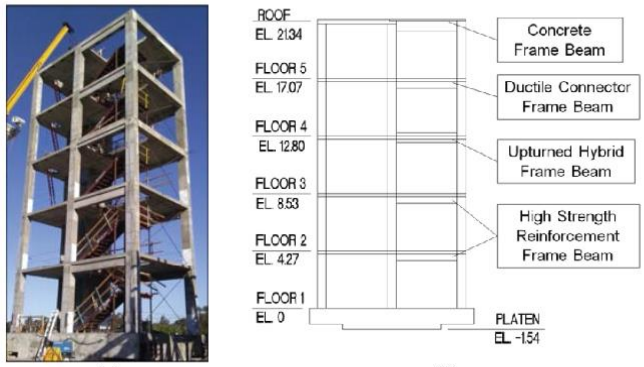
Fig. 1. LHPOST at the test site.

BUILDING DESIGN

The building specimen was designed with the assumption that it was to be located in a high seismic zone in Southern California (Site Class D [14]). Spectrally matched and chosen from seven maximum considered earthquake (MCE) ground motions and three serviceability motions, the design targeted an inter-story drift ratio (IDR) of 2.5% and maximum peak floor acceleration (PFA) of 0.7 g to 0.8 g [8]. IDR and PFA are commonly used earthquake demand parameters, where IDR is defined as the relative story displacement divided by the story height and PFA is defined as the maximum absolute floor acceleration.

Building Specimen

The building specimen was constructed of poured-in-place concrete and had plan dimensions of 6.6 m by 11m with floor-to-floor heights of 4.27 m at all levels. A 0.2 m thick concrete slab was placed at each level, with two large openings of 2.1 m by 2.6 m and 2.3 m by 4.2 m at all floors to accommodate an operable elevator and complete stair assembly, respectively. At the back and sides of the elevator shaft area, small penetration openings for various building services such as plumbing and automatic fire sprinklers were provided. A 15 cm thick concrete wall was constructed on both the east and west sides of the elevator opening to provide support for the elevator guardrails. Seismic resistance for the building was provided by special one-bay moment resisting frames in the Northeast and Southeast bays. Moment resisting beams at each floor were designed with the same capacities but with varying components as shown in Fig. 2b. Each of the six 66 cm by 46 cm rectangular columns were reinforced with longitudinal bars and a prefabricated transverse reinforcement grid. Details of the structural system are provided in [8, 9].



(a) (b)

Fig. 2. Test specimen (a) skeleton; (b) elevation view (elevation in m) [images and schematic from 8].

Architectural Components

The building specimen was outfitted with a number of architectural components to reflect a typical multi-story building. This included enclosed interior stairway, compartments framed with lightweight steel studs and covered by gypsum board panels, doorways with swinging doors, and a variety of ceiling systems. Such architectural components are important for fire safety analysis as they provide full loading for the fire and also provide compartments to resist the spread of smoke and flame as well as required egress system components. The building frame was enclosed using two architectural façade systems. The first three floors were enclosed by a balloon framing system comprised of lightweight steel studs, gypsum board interior faces and an exterior insulation and finishing system (EIFS) as shown in Fig. 3a. On Floors 4-5, precast concrete cladding panels were used [8]. Each façade system included window openings but no glazing system. The interior gypsum board on the balloon frame façade was 1.6 cm, fire-rated, Type X. Ceiling systems were installed in the Northeast and Southeast portions of each floor of the specimen. Different ceiling were installed on each floor. Details on the various ceiling systems can be found in project publication [8]. The ceiling system of Floor 3, focus of fire testing, was a gypsum board grid system (Fig. 3b). Interior partition walls were installed on all floors of the building specimen. Partition walls on Floor 3 featured two layers of 1.6 cm (5/8 in) Type-X gypsum board on steel studs as shown in Fig. 3c [8]. The elevator shaft was enclosed using a layer of 1.6 cm (5/8 in) Type X, fire rated gypsum board on each side of the walls. The elevator lobby on Floor 3 was enclosed using one layer of 1.6 cm (5/8 in) Type X, fire rated gypsum board. The stairwell was partially enclosed by one layer of 1.6 cm (5/8 in) gypsum board.

(a) (b) (c)

Fig. 3. (a) Façades systems; (b) Floor 3 ceiling system (c) Floor 3 partitions.

The focus for assessment of fire performance of NCS was Floor 3, as live fire testing was limited to this floor (however, data on other floors was also collected). The architectural layout for Floor 3 is shown in Fig. 4. Floor 3 was separated into four different compartments and designated as the Large Burn Room (LBR), Small Burn Room (SBR), area behind the Elevator Shaft (ES) and the Elevator Lobby (EL). The

LBR and SBR were separated by a partition wall that extended up to the ceiling height. Ceiling systems were installed in the LBR, SBR and EL spaces. Window openings were provided in all compartments but no glazing system was installed in any of the openings. While the focus was on Floor 3 NCS performance for fire, data and observations from other systems on other floors were also recorded.

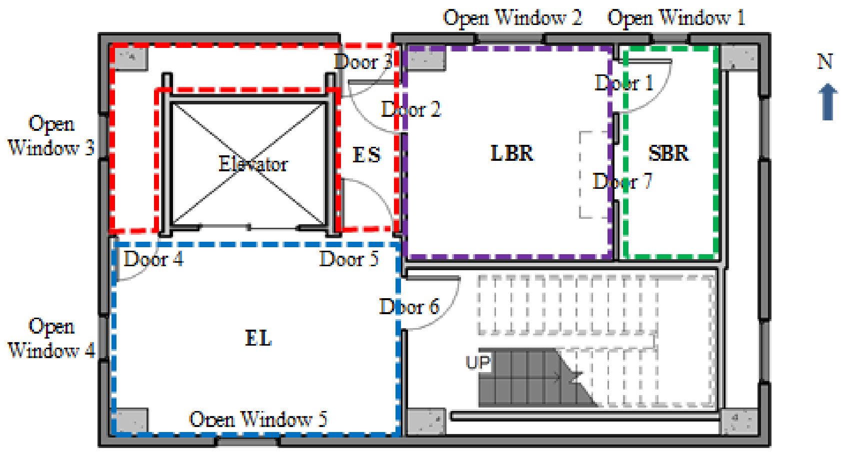


Fig. 4. Floor plan of Floor 3

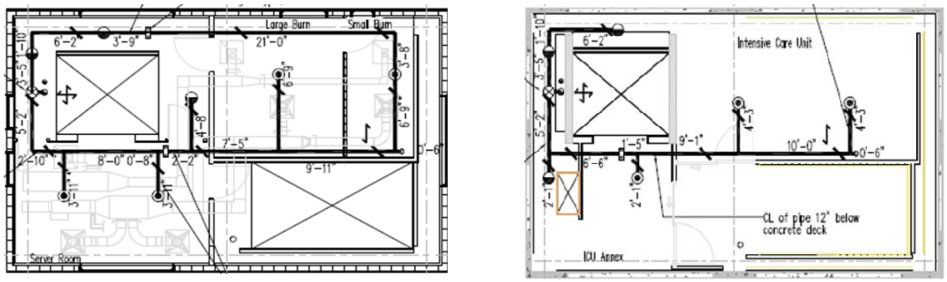
Fire Protection and Mechanical Systems

A functional wet pipe automatic sprinkler system was installed throughout the building specimen. Risers (6.35 cm (2½ in)) and control valves were installed on the West elevator shaft wall at each floor level. Branch and loop line pipe material and layout varied by floor. The details of the sprinkler system components are listed in Table 1. All horizontal sprinkler branch and loop lines were installed 30 cm (12 in) below the deck of the floor above.

Table 1. Sprinkler system components

Level	Pipe	Sprinkler Head
Floor 1	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	4 Quick Response Pendent 3 Quick Response Upright
Floor 2	3.8 cm (1 ½ in) CPVC main line 2.5 cm (1 in) CPVC branch line	2 Quick Response Pendent 2 Quick Response Upright 2 Residential Concealed Pendent
Floor 3	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	4 Quick Response Pendent 3 Quick Response Upright
Floor 4	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	3 Quick Response Pendent 3 Quick Response Upright
Floor 5	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	4 Quick Response Pendent 3 Quick Response Upright

Differences in pipe material and layout were used to assess performance of the various configurations under seismic load. Hangers and bracing were provided to comply with current building code requirements. On Floors 1 and 4, sand weights were attached on branch / loop lines to represent pipes with larger diameters to assess seismic performance given increased loads. Representative sprinkler system layouts are shown in Fig. 5. The figures reflect U.S. units, as presented in [10]. Additional detail on the sprinkler system design, including calculations, components and layout, can be found in [10]. To obtain realistic seismic performance, while minimizing any possible water damage to equipment for potential pipe rupture, the system was charged with only 57 liters (15 gallons) of water at each floor during motion tests.



(a) (b)

Fig. 5. Sprinkler system layout for (a) Floor 3 and (b) Floor 4 [10].

Heating, ventilation air-conditioning (HVAC) ductwork was installed on Floor 3 and vented to the outside through a vertical duct on Floor 4. Ductwork was comprised of sheet metal. Flexible duct connections were installed between ducts and diffusers located in the Floor 3 ceiling. The supply and return ducts were located in the plenum spaces. Fire and smoke dampers were located in the ductwork portions in the ES and the stair landing area. This is shown in Fig. 6.

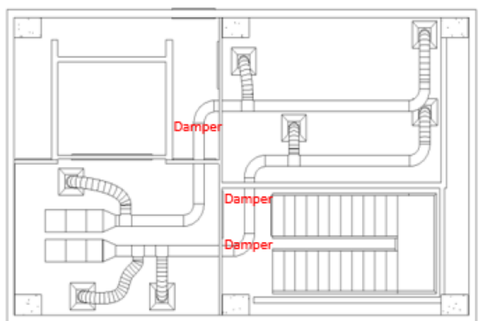


Fig. 6. Location of fire and smoke dampers

The duct connections were firestopped with fire caulk. Spaces around the ducts, where they penetrated interior partitions, were sealed with fire stop material. HVAC ducts in the corridor around the elevator shaft and within the stairway landing were exposed (no ceiling systems). A portion of the actual HVAC system is shown in Fig. 7b. The HVAC and other mechanical systems are described in more detail in [8].

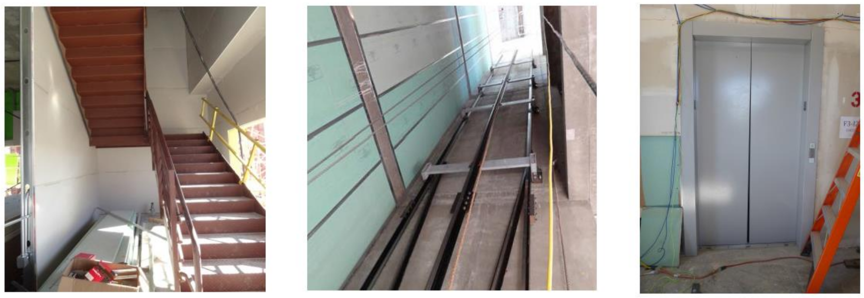
(a) (b) (c)

Fig. 7. (a) Diffuser in ceiling; (b) HVAC ductwork; (c) fire-stopping around duct [figure 7b from 8]

Egress Systems

A prefabricated stair assembly was installed at each floor of the building as shown in Fig. 8a. Each floor consisted of lower and upper flights and an intermediate landing. The stair flights were connected with the concrete floor slabs at one end via field welds, while they were connected with a stair landing via bolts at the other end. A fully functioning elevator with 17.1 m travel height and access to all floors was installed in a 2.64 m by 2.1 m elevator shaft as shown in Fig. 8b-c. During the seismic tests, the 1.92 m by 1.7 m by

2.36 m cab was loaded with sand bags equivalent to 40% of the full cab capacity of 160 kg [8]. The opening of the cab door was 2.1 m by 1.1 m as shown in Fig. 8c.



(a) (b) (c)

Fig. 8. Egress systems (a) stair; (b) elevator guiderails; (c) elevator door. [images 8a and 8b from 8]

Additional Fire Protection Features

In addition to a sprinkler system and fire dampers in the HVAC ductwork as overviewed above, various other fire protection features were installed on Floor 3, which was designated for later live fire tests. A 1-hr fire resistance rated roll-down steel fire door was installed in the middle of the partition wall separating the LBR and SBR (see Fig. 4). Door closers and magnetic door holders were installed for all interior doors, which were 20-minute fire resistance rated. As noted above, compartments walls were comprised of two layers of Type X gypsum, with exterior walls including window openings without glazing systems. Smoke detectors were located at various locations and programmed into the fire alarm control panel system. Firestop sealants and devices were installed in all vertical and horizontal pipe, cable, wire and HVAC penetration openings on the third floor. Various firestop components of intumescent, non-intumescent and mineral fiber wool were applied, as dictated by previously fire-tested and listed firestop designs from the Underwriters Laboratories (UL) Fire Resistance Directory. The fire door, door closers and magnetic door holders, and firestop systems are shown in Fig. 9 [10].

(a) (b) (c)

Fig. 9. Fire protection systems on Floor 3 (a) fire door; (b) door closer and holder (c) fire stop systems.

Occupancies and Contents

The building specimen was designed to have spaces reflective of different building occupancies, including hospital surgery suite (Floor 5), intensive care unit (ICU) (Floor 4), computer servers (Floor 3), residential and laboratory content (Floor 2) and building services (Roof and Floor 1). Specific floors were outfitted with additional architectural features based on occupancy and test objectives, including ICU smoke doors (Floors 4 and 5) and a roll-down fire door on Floor 3 (level of fire testing). The occupancy characteristics are summarized in Table 2 and representative photos are shown in Fig. 10.

Table 2. Occupancy characteristics

Floor	Figure	Occupancy	Floor	Figure	Occupancy
1	10a	Utilities	4	10d	Medical equipment: ICU
2	10b	Residential and laboratory content	5	10e	Medical equipment: surgery suite
3	10c	Computer servers	Roof	10f	Roof mounted equipment

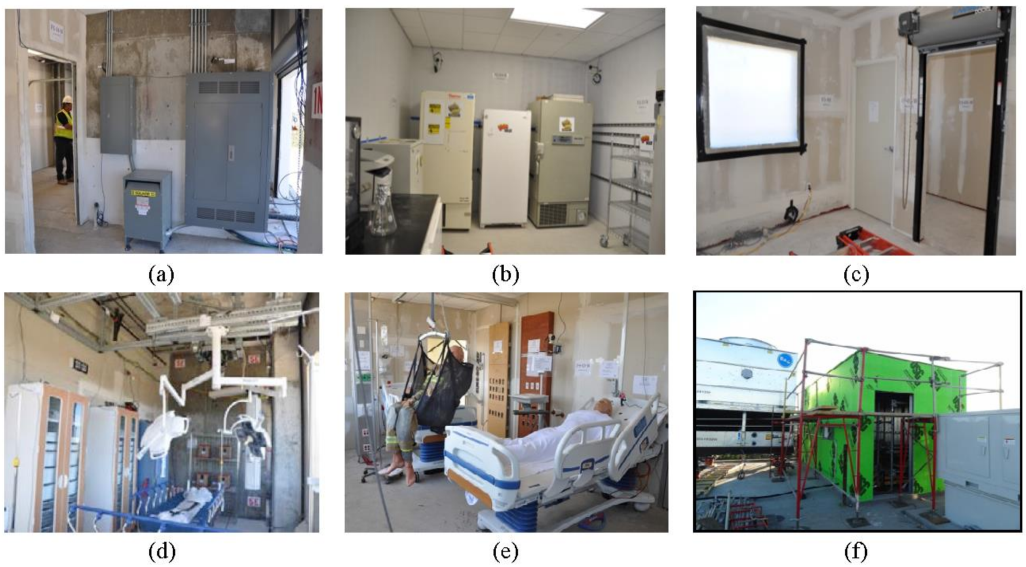


Fig. 10. Photos of the various floors of the building – refer to Table 2 [images from 8]

EARTHQUAKE MOTION TESTS

Earthquake motion tests consisted of 13 tests conducted in 2 configurations, namely while the building was base-isolated (BI) and fixed base (FB). Seven tests were conducted while the building was BI and six while it was FB. Four high damping rubber isolators were installed at the four corners of the building for the BI tests and subsequently removed for the FB tests. The seismic motions for the BI configuration and FB configuration are shown in Table 3.

Table 3. Input ground motions.

Date	Name	Seed Motion
April 16, 2012	BI-1: CNP 100	Canoga Park 1994 Northridge Earthquake
	BI-2: LAC 100	LA City Terrace 1994 Northridge Earthquake
April 17, 2012	BI-3: LAC 100	LA City Terrace 1994 Northridge Earthquake
	BI-4: SP 100	San Pedro 2010 Maule (Chile) Earthquake
April 26, 2012	BI-5: ICA 50	2007 Pisco (Peru) Earthquake
April 27, 2012	BI-6: ICA 100	2007 Pisco (Peru) Earthquake
	BI-7: ICA 140	2007 Pisco (Peru) Earthquake
May 7, 2012	FB-1: CNP 100	Canoga Park 1994 Northridge Earthquake
May 9, 2012	FB-2: LAC 100	LA City Terrace 1994 Northridge Earthquake
	FB-3: ICA 50	2007 Pisco (Peru) Earthquake
May 11, 2012	FB-4: ICA 100	2007 Pisco (Peru) Earthquake
May 15, 2012	FB-5: DEN 67	Pump Station #9 2002 Denali Earthquake
	FB-6: DEN 100	Pump Station #9 2002 Denali Earthquake

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 and applied in a progressive manner to increase the seismic demand on the test specimen. 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 intended to be similar. 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 the performance target of about 2.5% PIDR and 0.8 g peak floor acceleration selected initially in the specimen design. The achieved peak input acceleration range for the FB earthquake motions ranged from about 0.2 to 0.8 g, while the pseudo-spectral acceleration at a period of 1 second (the target fundamental period of the building) ranged from about 0.3 to 1.3 g. Motion FB-5 imposed inter story drifts associated with the design performance target of about 2.8% PIDR for the building specimen, while the final motion FB-6 damaged the building specimen severely, and compromised its lateral resisting structural system, resulting in very large PIDR of approximately 6% - a value well outside of anticipated design code performance targets under design earthquakes [9]. The motions are detailed in [8, 9, 11, 12].

FIRE SAFETY SYSTEMS PERFORMANCE

The earthquake motions induced damage to compartment barrier components, façade and egress systems, caused displacement of heavy contents, exposed steel reinforcing bars, and disconnected pipes. Regarding compartment integrity, gaps were formed in joint areas and ceiling tiles were displaced, while door components were damaged, providing potential means of smoke and flame spread. Egress component damage included disconnected stairs and elevator door failure. Corridors became obstructed with displaced items which could possibly hinder occupants from safely evacuating. Concrete spalling rendered steel reinforcing bars exposed, which could degrade fire resistance of structural reinforced concrete. All of the active fire protection systems remained undamaged and intact throughout the motion tests. Several of these issues are discussed in more detail below.

Contents / Fuel Distribution

Fire intensity and duration can be affected by the amount, distribution, shape, arrangement and moisture of fuel loads. Fuel distribution and arrangement can be greatly altered due to earthquakes since contents can be displaced from their original location, in some cases bringing fuels close together, which could facilitate fire spread. The displacement of items during earthquakes can also cause a reduction in occupant walking speed and impact evacuation behavior. Research by Hokugo et al. [15] revealed that the total evacuation time was longer with obstructed pathways than without, becoming longer as the size of obstructions increase and the effective egress width and travel speed decrease.

A range of contents reflective of the occupancies on Floors 2, 4 and 5 were located in the specimen. Some contents were anchored while others were not. Displacement of unsecured contents (potential fuel items) was experienced on each floor during motion tests, with the extent of displacement increasing with the size of the simulated events (see [11] for details on motions, contents and anchorage, and resulting acceleration, drift and displacement). As an example, Floor 2 included chemical laboratory and storage equipment in one space and living room contents in another. Only minor displacement of the smaller items such as cups and dishes on the dining table were observed during all the seismic motion tests leading up to FB-4. Following the largest seismic motion tests of FB-5 and FB-6, not only did small items such as cups and dishes get displaced and shattered but also large items such as a fully loaded bookshelf and anchored TV were displaced. The glass beakers and testing tubes fell off the workstations and shattered on the ground. Pictures of the Floor 2 areas with displaced contents following FB-6 are shown in Fig. 11.

(a)

(b)

Fig. 11. Displaced items on Floor 2 following FB-6 (a) living room space (note large gap in elevator door in background) (b) chemical lab and storage space.

Means of Egress Issues

Egress systems require continuous and unobstructed paths, either vertical or horizontal, that allows occupants not intimate with the initial incident such as a fire, to escape or reach a place of safety from the hazard before being exposed to untenable conditions. Damage to the egress systems components due to earthquakes is a concern since it could hinder occupant evacuation and the fire service operations. As a result of the FB-5 and FB-6 motion tests, damage to multiple egress components was observed. Interior door frames became distorted and some door latches were damaged. These conditions either prevented doors from closing completely or made doors difficult to open. In one case the strength of the magnetic door holder exceeded the strength of the connection of the strike plate, resulting in the strike plate being ripped off the door. In another case a door was completely jammed and shut and required tools to pry the door open [10]. Stairs became detached from the concrete floor slab and handrails fractured at a number of locations. Fig. 12 reflects damage levels of the stairs at all floors during FB-5 and FB-6. The minor damage level means no repair required, the moderate damage level means repair required, and the severe damage level means immediate repair required to assure safe operability of the stairs [13]. At various locations throughout the egress system gypsum wallboards were detached from the walls, including exit access (e.g., within compartments and elevator lobby) and exits (stairways), as well as on shaft enclosures. More complete discussion of egress system component damage after all motions can be found in [10, 13, 14]

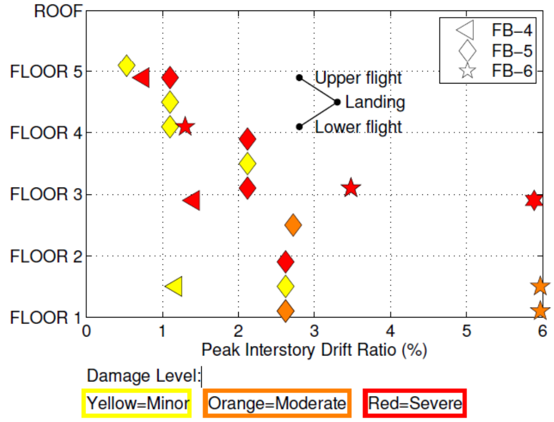
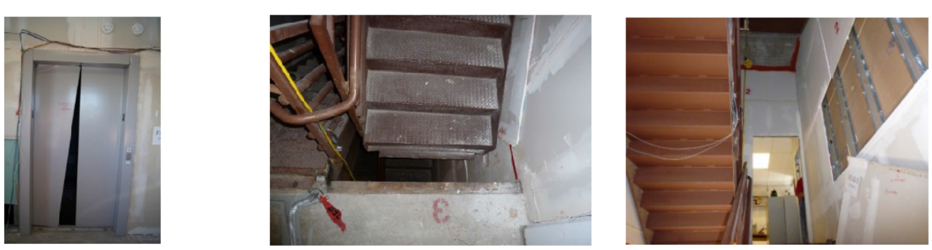


Fig. 12. Summary of damage to the stairs [figure from 13].

While not a component of all means of egress, the use of elevators for occupant evacuation is increasing in tall buildings. As such, its performance is of particular concern for high-rise buildings. During these tests, the elevator system performed quite well, remaining functional until the FB-5 motion despite minor gapping at the elevator doors. Following the FB-6 motion, although there was minimal damage to the mechanical components and rail subsystem of the elevator, the elevator was inoperable as the elevator doors experienced severe distortion at floors one to three. The various damage conditions outlined above are illustrated in Fig. 13, including damage to the elevator door (Fig. 13a), stairs detachment from the concrete floor slab (Fig. 13b) and loss of gypsum wallboard within the stair at Floor 3 (Fig. 13c).



(a) (b) (c)

Fig. 13. Damage to egress systems following FB-6 (a) distorted elevator door on Floor 3; (b) stair detached from landing; (c) detached gypsum board around stair landing area.

Compartmentation Issues

Compartment integrity can have a significant effect on fire growth, size, impact and spread, since ventilation openings serve both to supply oxygen to the fire and provide an avenue for hot gases to escape. Regarding fire growth, the rate of combustion is greatly affected by the availability and rate of airflow [16]. In addition, if forced ventilation or wind-driven fire conditions exist, fire growth and spread can be significantly affected [17], as movement of air through compartment openings can influence the shape, length and orientation of the flame, which can impact ignition of secondary materials inside and outside of the compartment (e.g., flame extension outside of a door or window opening) as well as influencing the direction of spread of smoke and hot gases. The location of ventilation openings along vertical compartment barriers is also important, as openings in the lower half of a compartment barrier (below the neutral plane) will tend to supply oxygen to the fire while openings in the upper half of a compartment barrier (above the neutral plane) will act as an escape route for the upward travelling, more buoyant smoke.

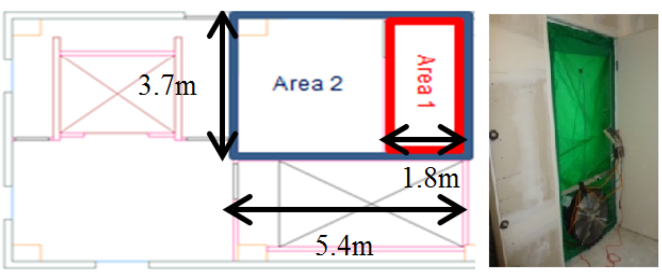
The major performance concern during and following earthquakes is that compartment barriers (walls, ceilings, glazing systems) and opening protectives (doors, dampers) can become damaged, thus contributing to the spread of fire and smoke. For some aspects, such as performance of door closure, visual indications of damage (e.g., door not able to close completely) and direct measurement of resulting ventilation openings (e.g., area of gap resulting from incomplete door closure) was possible. For other aspects, such as the total ventilation area created by cracks in barrier linings (e.g., gypsum wallboard and ceiling systems), direct measurement of ventilation openings was not feasible. However, an approach to measure the total area of ventilation openings was devised using a blower door fan system.

Blower Door Fan Tests

A blower door fan system was used to measure total leakage area of compartment boundaries. In this type of test, a fan blows air into or out of a building compartment, creating either a positive or negative pressure differential between the inside and the outside. As the pressure differential is created, air is forced through all holes and penetrations of the building enclosure. This approach is commonly used to measure leakage areas and locations in building compartments as part of energy performance assessments.

Compartment integrity tests using the blower door fan system were performed on the Northeast room area of Floor 3 following each seismic motion tests using an Infiltec E3 blower door fan. Testing was limited to the Area 1, the SBR separated by the partition wall, and Area 2, the entire SBR and LBR area combined as shown in Fig. 14a. The compartment space characteristics, such as the area and volume, were measured prior to testing. The leakage area measured after construction and prior to the first motion test served as the benchmark data to compare the degradation of the compartmentation caused by the ground motion tests.

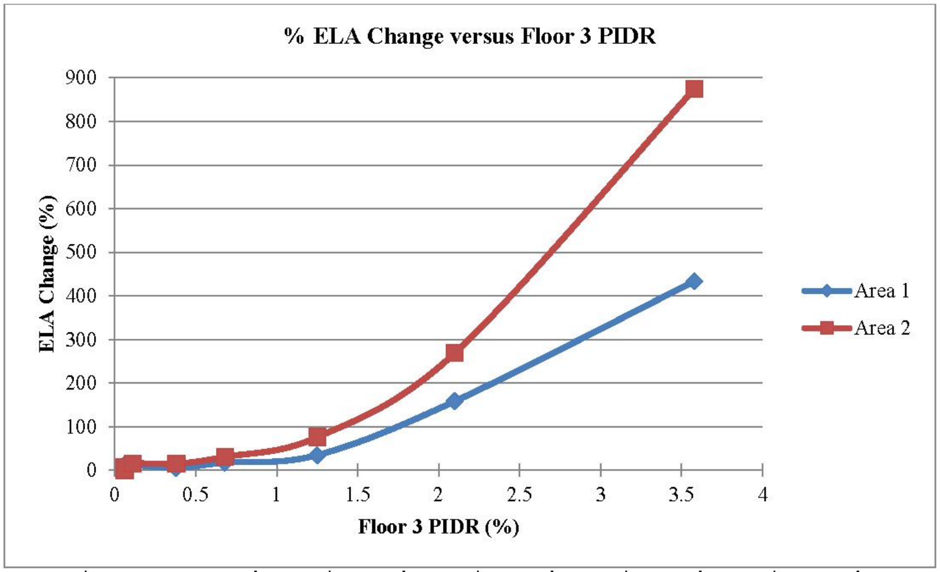
To accurately measure the leakage area all of the window openings and ceiling vents were sealed. The door fan system was installed tightly against the door frame as shown in Fig. 14b. Pressurizing and depressurizing of the room was achieved by setting the fan to supply or extract air from the compartment configuring the equipment appropriately. The manometer was adjusted as needed to provide the fan flow and pressure values of the compartment. These values are provided by measuring the pressure differentials between the outside and inside pressures of the compartment under investigation. Several readings from the manometer were used for each test to determine the effective leakage area (ELA) at 4 Pascal [10].



(a) (b)

Fig. 14. Compartment integrity tests on Floor 3: (a) test areas 1 and 2 and (b) installation of blower door.

Given the brief period of time between each motion test and subsequent building inspection, only one set of ELA data was able to be collected for each building damage state. Fig. 15 shows a plot of the change in ELA as a percentage, relative to the ELA measured before BI-1, versus the Floor 3 PIDR values of the building specimen from the motions. These ELA values are determined by performing a linear regression analysis on the five to seven readings of the fan flow rate and the pressure difference recorded during each test. This plot shows there was not much variance in the ELA for the smaller amplitude earthquake motions. Initially, the ELA of Area 1 was greater than the ELA of Area 2 up to FB-4, which was attributed to the leakage areas formed in the partition wall at the edges where the fire door frame was installed. A significant increase in the ELA for both testing areas is seen following the larger amplitude earthquake motion tests of FB-5 and FB-6. With more gaps created during the larger motion tests and taking into consideration the great disparity in size between the two compartments, the ELA of Area 2 surpassed the ELA of Area 1 following FB-4 [10].



Motion	BI-2	BI-3	BI-6	FB-1	FB-3	FB-4	FB-5	FB-6
Floor 3 PIDR	0.06	0.06	0.11	0.38	0.68	1.25	2.1	3.58

Fig. 15. Plot of % ELA change relative to 'Before BI-1' versus PIDR of Floor 3

As a result of the large inter story drifts imposed during FB-5 and FB-6 [9], damage to compartment barriers became significant. The balloon framed façade system for Floors 1-3 developed large gaps in joint areas, particularly where the interior sides (gypsum board) met floor slabs, columns, ceiling systems and any perpendicular bracing walls. Examples of wall-ceiling system joints, façade connection to floor slab, and exterior façade separation are shown in Fig. 16a-c.

(a) (b) (c)

Fig. 16. Issues affecting compartment integrity (a) Gap formed at North balloon framing and ceiling joint of Floor 3; (b) detached balloon framing connection clips; (c) gaps developed at the EIFS façade.

Compartment Damage Observations

In addition to the outcomes of the blower door fan tests discussed above, other compartment barrier damage, which could potentially affect and degrade compartment barrier performance in real buildings, was observed on Floor 3 and other floors as well, including:

- All dynamic firestop systems remained largely intact during the motion tests, as did static firestop systems on joints which remained intact. However, during earthquake motions, some joints that would be static in normal building operation became dynamic and did not remain intact, and gaps of up to 25 mm were observed. An example is the joint areas where the interior side of the exterior wall met columns, floors and ceilings [10]. Damage to fire stopped joints can allow for smoke and fire spread.
- While the ceiling system on Floor 3 performed generally well, with the exception of gaps forming at wall joints (Fig. 16a), the ceiling system on Floor 1 showed progressive damage with increased earthquake motion intensity. Damage to ceiling systems can allow for smoke and fire spread.
- Two ICU breakout doors were installed in the stair landing area of Floor 4. These doors performed well throughout the motion tests, except during FB-5, when the ICU door from the landing to the Southwest room area became partially detached from the doorframe [10]. Damage to smoke doors can allow for smoke and fire spread.
- Fire dampers performed generally well. However, after FB-6, one damper out of three was not fully closed. This was due to the damper's blade rotation being prevented by a screw used for the damper installation which, once adjusted, allowed the damper to close completely [10]. Damage to dampers can allow for smoke and fire spread.

Additional Observations [9]

In addition to the damage detailed above, several other areas of concern and observations were noted, some of which were observed during fire testing, including:

- While glazing systems were not installed within the building specimen, fire tests were conducted with window openings closed and 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 concern here is 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 than the building fire protection systems are designed for or the fire department might expect.
- In various locations within the test specimen gypsum wallboard sections became detached during motion tests. The potential fire concern is loss of compartment integrity and spread of fire and smoke.
- Following the largest ground motions, significant spalling occurred on some of the concrete beam-column connections on the lower floors. This resulted in exposed steel reinforcing. The combination of connection damage and reinforcing bar exposure could impact the structural load-bearing capacity and fire performance of the connections and structural system. The potential fire performance concerns here are that the building could be at risk for localized structural failure and even collapse.
- The automatic fire sprinkler system performed well. In part this is attributed to the small floor areas, small pipe sizes, short pipe lengths, hanger spacing and seismic bracing needed to comply with code requirements. Testing of sprinkler system arrangements that reflect existing installations, which pre-dated code requirements following the 1994 Northridge earthquake, for example, might yield different outcomes. Assessment of the performance of existing installations could yield interesting information.

CONCLUSIONS

The BNCS Project was undertaken to better understand building nonstructural system performance during earthquakes and post-earthquake fire hazards. Based on observations and data collected during these tests, a number of fire safety issues were identified. Most notably these include:

1. Earthquake motions can damage compartment barrier components by creating gaps at joint areas due to the movement of the components. In addition, earthquake motions can damage door frames and doors,

leaving them unable to perform intended compartmentation functions. Such gaps and unintended openings reduce compartment integrity, resulting in unlimited flow of oxygen to a fire and unconstrained spread of smoke and flame, impacting both the control of the fire and the tenability of escape routes during the evacuation process.

2. Earthquake motion can render key portions of the means of egress unusable or can significantly hinder time to escape. During the earthquake motion tests, several means of egress components and alternate egress options were damaged, including the stairway and the elevator. In addition, the earthquake motions displaced contents, which could serve to hinder occupants from quickly and safely evacuating. The damage to the egress system and distribution of building contents can also impede emergency responder operations.

3. Important structural connections were damaged following the largest earthquake motions conducted in this test series, resulting in spalling of concrete and exposure of reinforcing steel. Such damage could degrade the fire resistance rating and load-bearing capacity of the structural member and/or system.

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Appendix B

"Fire Performance of Full-Scale Building Subjected to Earthquake Motions: Fire Test Program and Outcomes" published in the proceedings of the 11th International Symposium on Fire Safety Science.

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].

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.

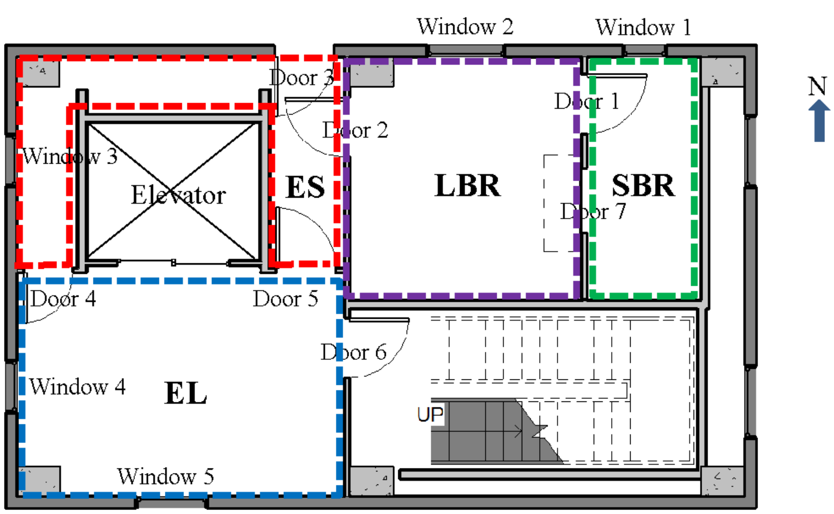


Fig. 1. Floor plan of the third floor

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.

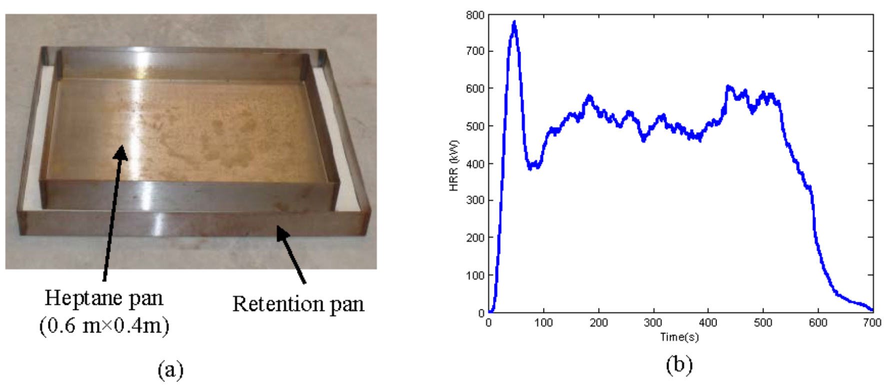


Fig. 2. Heptane pan design (a) and HRR of 9L of heptane (b)

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.

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

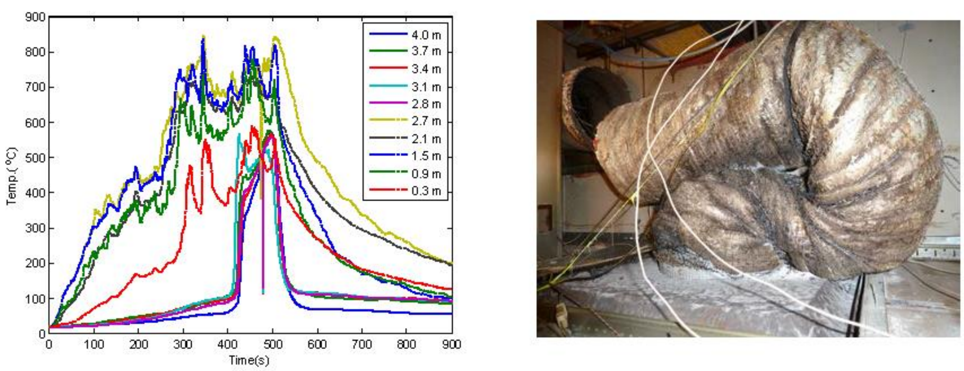
The elevator was not operational after the largest ground motion test due to the distorted elevator doors, especially from the 2nd to 4th floor. The elevator door damage on the 3rd floor is shown in Fig. 4 (a). In EL-1 fire test, the elevator button panel melted and wires behind the panel were burned 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.

(a) (b)

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.



(a) (b)

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.

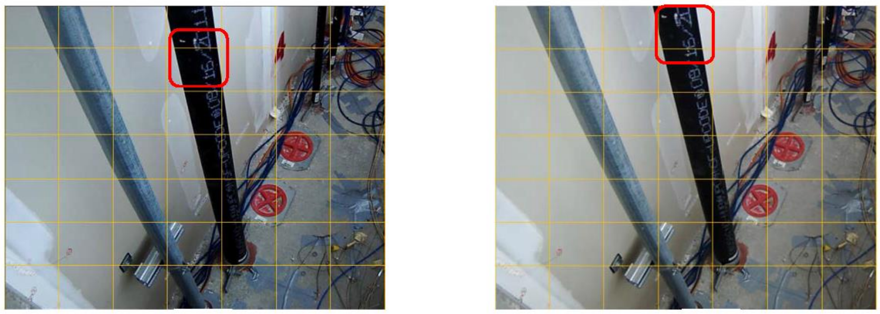
Depending on the configuration of joints and assembly materials, building joints can be largely divided into two: dynamic and static, and different fire stop sealants are used for each. All dynamic and truly static joints performed well in fire tests. However, it was found that in earthquake conditions, 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.

(a) (b)

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.



(a) (b)

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 550ºC 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

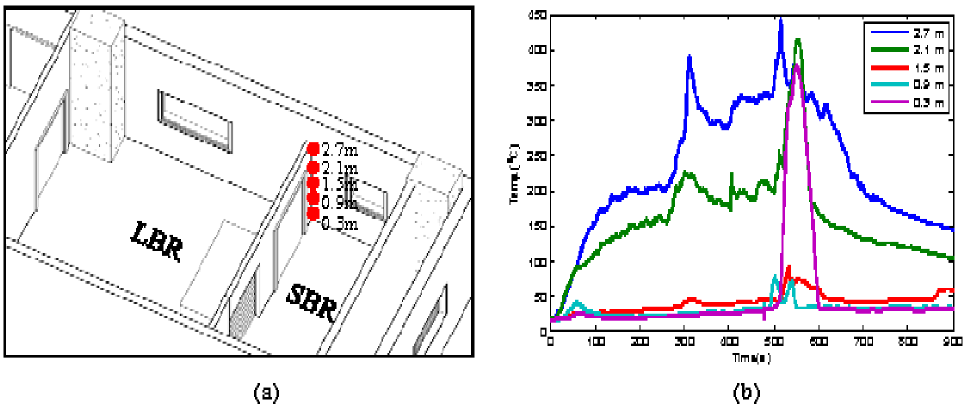


Fig. 11. Locations of thermocouples and temperature profile in LBR-2 fire test

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°C and 200°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°C and 300°C. This temperature range may be high enough to cause ignition with a pilot flame ignition source and large enough burning time.

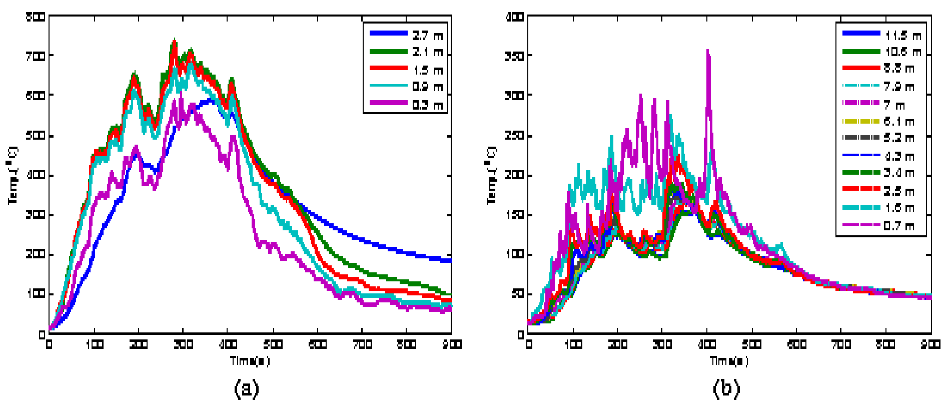


Fig. 12. Gas temperatures in elevator lobby (a) and gas temperature in elevator shaft (b)

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.

(a) (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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