2013

Performance-Based Engineering Framework for Earthquake and Fire Following Earthquake

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PERFORMANCE-BASED ENGINEERING FRAMEWORK FOR EARTHQUAKE AND FIRE FOLLOWING EARTHQUAKE

By

Aerik Carlton

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Civil Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2013

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Civil Engineering.

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List of Acronyms

ASCE – American Society of Civil Engineers

ASCE 7 – American Society of Civil Engineers Code Book "*Minimum Design Loads for Buildings and Other Structures"*

ASD – Allowable Stress Design

ASTM – American Society of Testing and Materials

CFAST – Consolidated Model of Fire and Smoke Transport

EQ – Earthquake (in text), Equation (next to equations)

FEMA – Federal Emergency Management Agency

FFE – Fire Following Earthquake

FS – Factor of Safety

HVAC – Heating, Ventilation, and Air Conditioning

LRFD – Load and Resistance Factored Design

NFPA – National Fire Protection Association

NIST – National Institute of Standards and Technology

PBE – Performance-Based Engineering

PBEE – Performance-Based Earthquake Engineering

PEER – Pacific Earthquake Engineering Research Center

USGS – United States Geologic Society

1 Acknowledgements

I would like to thank Dr. Li for his willingness to welcome me into his research pursuits. Dr. Li is the reason I enrolled at Michigan Tech and I cannot thank him enough for his efforts, guidance, excellent listening skills, and a solid foundation with which to start my career. I would like to thank Dr. Bulleit for his support and excellent instruction. I have become a much more thoughtful and thorough engineer because of his courses, and I appreciate the efforts and involvement he has given to the Michigan Tech community.

I would like to thank the other professors in the department for their additions to my graduate education, especially Dr. Mukherjee and Dr. Mattila. I would like to include the departmental staff who are all too often excluded from research acknowledgments, without their efforts the students and faculty would suffer; thank you Amanda Cadwell, Angela Keranen, Julie Ross, Shelle Sandell, Rob Fritz, and Kiko de Melo e Silva.

I would like to thank Dr. Ibrahim Miskioglu and Mr. Michael T. Drewyor for agreeing to sit on my thesis committee. I would also like to thank Clive Gasparka, Brad Kuehl, and Robert Kuehl from Rice Engineering, Inc. who gave me some much needed information which changed the direction of this research project. I would like to thank all of the students in Dr. Li's research group both past and present, with special thanks to Ruiqiang Song and Carley Feese.

I would like to thank my parents and family for their support without which very little would have been possible. And lastly, I would like to thank my fiancée Jennifer, who's patience and support during this graduate degree has been nothing short of phenomenal; thank you, sweetheart.

2 Abstract

The objective for this thesis is to outline a Performance-Based Engineering (PBE) framework to address the multiple hazards of Earthquake (EQ) and subsequent Fire Following Earthquake (FFE). Currently, fire codes for the United States are largely empirical and prescriptive in nature. The reliance on prescriptive requirements makes quantifying sustained damage due to fire difficult. Additionally, the empirical standards have resulted from individual member or individual assembly furnace testing, which have been shown to differ greatly from full structural system behavior. The very nature of fire behavior (ignition, growth, suppression, and spread) is fundamentally difficult to quantify due to the inherent randomness present in each stage of fire development. The study of interactions between earthquake damage and fire behavior is also in its infancy with essentially no available empirical testing results.

This thesis will present a literature review, a discussion, and critique of the state-of-the-art, and a summary of software currently being used to estimate loss due to EQ and FFE. A generalized PBE framework for EQ and subsequent FFE is presented along with a combined hazard probability to performance objective matrix and a table of variables necessary to fully implement the proposed framework. Future research requirements and summary are also provided with discussions of the difficulties inherent in adequately describing the multiple hazards of EQ and FFE.

3 Introduction

This thesis will propose a Performance-Based Engineering (PBE) framework to evaluate damage and loss associated with various design or retrofit options for cost effective hazard mitigation strategies. By individualizing the sources of unnecessary costs over the long term (building life cycle), adequate and specific retrofit options become apparent and available to mitigate hazard loss, possibly to the point of needing no significant repair. Various sources of uncertainty in fire behavior modeling and structural response will be included within the proposed framework. The inclusion of uncertainty bestows longevity on the framework. The models used to evaluate damage and loss become available to optimization, or even re-characterization, by giving indication of the high level of uncertainty within variables. The uncertainty, therefore, can directly indicate which materials should be improved or more accurately described, which codes need to be more stringently enforced or updated, and even which portions of accepted models relate deficiencies to the overall characterized behavior.

Within the proposed research project, there exist several questions, some of which are discussed within the overall scope of this thesis. The current *HAZUS* fire model exhibits an ignition function with an R-squared value of 8%, and shows a place where epistemic uncertainties could possibly be reduced or, at the least, quantified. The development of a different approach, however, could be incredibly time consuming and may not provide a worthwhile result due to the random nature of ignition locations. The model used by *HAZUS* utilizes a data set comprised of 238 ignitions from seven post-1969 seismic events, but may not be a enough data to gain a reasonable level of accuracy in the resulting output. The more advanced ignition models presented in fire specific state-of-the-art software pull data from multiple countries. *HAZUS*, however, has described the difficulty in quantifying the differences in resulting Fire Following Earthquake (FFE) due to differences in codes and suppression efforts between countries. *HAZUS* expressly stated reduced correlation when data from outside the United States (US) or when pre-1970 data was used (FEMA 2012).

Additionally, quantifying the relationship between the damage state of the structure from a seismic event and the structures change regarding fire susceptibility is a primary question. Zolfaghari et al. (2009) illustrated the increased probability of ignition and increased total number of ignitions based on displacement from seismic activity. For example, a gas range has the ability to cause spark and also holds fuel to propagate the ignition, and any other household appliance relying on electricity has a capacity for initiating spark with carpet, furniture, clothes, and the structural components themselves provide fuel. Seismically damaged buildings also reduce the compartmentalization of areas within the structure. Cracked walls, broken windows, and compromised sprinkler systems, for example, all increase a structure's ignition and spread capacity. Therefore, displacement can play a significant role in ignition and spread. The quantification of this relationship is expected to be the goal of future research continuing from this project's results.

Current structural engineering design practice for civil infrastructure relies upon our current codes, standards, and additional regulatory documents, which are prescriptive requirements taken from experiential and short term historical record (Ellingwood 2008). The advancement of structural engineering design through Factor of Safety design (FS) to

Allowable Stress Design (ASD) to Load and Resistance Factor Design (LRFD) throughout the 20th century can be attributed in part to improved understanding of load prediction and material performance. The greatest influence can arguably be credited to the increase in probabilistic analysis and subsequent incorporation into structural design methodologies. As a result, the structural performance of our built infrastructure is becoming more positive with each successive step in design methodology (Ellingwood 2008).

PBE is the most recent development in structural design practices, extending beyond LRFD and satisfying different performance objectives. LRFD and similar design protocols rely on prescriptive criteria which allow for relatively unambiguous code interpretation and are quantitative and detailed (Ellingwood 2008). However, prescriptive codes and design practices can lull the design specialist into believing that simply meeting the code requirements is sufficient to meet structural performance expectations of owners and society. Natural disasters have repeatedly illustrated this flaw in prescriptive code protocols in terms of owner and occupant expectations with structures failing to yield adequate performance; just review the structural losses from Hurricane Katrina (2005) or the Northridge earthquake (1994) (Ellingwood 2008). PBE has become the new paradigm in structural practice, which will follow similar protocols in use in aerospace, marine, and automotive industries (Ellingwood 2008).

The development of PBE in structural engineering will allow design to adapt to rising social expectations enabling better prediction and control over our infrastructure (Ellingwood 2008). By meeting increased public expectation and focusing on structural performance instead of prescriptive code fulfillment, we as engineers can decrease overall structural damage. Through the change to PBE, our buildings and infrastructure can become less expensive to repair and maintain in the long term. Design lifetimes are currently being exceeded and the need for increased performance, while keeping construction and maintenance costs reasonable, has become more apparent.

There exists a need for increased research and subsequent code development concerning structural fire engineering within the US (Kodur et al. 2007). Hadjisophocleous et al. (1998) explained the lack of sufficient code development within the US is in drastic disparity when compared with other developed nations, such as Japan, New Zealand, the United Kingdom, Australia, and Canada. Concerning structural fire engineering, the greatest obstacle in the creation of relevant and substantial code development is the nature of fire. Traditional structural engineering codes offer tightly controlled line provision requirements, which are difficult to define in terms of theoretical reasoning. The probabilistic nature of fire behavior, and the variables required to adequately model and predict fire behavior, makes the introduction of probabilistic analysis necessary. The reliance upon probability methods makes PBE a strong candidate for fire hazard design (Ellingwood 2008). Historically speaking, the defined load factors and equation coefficients can be arbitrarily selected by a group of experienced engineers recalling pragmatic solutions they have made in the past. The call to develop and detail PBE design criteria is necessary, if not required, to flesh-out an effective and rational code, and the development of PBE criteria in other developed countries strengthens this argument for a US code (Buchanan 1994).

This thesis will present a literature review, a discussion and critique of state-of-the-art software, a generalized PBE framework, and a discussion on future testing and research needs.

3.1 Research Objective and Motivation

The overall goal of this research project was to establish a generalized but thorough Performance-Based Engineering (PBE) framework to describe the interaction between Earthquake (EQ) and Fire Following Earthquake (FFE). The methodology presented within the PBE framework will provide an outline to more accurately model EQ and subsequent FFE for a structure as well as a collection of structures. The framework will illustrate current voids in empirical data to describe EQ and FFE interaction, and act as a guide for future research. By laying out the necessary areas of computation, the uncertainty in each variable and equation set can be quantified to establish a definitive confidence in the model.

The framework has the potential to touch multiple fields. Emergency planners could have better information concerning the likely damage, loss of life, and necessary emergency staff and equipment to adequately handle a seismic event and FFE. City emergency planners will also be better informed to organize emergency evacuation plans. Fire fighters may have a safer work environment as structures will be designed to better cope with the combined hazards from EQ and FFE. Building owners may reap the benefits of lower costs for damages. As structural engineers and designers are presented with better information to handle the risks associated with EQ and FFE, city dwellers will have the benefit of infrastructure built to perform well under seismic and fire hazards leading to reduced loss of life, reduced repair time, and reduced repair costs. There exists a possibility of slightly increased building costs; however one of the main goals and strengths of PBE is the ability to optimize the structural performance of the building, such that the desired performance is achieved while minimizing construction and repair costs.

3.2 Performance-Based Engineering

Performance-Based Engineering (PBE) is an engineering design, evaluation, and construction process which approaches engineering solutions from a new perspective and relies on probability analysis. The PBE perspective assesses the uncertain demands a facility could, and in some cases will, experience while promising a given facility will exhibit the desired performance (Stanford 2013). The goal of PBE is to optimize the response a given facility will yield under demand, while keeping economic boundaries and societal expectations in consideration.

Additionally, PBE supplies a rational foundation for design encompassing an innate flexibility to accommodate a range of stakeholder needs, while maintaining the necessary goal of reduction in structural damage and life loss. PBE displays the promise of quantification of more than just life safety objectives, allows for analytical performance prediction including confidence intervals, and allows risk management concerning innately uncertain natural hazards. The inherent strengths of PBE are the ability to change with social expectations from building occupants, building owners, and other stakeholders and to quantify the certainty to which the predicted performance objective is met.

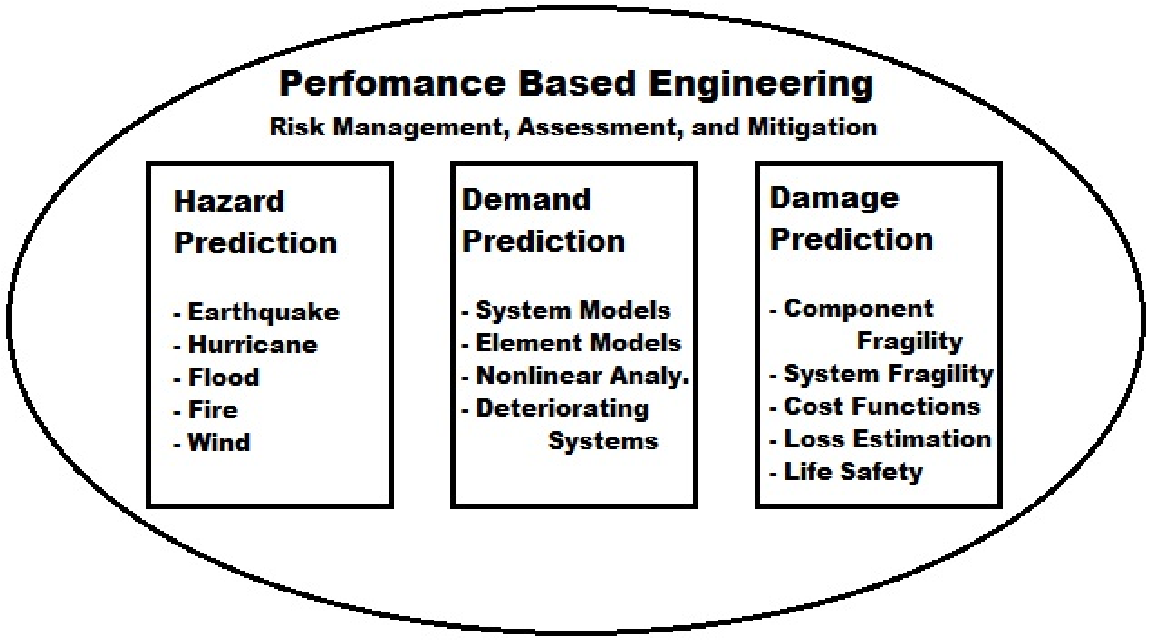

Figure 1: Performance-Based Engineering Components

(Based upon Figure from Stanford 2013)

Figure 1 illustrates the three main components of PBE with hazard prediction largely based upon the loadings from such codified guides as ASCE 7; demand prediction is completed through engineering analysis consistent with any design methodology (ASD, LRFD, etc.); and damage prediction, which utilizes probabilistic analysis to estimate damage state and cost of repair.

Risk management, assessment, and mitigation are the guiding boundaries for the three components described in the previous paragraph. The statistical probability of the proposed facility experiencing a hazard based on physical location and the societal expectation of performance during and after experiencing the hazard typically controls the risk involved with the proposed facility. Generally, society expects a facility to weather a hazard with minimal loss of life, which is typically consistent with the magnitude of the hazard (i.e., during a M3.0 earthquake in California the expectation is zero life loss, while a M8.0 earthquake in California a greater than zero loss of life is accepted due to the prohibitive cost of making all structures able to withstand an earthquake of large magnitude). The assessment, mitigation, and management of the risk are portions of the prediction components of PBE, where iteration of the structural design is expected until the desired performance is met (Ellingwood 2008).

As an example of PBE, the lateral response of a building is dictated either by seismic or wind loading under current structural code design methods given in ASCE 7, whichever is the greater load controls. The controlling load is then the only lateral design load considered. When considering lateral loading effects for this example, the roof weight becomes important with seismic response benefiting from a lower roof weight, while wind response benefits from a heavier roof. Therefore, in current design practice the more likely lateral loading dominates the design process, which increases the deficiency for the non-controlling lateral load. PBE design for this case provides a method of optimizing the roof weight such that it will perform well under both lateral load cases, while still maintaining economic boundaries.

3.2.1 Boundaries

Ellingwood (2008) reviewed Performance-Based Engineering (PBE) codified design methods illustrating the equations used to develop probability of failure and the current limited application of PBE within Load and Resistance Factor Design. Discussing the flaws in the current codified design, Ellingwood (2008) continued, outlining the major equations and methodology necessary for the next step in code development; the movement to PBE. PBE relies heavily upon probability analysis for failure and losses due to risk of hazard, but describes difficulty within the definition of acceptable risk. Before a thoroughly evaluated PBE design can be outlined, a serious discussion between stakeholders and structural engineers must occur, and the discussion must also result in a clear definition of the acceptable risk (Ellingwood 2008). For example, is it socially acceptable to design a building to handle a storm with a recurrence interval of 500 years (a probability of 0.20% of occurring within any given year) without damage? Meaning the designed structure would pose no risk to human life or financial strain for repairs after such a storm. However, the cost of construction might be 10-20% more costly compared to a current 100 year (probability of 1% of occurring within any given year). Without a rigorous set of publications detailing the possibilities of life loss, property destruction, and cost of repair, the necessary discussion to define acceptability is impossible. The definition of socially acceptable performance for an engineered facility is integral to the development of PBE as a design method, because without the definition of acceptable performance PBE design has no boundaries.

3.2.2 Uncertainty

Ang and Tang (2007) defined aleatory uncertainty as the uncertainty associated with natural and innate randomness present within any natural value that is quantified, while epistemic uncertainty is the uncertainty associated with inaccuracies inherent in models describing real-world systems. Understanding uncertainty as formerly described, it becomes apparent that all aspects of engineering are affected by uncertainty in one or more forms. The ability, to separate the two forms of uncertainty can be completed. Aleatory uncertainty is natural and rather difficult, if not impossible, to remove. Epistemic uncertainty is the more valuable quantity in Performance-Based Engineering (PBE), because epistemic uncertainty allows for equations and models to become more rigorous and descriptive of reality in a thoughtful and useful way. Finding and quantifying the sources of epistemic uncertainty gives a road map to increasing the quality of designed models as well as an indication of which portions within a model are most uncertain. We can then, from adjustment and research, adequately reduce our uncertainty (Ang 2007).

Baker and Cornell (2006) continued the discussion stating decision makers are primarily interested in the financial and life losses resulting from seismic events, which is contingent for any hazard. Evaluation of the damage and sources of uncertainty in our models is paramount to make the necessary changes to our building codes. Baker and Cornell (2006) defined the current challenges exhibited by the method to consider ground motion, hazard, building response, element damage, individual element repair cost, total repair cost propagating the uncertainty throughout each portion of the model. Baker and Cornell (2006) set goals to establish a framework for estimating annual loss incurred from seismic events using PBE with first-order second-moment approximations, and attempt to quantify both epistemic and aleatory uncertainty. Baker and Cornell (2006) have laid out the base equations and progressed through each step to full development of a PBE framework, which identified and propagated uncertainty. The understanding and quantification of uncertainty is the strength and advantage that PBE provides.

3.2.3 Application

Though limitedly, Performance-Based Engineering (PBE) has permeated into our existing design process through the development of hazard loadings. The incorporation of PBE into our load development can largely be seen as an acceptance of probabilistic analysis in our design process. The structural engineering community has been using and working with increasing influence from PBE, and as such, development of PBE frameworks for all hazards is necessary to increase our progression to sustainable, resilient, and cost effective structural design.

An inherent strength of PBE is the ability to consider multiple hazards for a structure. Li and van de Lindt (2012) discussed the formulation of loss estimation from buildings experiencing multiple hazards, addressing the radically different nature between hazards, the relative frequency of each hazard's occurrence, the consequences, and hazard resistant design.

Typically structures, regardless of the location, will be subjected to multiple hazards such as wind and surge loadings from a hurricane. While some hazards that a structure might be exposed to are nearly negligible, climate change has possibly increased the likelihood and range of some hazards such as hurricanes, tropical storms, and severe windstorms (Bjarnadottir 2011). In other cases, hazards are of such rarity that the current structural design code allows complete neglect in certain cases, such as seismic considerations for non-essential structures within the Midwestern United States (US) from the New Madrid Fault located in southeastern Missouri (ASCE 2010). The 1811 and 1812 earthquakes from the New Madrid Fault exhibited exterior component damage as far away as Pennsylvania, yet current building code for non-essential structures in the US Midwest is dominated by lateral wind loading with seismic consideration typically being omitted from structural design (USGS 2013).

A 2000 FEMA study estimated economic losses within the US averaging $5.4 billion dollars a year due to hurricane and $4.4 billion annually for structural damage due to seismic activity. Because of the large costs associated with natural hazards, a way of accurately and economically designing buildings for a desired response is of great importance, therefore PBE has become a paradigm in structural engineering with the goal of accurately predicting structural response to a spectrum of hazards both natural and anthropogenic. A flaw in current code could be attributed to the practice of designing for a dominating hazard (Li and van de Lindt 2012).

Griffis et al. (2012) present a PBE framework for wind engineering with the goal of providing a method for evaluating existing structures with regard to wind hazard as well as aiding in building design to optimize performance and building cost in response to wind loading. Griffis et al. (2012) point out that the threshold for traditional wind engineering design can be extended, if inelastic behavior under wind loading is accounted for, and the presented framework allows for the inclusion of inelastic behavior.

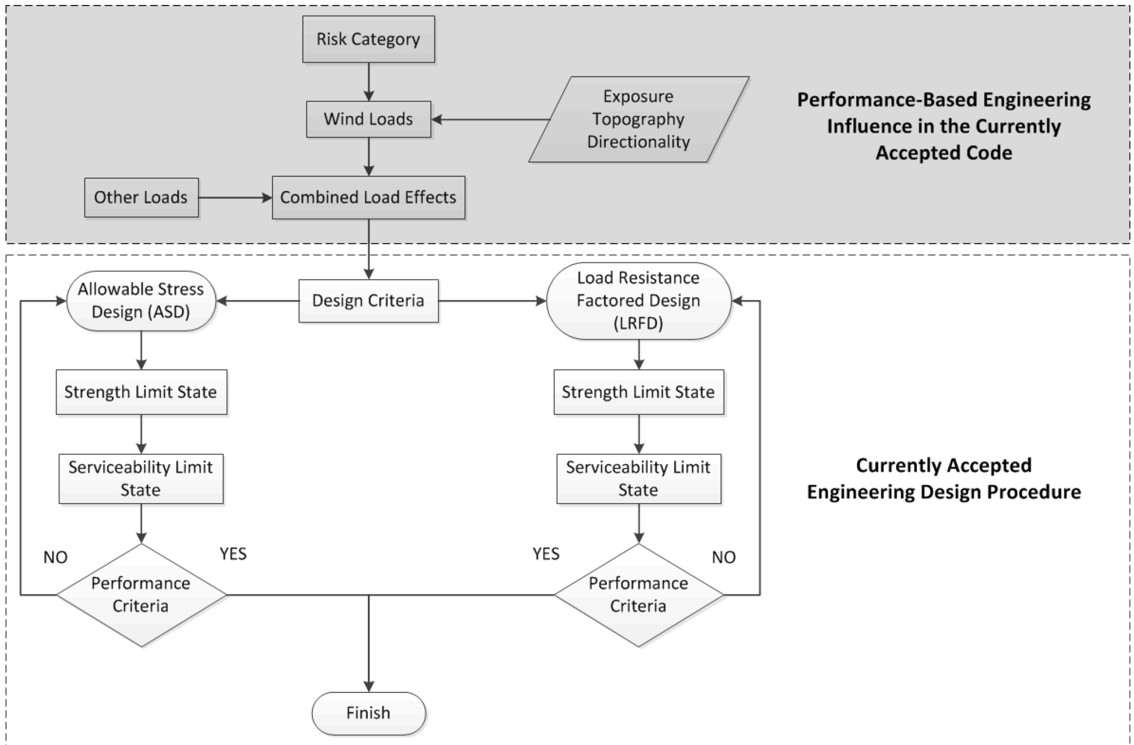

Figure 2: Performance-Based Wind Engineering Framework

(Based upon Figure 1 in Griffis et al. 2012)

Figure 2 is a modified version of Griffis et al. (2012) PBE wind framework. The generality of the framework allows flexibility. As additional techniques are developed in the refinement of wind loading description, additions to the framework can be readily completed allowing for prolonged use. Note, that the upper portion of the framework is where PBE is introduced into the evaluation process, and mirrors the method currently in use within ASCE 7. Also of note, is the inclusion of other loads into the framework just before the design criteria is selected. The inclusion of non-wind loads is where additional hazards can be included, and allows this framework to be paired with additional hazard frameworks such as: seismic, surge, and fire loadings.

There exists a fair volume of PBE publications discussing seismic events as evidence of the current ASCE 7 acceptance of PBE seismic performance estimation. The nature of fire behavior, and subsequently fire engineering, naturally leans toward a PBE process due to the necessity of probabilistic analysis. Fire ignition, spread, and suppression all heavily rely upon probabilistic variables such as: spark to fuel proximity, ignition origin, fuel availability, sprinkler head effectiveness, and human behavior (Zolfaghari 2009). The collapses at the World Trade Center from fire loading have drawn attention to current code deficiencies. As a result, research interest in structural fire engineering has increased. However, the US currently lags behind Japan, New Zealand, and Canada where PBE has already been instituted considering fire design (Buchanan1994). Therefore, PBE has become a paradigm within structural engineering, which aims to optimize structural design by focusing on performance instead of meeting codified line provisions.

3.3 Performance-Based Earthquake Engineering

Performance-Based Earthquake Engineering (PBEE) is the application of the Performance-Based Engineering (PBE) method to seismic hazard. The goal of PBEE is to establish a methodology to accurately assess structural performance and influence the design process such that the desired performance can be obtained. To achieve the method, PBEE has developed a defined seismic intensity metric, defined the necessary engineering demand parameters, defined metrics for damage state parameters, defined measures for damage, and introduced decision variables. In summation, PBEE is a method for making informed decisions which influence seismic risk mitigation making our structures more resilient in seismic events. (Moehle et al. 2004)

PBEE methodology can be described in three parts which have become the codified standard: the definition of the seismic design hazard based upon geographic location, evaluation of the lateral earthquake design forces, and the introduction of prescriptive design requirements to adequately handle the energy dissipation necessary to achieve the desired structural performance (Hamilton 2011, ASCE 2010). PBEE is widely accepted and is typically referred to as the first PBE criteria to reach such adoption. PBEE has also acted as a reference point for PBE framework development concerning other hazards: wind, fire, and hurricane as examples.

The equation of loss estimation from the methods of Baker et al. (2008) and Wen et al. (2003), illustrated below, where P denotes the probability of occurrence, is an illustration of the basis for the proposed probabilistic analysis necessary to complete computation proposed by the framework.

$$P(Loss) = \iiint \int P(Damage|Response)P(Response|Demand)P(Demand|Hazard)P(Hazard)$$

(EQ. 1)

Where, P(Hazard) indicates the probability of hazard, for the proposed framework, the probability of earthquake occurrence given the structural facility location and also the probability of fire ignition due to the given seismic hazard. P(Demand|Hazard) represents the probability of demand upon the given structure given the probability of earthquake and fire hazards. P(Response|Demand) is the probability of structural response to the given demand. P(Damage|Response) indicates the probability of damage given the response of the structural facility to the structural response.

Moehle et al. (2004) establish the formalization of the PBEE framework within a probabilistic foundation due to the inherent uncertainty and variability in seismic demand and response, and categorize the framework in four simplified variables: Intensity Measure (IM), Engineering Demand Parameter (EDP), Damage Measure (DM), and Decision Variable (DV). These variables are then expressed within a probabilistic analysis in terms of conditional probabilities due to the interrelated nature of each parameter:

$$v(DV) = \iiint G(DV|DM)|dG(DM|EDP)|dG(EDP|IM)|d\lambda(IM) \qquad \text{(EQ. 2)}$$

where v(DV) is the decision variable quantity to be compared with the desired performance metric. The equation is based upon the total probability theorem, and is a relatively simplified representation of an extensive and complex problem, while still yielding a consistent format for comparison and emphasizing the uncertainties within each variable. (Moehle et al. 2004)

ArcGIS is a Global Positioning Satellite Information System that utilizes satellite imaging and positioning to output detailed and accurate surveying values, and uses United States census data for structure age, population, and density. *HAZUS*, a state-of-the-art software plug-in for *ArcGIS*, implements a simplified version of the PBEE method to allow ease of computation for city scale seismic damage. *HAZUS* utilizes structural fragility curves and building age to formulate the damage output, and is described in detail for PBEE below and for fire within the "Critical Appraisal" section of this thesis.

3.3.1 Performance-Based Earthquake Engineering Application

HAZUS, a hazard loss software package developed by the Federal Emergency Management Agency (FEMA) under the Department of Homeland Security, has become an invaluable tool in hazard evaluation for engineers, city planners, police and fire fighters, insurance agencies, and political officials tasked with emergency hazard response. The program's basis within *ArcGIS*, a Global Positioning Satellite Information System that utilizes satellite imaging and positioning to output detailed and accurate surveying values, and use of United States census data concerning structure age, population, and density allows for in-depth description of varying hazard responses.

HAZUS relies upon Performance-Based Earthquake Engineering (PBEE) analysis for seismic hazard consideration. Based upon the ground acceleration, the model develops building response in terms of maximum spectral displacement to compare to a set of fragility curves. Fragility curves are plots that illustrate the level of damage to the building due deflection incurred from the structural response due to ground movement during seismic events. Figure 3, below, is an illustration of a fragility curve.

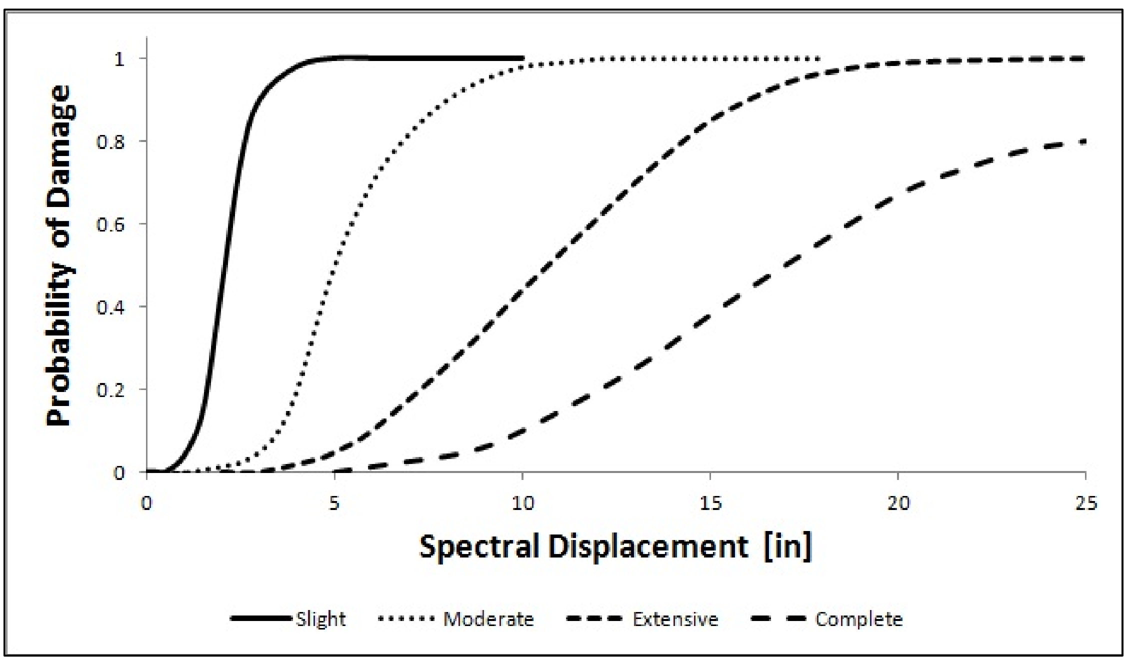

Figure 3: *HAZUS* Fragility Curve Displacement to Probability of Damage (Based upon Figure 5.1 FEMA 2012)

Fragility curves are generated for building material construction and types of codes used during the year of construction. Table 1, below, illustrates the methodology *HAZUS* utilizes to determine the code type in relation to the structure's year of construction. Due to the large body of research governing the models within *HAZUS*, it can be assumed the probability damage outputs are fairly reliable, and uncertainty can be quantified from the analysis.

Table 1: Guidelines for Selection of Damage Functions for Typical Seismic Zone and Building Age

Seismic Zone	**Post-1975**	**1941-1975**	**Pre-1941**
Zone 4	High-Code	Moderate-Code	Pre-Code
Zone 3	Moderate-Code	Moderate-Code	Pre-Code
Zone 2B	Moderate-Code	Low-Code	Pre-Code
Zone 2A	Low-Code	Low-Code	Pre-Code
Zone 1	Low-Code	Pre-Code	Pre-Code
Zone 0	Pre-Code	Pre-Code	Pre-Code
Note: Seismic Zone based upon the Universal Building Code (UBC) definition. Table Based upon Table 5.20 in FEMA (2012).			

HAZUS has been successful in providing an invaluable tool to engineers and city planners to adequately describe structural performance from seismic hazards. The simplifications made have been effective due to the mass of research concerning PBEE, and highlights the need for similar research for FFE.

3.4 Fire Engineering

Constructing adequate descriptions for fire dynamics within buildings and the effects on the structural integrity of a building has been a difficult task. The unpredictable nature of ignition, the origination point of ignition, proximity between the ignition point and fuel, the availability and type of fuel, compartment size, compartment ventilation, effectiveness of code prescribed suppression systems (e.g., fire sprinklers and HVAC system fire cutoff), and human behavior such as use of fire extinguishers and door closing have made the attempts to quantify and model fire behavior in buildings a daunting task. As a result of the very nature of fire, the use of probability analysis and probabilistic estimation will likely always dominate most aspects of fire modeling. (Hadjisophocleous et al. 1998, Kodur et al. 2007)

The standard fire testing method is outlined by the American Society of Testing and Materials (ASTM) in Designation: E119-00a. The standard testing method utilizes what is known as the "Standard Fire Curve," which has been used extensively in furnace tests for materials. The curve, illustrated in Figure 4, has been in use for close to 100 years.

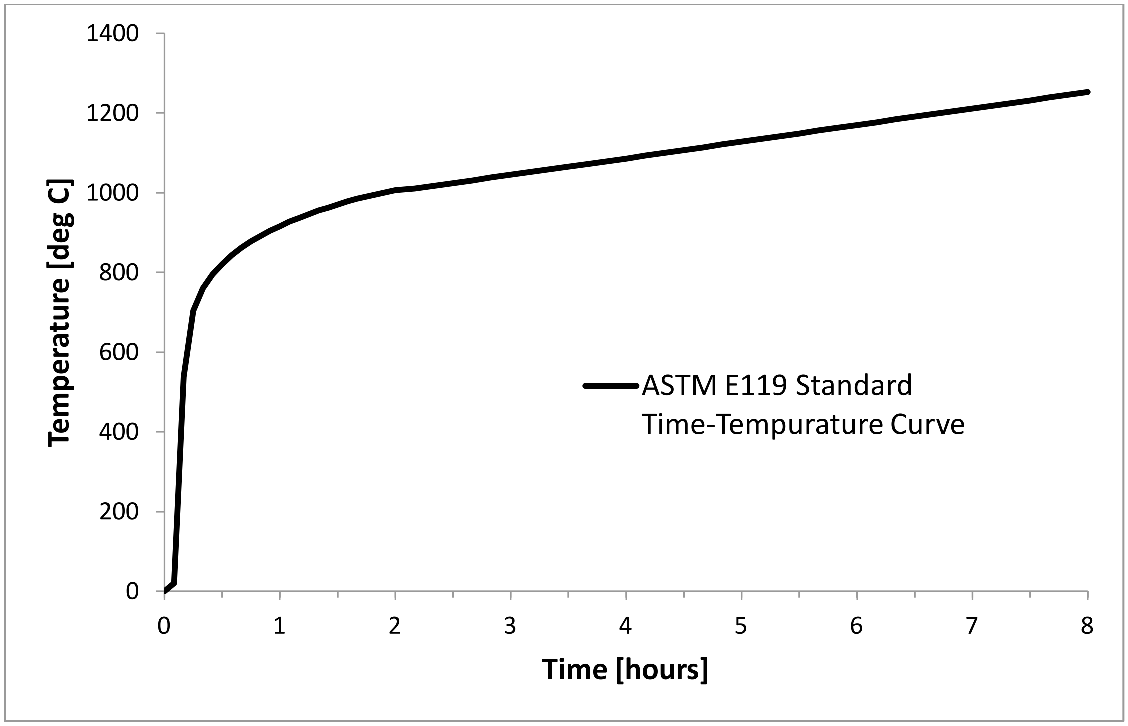

Figure 4: ASTM E119-00a Standard Fire Curve
(constructed from values assigned in Appendix X1 of ASTM E119-00a)

Note the lack of diminishing temperature as time progresses. There have been numerous papers which discuss the flaws in the Standard Fire Curve, however all current fire codes and testing procedures have adapted such that results from the Standard Curve can be modified to values more consistent with more accurate fire time-temperature curves. The beginning of ASTM E119-00a even specifies that the standard has been superseded or replaced by a new version. The illustration of this curve is fundamental to all structural fire engineering research, and is necessary to note. The following, Figure 5: Generalized Compartment Fire Curve, is more representative of the currently accepted fire curves.

There exist three distinct progressions exhibited by fire: growth, full development, and decay, which result in distinct implications for the structural integrity of the building (Babrauskas 1976, Buchanan 2001, Drysdale 1998, Feasey and Buchanan 2002, Lie

1992, Shields and Silcock 1987, Wang 2002). Figure 5 illustrates temperature as a function of time for a compartment fire with the three fire behavioral phases labeled. Figure 5 is based upon the standard fire curve.

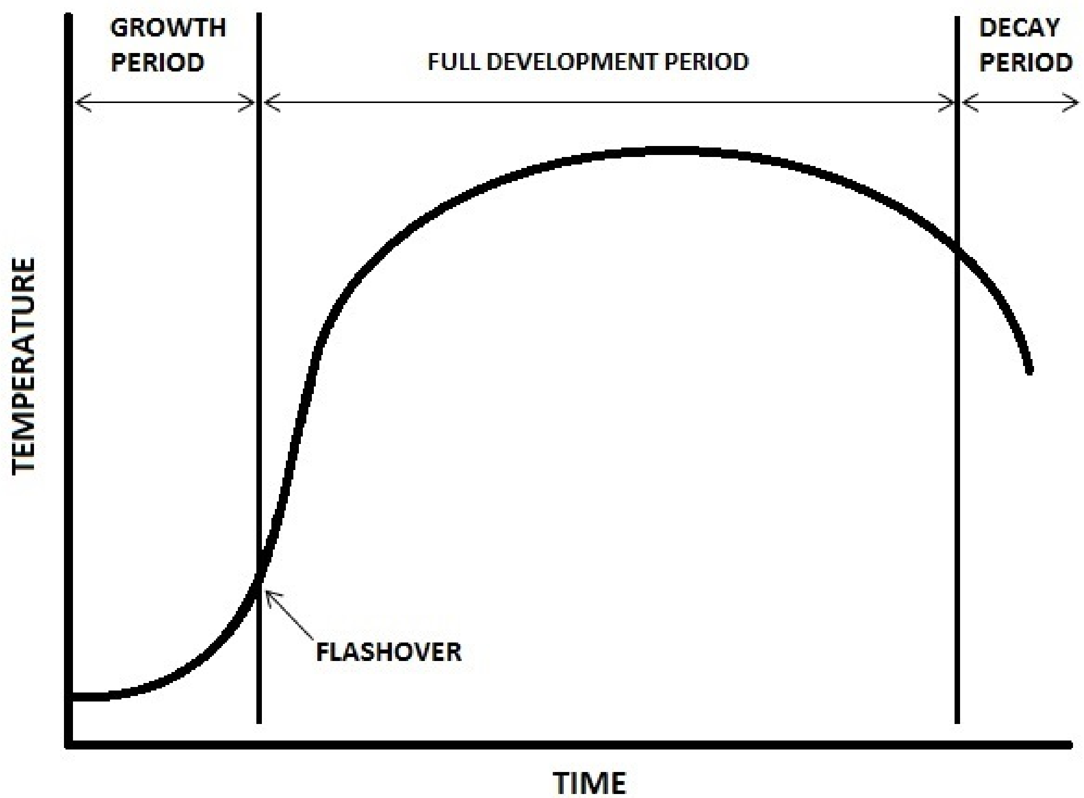

Figure 5: Generalized Compartment Fire Curve (based upon Figure 2-1 Hamilton 2011)

The growth period begins with ignition and is characterized by the accumulation of heat from burning fuel near the ignition point. Rapid increases in gas temperatures within the compartment occur during the growth phase and allow additional fuel ignition. All the contents and surfaces within the compartment begin thermal decomposition initiating pyrolysis, the process of volatile gas production from thermal decomposition. A two zone temperature model for the growth period characterization is typical; however fire engineering neglects this phase due to the relatively low temperatures (Hamilton 2011; Wang 2012).

The fully developed period begins at flashover, a term used to describe the sudden ignition of the gases produced during pyrolysis and all of the available fuel within the compartment. Flashover is reached when the critical heat flux occurs, a state when fluid flow within the compartment (both air and combustible gases) becomes turbulent. The period of full development is of most interest to structural fire engineering, because temperatures meet and exceed 1000°C. At temperatures in excess of 1000°C heat transfer to structural elements creates significant thermal stresses and reduced member strength. The availability of air and fuel create conditions within the fully developed phases which characterize the burn rate and released heat. Fire engineers refer to reduced air availability states as ventilation-controlled and reduced fuel availability states as fuel-controlled. The fully developed period typically ends as a ventilation-controlled fire (Hamilton 2011; Wang 2012).

The decay period begins as nearly all of the available compartmental fuel is used. The fire will remain ventilation-controlled if the burning surface area is large, but typically switches to a fuel-controlled fire at a point during the decay period. The decay period is marked by lower temperatures than the fully developed period, but maintains fire spread capacity as a greater heat transfer to the compartment boundaries is present (Hamilton 2011; Wang 2012).

Ventilation-controlled fire behavior occurs when the limiting factor for combustion is air exchange; illustrated in Figure 6. The insufficient air exchange between cool input airflow and hot exhaust in the presence of readily available fuel for combustion requirements defines the ventilation-controlled fire state, and the rate of combustion is controlled by airflow. Ventilation-controlled fire is marked by flames lapping out of the compartment through the top of openings caused by the more buoyant high temperature gases rising with less buoyant cooler input air descending and entering the compartment through the bottom of openings. The current fire engineering assumption is that all window glass will fall out after temperature induced breakage during flashover transition, and all compartment widow opening areas are considered for ventilation (Hamilton 2011; Wang 2012).

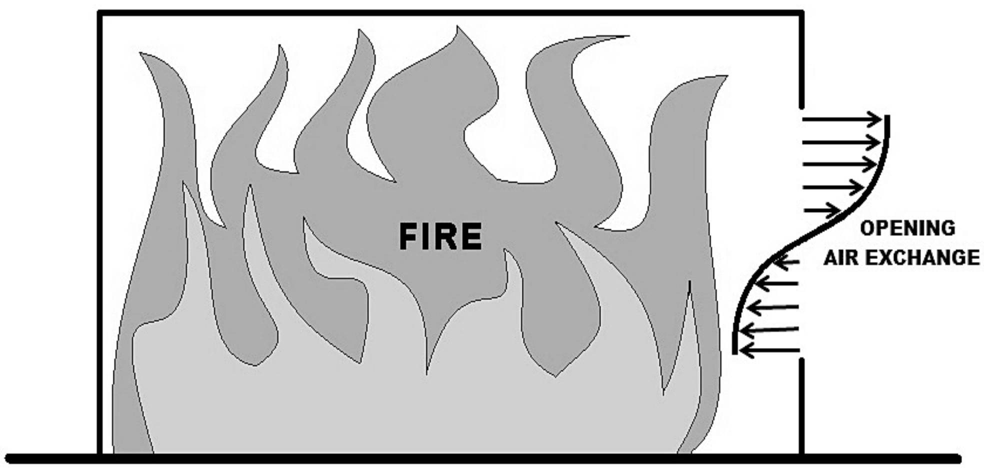

Figure 6: Ventilation-Controlled Fire Air Exchange
(based upon Figure 2-2 Hamilton 2011)

Fuel-controlled fire behavior is defined by the rate of combustion limited by the fuel surface area. A typical description of fuel-controlled fire behavior would be an outdoor camp fire where an effectively limitless quantity of fresh air is available and the type and proximity of fuel exhibit the limiting behavior of the fire. Well-ventilated large compartments, typical in contemporary buildings with large rooms, are normally fuel-controlled due to limited combustible surface fuel sources. Fuel-controlled fires are marked by inter-compartment burning with an absence of extra-compartment flame lapping. Fuel-controlled fire behavior can be seen during the full development period; however, is most typically observed during the decay period (Hamilton 2011; Wang 2012).

Ventilation-controlled fires are considered to be of greater concern because temperatures are greater than those of fuel-controlled fires. The temperature differential can be explained by the presence of cooler input air for combustion. Fuel-controlled fires have plenty of cooler input air; and therefore experience a cooling effect and exhibit lower temperatures than ventilation-controlled fires (Hamilton 2011; Wang 2012).

Fire Following Earthquake (FFE) presents a focus on issues separate from those of structural fire engineering. The aim of fire engineering typically depends on making improvements within an individual structure to prevent ignition, isolate spread, and provide additional suppression, while FFE examines fire ignition, spread, and suppression within the system as a whole (i.e., taking the perspective of building to building interaction or an extra-structure view). Fire has caused significant damage and loss to infrastructure and loss of life. The 1906 San Francisco earthquake exemplifies the danger of FFE. The reported 3 day conflagration, after the earthquake event, resulted in more severe damage from fire than from seismicity (USGS 2012).

According to Lee et al. (2008), the beginning of Fire Following Earthquake Modeling stems from the attempts to characterize fire behavior (ignition and spread) in the 1950s and 1960s in response to urban firebombing common-place in World War II by both sides. It is important to note that the 1906 San Francisco and 1923 Tokyo earthquakes and subsequent FFE events initiated a search for mitigation strategies; these disasters did not result in the creation of analytical models. Lee et al. (2008) theorize the threat of fire imposed by nuclear weaponry spurred urban fire spread modeling. FFE was first addressed by Hamada in 1951, where a series of equations were developed which accounted for fire spreading as a function of wind, fuel, and building proximity among additional factors. Studies Horiuchi et al. (1974), Mizuno and Horiuchi (1976) and Mizuno (1978) have compiled data to develop equations and utilized scenario models to test, as well as develop, mitigation strategies. In the United States researcher Steinbrugge (1968 and 1971) also collected data, however failed to develop concurrent models.

Ellingwood (2008) discusses the flaws in the current Load and Resistance Factor Design code, and with Baker et al. (2008) give a thorough presentation of the method for uncertainty and damage assessment within PBE; also illustrating the need to move to PBE. PBE relies upon probability analysis of failure and loss, but contains a hurdle in quantifying acceptable boundaries of uncertainty. These methods are the basis for the proposed research project to evaluate earthquake and FFE through probabilistic analysis and reliability.

3.5 Critical Appraisal

The literature for building codes and current state-of-the-art software is presented below focused upon fire. The building codes presented in the "Critical Appraisal" section illustrate the history of United States (US) based codes and the overwhelming instances of calls to move the US system away from a prescriptive code toward a performance-based code which is already in place in a list of other developed countries. This software critique examines the issues inherent in three software packages concerning multiple hazard analysis for earthquake and subsequent fire following earthquake.

3.5.1 Building Codes

The current *ASCE 7: Minimum Design Loads for Buildings and Other Structures* (ASCE 7-10) outlines limited consideration for fire loading. The deficiency of fire consideration in the most basic of structural engineering guides illustrates the early stages of fire engineering inclusion into structural design. The events leading to the collapse of the World Trade Center towers in New York on September 11th has brought attention to the need for increased scrutiny of the current design codes (Hamilton 2011). ASCE 7 (2010) mentions fire loading as an addendum to the design load combination equations in Chapter 2: "Combinations of Loads" in a newly added section for the 2010 edition as:

> "**2.3.4 Load Combinations Including Self-Straining Loads**
>
> Where applicable, the structural effects of load T shall be considered in combination with other loads. The load factor on load T shall be established considering the uncertainty associated with the likely magnitude of the load, the probability that the maximum effect of T will occur simultaneously with other applied loadings, and the potential adverse consequences if the effect of T is greater than assumed. The load factor on T shall not have a value less than 1.0" (ASCE 2010).

ASCE 7's description of fire consideration results in rare inclusion of fire load, T, into the combined loads equations.

ASCE 7 (2010) mentions glass fallout in Chapter 13 (considered the state resulting if all of the exterior glass falls out of the window frame), but only as a function of seismic displacement. No equations considering fire are shown within the code, and temperature is largely neglected throughout the code. Fire loading is a rare loading scenario due to the rigorous fire regulations developed and implemented by the National Fire Protection Association (NFPA) and should not necessarily be included as a minimum load.

The NFPA has a series of codes addressing a range of fire requirements, but the most commonly used and referenced code, *NFPA 1: Fire Engineering*, relies exclusively upon provisional line equation requirements. Typical provisions include equations requiring a specified number of sprinkler heads per floor area, sprinkler system pressure requirements and passive pressure delivery systems, and thermal insulation thickness requirements for exposed steel frame elements (NFPA 2012). The NFPA 1, however, has the same issues as other design codes where structural performance is not a clearly defined and dominating requirement, but instead line item requirements must be met. The use of line item provisions has been the standard due to pragmatism; either a design meets the required provision or not, there is no performance analysis necessary to check the design.

Hadjisophocleous et al. (1998) review the historical progression of performance codes concerning fire design for the field as a whole. Considering only the United States (US), Hadjisophocleous et al. (1998) start with Sandersons statement that current codes exhibit both specification and performance-based requirements, however many requirements were based on experience instead of analysis. According to Nelson (1972), who pioneered the performance-goal approach to fire code, the transition from prescription to performance in the US began in the 1970s. Wehrilil and Kapsh (1972) then produced a set of checklists to evaluate fire safety designs as well as introduced a glossary of terms necessary to begin adequate discussion of innately different approaches.

Haviland (1978) has provided a set of fire safety performance criterion largely established from fire safety expert opinion, while still drawing attention to the deficiencies in the current code. Boring, Spence, and Wells (1981), through the American Iron and Steel Institute, detailed fire safety provisions and suggested the first series of fire safety objectives based on the then current codes. Cohn (1991) proposes an outline for designing new PBE construction codes for the US, and establishes that new codes should not propose area limits, have no construction-type designations, utilize only four basic building-use groups, utilize individual room evaluations to aid in compartmentalization gains, provide unique risk within the building as a means of identification of the desired use, utilize rational methods as evaluation tools, and yield a computerized application.

Cote (1991) stated that during the last ten years there had been no net reduction in dollar loss or loss of life despite three national code systems and a plethora of standards. Cote (1991) gave evidence supporting the need for a performance-based approach. Hadjisophocleous et al. (1998) stated that Corbett, a San Antonio fire department administrator, proposed: the development of a single fire code; level specification of fire safety objectives to be established; the creation of a list of consensus calculation methodologies to evaluate structural fire performance; the placement of fire protection engineers into enforcement positions; the requirement of minimum levels of fire safety competency for architects and engineers; and mandatory inspections (Hadjisophocleous et al. 1998). Shapiro (1994) called out three impediments to the adoption of PBE code: reluctance to accept computer generated prediction, proprietary interest, and changes of design factors during building life cycle within the US (Hadjisophocleous et al. 1998).

Buchanan (1994) summarized the code developments in New Zealand, largely decrying the deficiencies of prescriptive codes as slowly evolving, having no statement of objectives, providing no input from engineers, and illustrating no flexibility to adapt to unusual situations. Buchanan (1994) stated that the US currently lags behind a large portion of the word, namely: Japan, Canada, New Zealand, and the United Kingdom in terms of fire safety. Buchanan (1994) stated that this lag was largely due to the inaction of the fire safety community to establish a performance-based code. The historical perspective Hadjisophocleous et al. (1998) has provided illustrates the consistent call over decades for a Performance-Based Eengineering (PBE) approach to fire safety engineering code.

3.5.2 State-of-the-art Software

There are several state-of-the-art software packages available and in current use by fire protection engineers. In this section three programs: *HAZUS*, *Vulcan*, and *CFAST* will be discussed to illustrate the current state of fire behavior modeling and the inherent limitations of these software packages to the generalized PBE framework presented in this thesis.

3.5.2.1 HAZUS

HAZUS, previously described as a hazard loss software package developed by the Federal Emergency Management Agency (FEMA), is a valuable tool in hazard evaluations for multiple disciplines. The program is based on *ArcGIS*, and uses United States (US) census data to allow in-depth hazard response on the city-scale.

The Hamada model for fire spread was selected by *HAZUS* largely due to the employment of a simplified method. The distances between buildings within a city block are averaged and utilized as an approximation. There are an assumed number of ignitions per 100,000 square feet of building floor area based on Peak Ground Acceleration. Hamada also assumes an elliptical pattern of spread longitudinal with the wind directionality, which is consistent with wilderness fire spread. Fire spread within urban areas however may follow different spreading patterns, and a large source of discrepancy in spread could be attributed to the lack of topological effects (Lee et al. 2008).

Zolfaghari et al. (2009) and Lee et al. (2008) have shown conservatism for fire ignitions as well as deficiency in the *HAZUS* fire model. Zolfaghari et al. (2009) illustrated a large discrepancy between the number of ignitions for a specific case study in Tehran via the paper's Fire Following Earthquake (FFE) ignition calculations and those of the current *HAZUS* model. *HAZUS* is clear in FEMA (2012) that the ignition modeling was based upon the Hamada (1971) model with data collected from seven US earthquakes occurring since 1970. *HAZUS* stated that ignitions are defined as being and individual fire after an earthquake that required the suppression efforts of the fire department; the model is only useful for a US location due to building code requirements for fire safety; and that only post 1970 data was utilized due to building standards, appliance safety standards, and urban development patterns (FEMA 2012). The large discrepancy between Zolfaghari et al. (2009) and the output via *HAZUS* can be attributed to the instances of ignition and the instance of ignition requiring fire department intervention as well as the code disparity between those in Iran and those within the US.

The most advanced current fire following earthquake models are rigorous, and require detailed information for a large number of specific building variables. The detail required is largely the reason for the more simplistic Hamada model. The Hamada based function developed by FEMA (2012) results in a 0.08 R-squared value for the scenario ignition data set. The poor performance against the matching data set draws attention to the reliability of the proposed model *HAZUS* is using. The majority of advanced models rely upon the work of Scawthorn from the 1980s to the present. The major models were produced by Cousins and Smith (2004), Ren and Xie (2004), Scawthorn et al. (2005), and Zhao et al. (2006) and offer greater accuracy depending on the region of study and the range of ground shaking (Lee et al. 2008).

3.5.2.2 CFAST

Consolidated Model of Fire and Smoke Transport (*CFAST*) is a fire modeling program developed and operated by the National Institute of Standards and Technology (NIST) through the United States Department of Commerce. The program exhibits a two-zone fire model allowing for compartment temperatures, fire gas, and even distributed smoke evolution determination for a specified building (Peacock et al. 2012).

CFAST input parameters include building geometry, fuel approximation, inter-compartmental connections, ventilation, suppression systems, and fire properties. The building geometry is defined such that compartment size and the material properties of the items used in compartment construction are taken into account. The compartment connections such as doors and windows are defined to account for horizontal fluid flow. The openings in floors and ceilings as well as HVAC and ventilation systems are defined within compartment connections. The specifications of sprinkler systems, detectors, and targets must be defined such that the position, size, heat transfer, and sprinkler flow behavior are taken into account. The fire properties must be defined such that the fire size and development as a function of time are given. Materials within the structure must be given with material properties of thermal conductivity, specific heat, thickness, density, and burn behavior including ignition properties and heat release to round out the input file for a given building (Peacock et al. 2012).

The equations utilized within *CFAST* to illustrate the fire model are developed from an initial value problem input into a series of ordinary differential equations. The differential equation set includes the typical fluid mechanics equations of conservation of mass, conservation of energy, and the ideal gas law as a function of internal energy and density. The reliance of these models upon time is crucial due to the importance of time in describing fire development and spread (Peacock et al. 2012).

CFAST is a robust fire model program, but lacks the simplicity needed to expand the model from a single structure to a collection of structures necessary to effectively describe Fire Following Earthquake (FFE) behavior. *CFAST* also lacks a relationship with Performance-Based Earthquake Engineering models to easily incorporate earthquake damage into the fire model. With adjustments *CFAST* could be a very valuable tool in delivering accurate FFE, but significant work must be completed to quantify the effects of earthquake damage to FFE behavior in a manner consistent with a city scale.

3.5.2.3 Vulcan

Vulcan is fire modeling software developed by Vulcan Solutions Limited through a partnership with the University of Sheffield, UK. *Vulcan* relies upon Finite Element Analysis (FEA) and is capable of three dimensional structural behavior under fire load for composite steel-framed structures. The software strives to be user friendly utilizing a graphical user interface to define structural geometry and reduce the user's need of extensive knowledge of FEA. *Vulcan's* analysis considers entire structural action including non-linear material and geometric behavior for beam-column and slab type elements (VSL 2005).

Vulcan utilizes thermal expansion characteristics included as functions of temperature for steel and concrete as well as standard stress-strain curves. The software allows for uniform and non-uniform heat distributions. Partial interaction between slabs and steel sections, the orthotropic nature of composite slabs using the concept of effective-stiffness are included also. Fundamentally, the software operates as a fire specific FEA program, reducing the time necessary to perform fire modeling in a simplified manner (VSL 2005).

Vulcan exhibits some significant limitations in the number of definable properties, beam sections, slab sections, and element numbers, but most significant to this research project is that the fire protection scheme is not included (VSL 2005). The limitations introduced into the software are designed to keep the program computation simplistic enough for reasonable processing time, but effectively makes interaction between earthquake damage and Fire Following Earthquake nearly impossible to evaluate. *Vulcan* also manifests the same issues as *CFAST* when examining city scale structure collections.

The movement of structural design methodologies to PBE necessitates further study in all aspects of multiple hazard analysis. The code change requires extensive research to quantify and illustrate appropriate methods to make PBE acceptable, safe, and efficient. The deficiencies in the current software give validity to the proposed research to develop a flexible framework for the establishment of Earthquake and FFE loss with quantified uncertainty.

There exist many issues within the current state-of-the-art software packages used to describe the interaction of EQ and FFE. *HAZUS* lacks a rigorous fire spread model for urban environments, lacks any description of intra-structure fire development relying only upon a standard fire curve and a boundary limit for fire department intervention before the structure is considered a total loss, and makes several severe simplifications for building and building proximity geometries. *CFAST* and *Vulcan* are successful at modeling individual structures experiencing fires; however lack options for earthquake affect inclusion and how a collection of structures interact on a city scale.

4 PBE Framework for Earthquake and Fire Following Earthquake

To establish a basis for the currently used hazard probability and structural performance objectives, the Hazard Probability to Performance Objective Matrix (Figure 7) was developed through the amalgamation of similar matrices from the Pacific Earthquake Engineering Research Center (PEER) concerning earthquake hazard and Tugnoli et al. (2012) concerning fire damage mitigation. The PEER matrix was utilized as a base with four hazard categories of hazard probabilities: 50% in 30 years, 50% in 50 years, 10% in 50 years, and 10% in 100 years. The equivalent recurrence intervals to the hazard probabilities for Earthquake (EQ) are: 43 years, 72 years, 475 years, and 970 years (PEER 2006). To match the same "Performance Objectives" given in the PEER matrix base for fire, hazard probabilities were calculated to be: 50% in 682 years, 50% in 6914 years, 10% in 10533 years, and 10% in 105355 years from the given frequency for each fire event via Tugnoli et al. (2012). The corresponding recurrence intervals for fire were determined to be: 985 years, 9975 years, 99975 years, and 999950 years.

To illustrate the computation for hazard probability and recurrence interval, consider the given frequency for a rare fire event, $f = 10^{-6}$ via Tugnoli et al. (2012).

$$T = \frac{1}{f} \qquad \text{(EQ. 4)}$$

$$P_n = 1 - (1 - f)^n \qquad \text{(EQ. 5)}$$

Where T is the recurrence interval, f is the frequency of occurrence, n is the number of years, and P_n is the probability of occurrence in n years. For the given frequency, the recurrence interval is equal to 999950 years with a hazard probability of 10% in 105355 years. The values corresponding to the fire hazard could be simplified, however, the following hazard to performance matrix was created to illustrate the differences between hazard probability and recurrence interval between Earthquake and Fire hazards, while providing similar performance objectives.

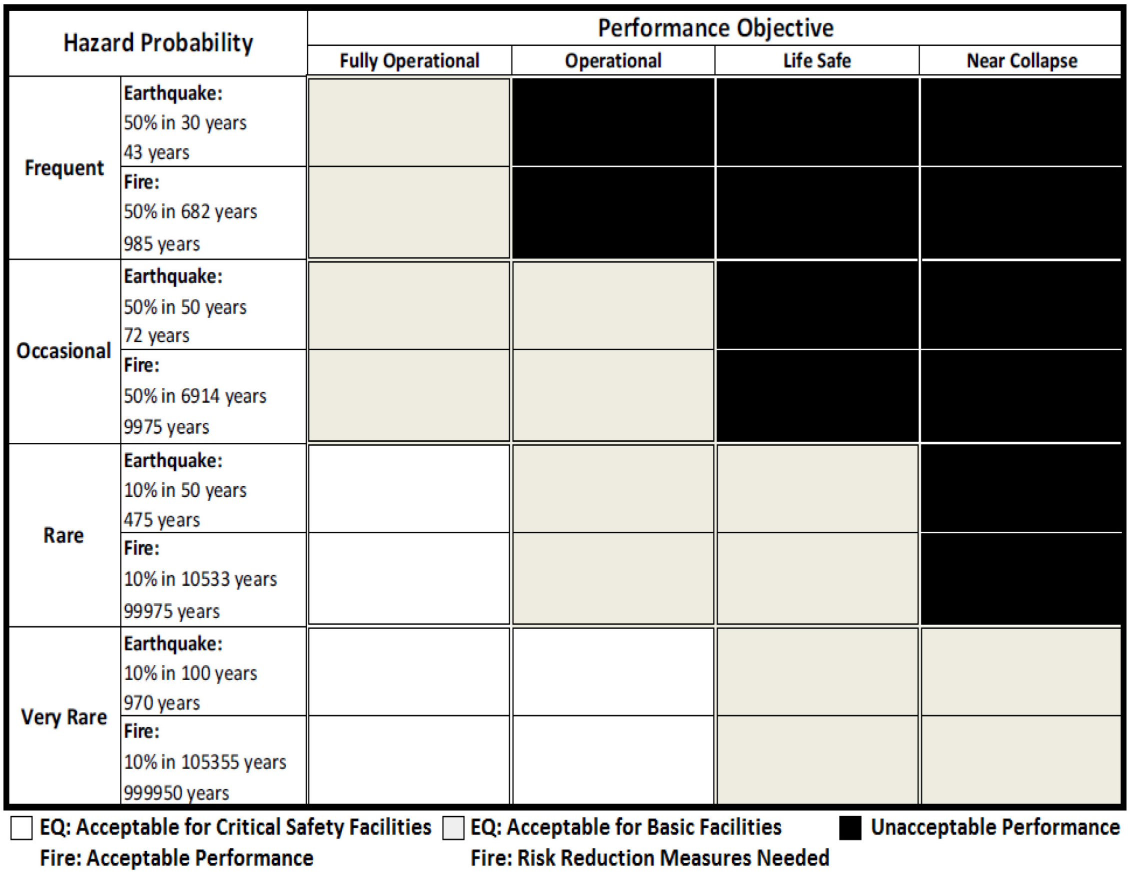

Figure 7: Hazard Probability to Performance Objective Matrix
(Based upon similar matrices from Berkeley PEER and Tugnoli et al. 2012)

Comparing the recurrence intervals illustrates the difference in hazard probability between EQ and fire. Note that the hazard probability for EQ is relative to magnitude with the greater magnitude relating to a rarer hazard probability. Fire is a rarer structural hazard than earthquake, which can be interpreted in two ways. The current threat of fire hazard has high recurrence intervals, therefore low frequency of occurrence, indicating that we as engineers have developed a thorough code that does an excellent job of preventing fire hazard in our structures. Or, the current codes may be overzealous in required prescription illustrating a possibility of efficiency improvements in the codes to facilitate increased economy.

Special attention should be given to the Hazard Probability to Performance Objective Matrix, because the matrix was developed as an amalgamation of independent earthquake and fire risk matrices. The interaction between the two hazard types has yet to be evaluated. Fire Following Earthquake (FFE) as a risk matrix will most likely have differences in the hazard recurrence intervals due to the interrelation between the earthquake hazard and the subsequent FFE. Additional empirical data must be collected and analysis methods developed before an adequate attempt can be made at quantifying return interval and appropriate hazard probabilities for FFE.

At a low magnitude EQ the probability of FFE is expected to match the background probability of fire hazard without an EQ occurrence. As the magnitude of the EQ increases, the corresponding FFE probability is expected to increase, however Scawthorn et al. (2005) illustrates a decrease in FFE ignitions for EQ magnitudes exceeding a Modified Mercalli Intensity of VII. The proposed predictions are based on the rational that the EQ will distribute fuel within the structure, break gas and electricity lines, and negatively affect the fire suppression systems and fire fighter effectiveness. At high EQ magnitudes, the FFE concern is not placed on the individual structure, but the fire affect upon the city as a whole and the building occupants.

Figure 8, below, is a graphical representation of the framework, and attempts to illustrate the interconnections between seismic demand, structural response, and fire behavior as well as incorporating both a single structure and city scale EQ and FFE interaction. The framework is a generalized starting point to act as a guide for EQ and FFE research, testing, evaluation, and code implementation.

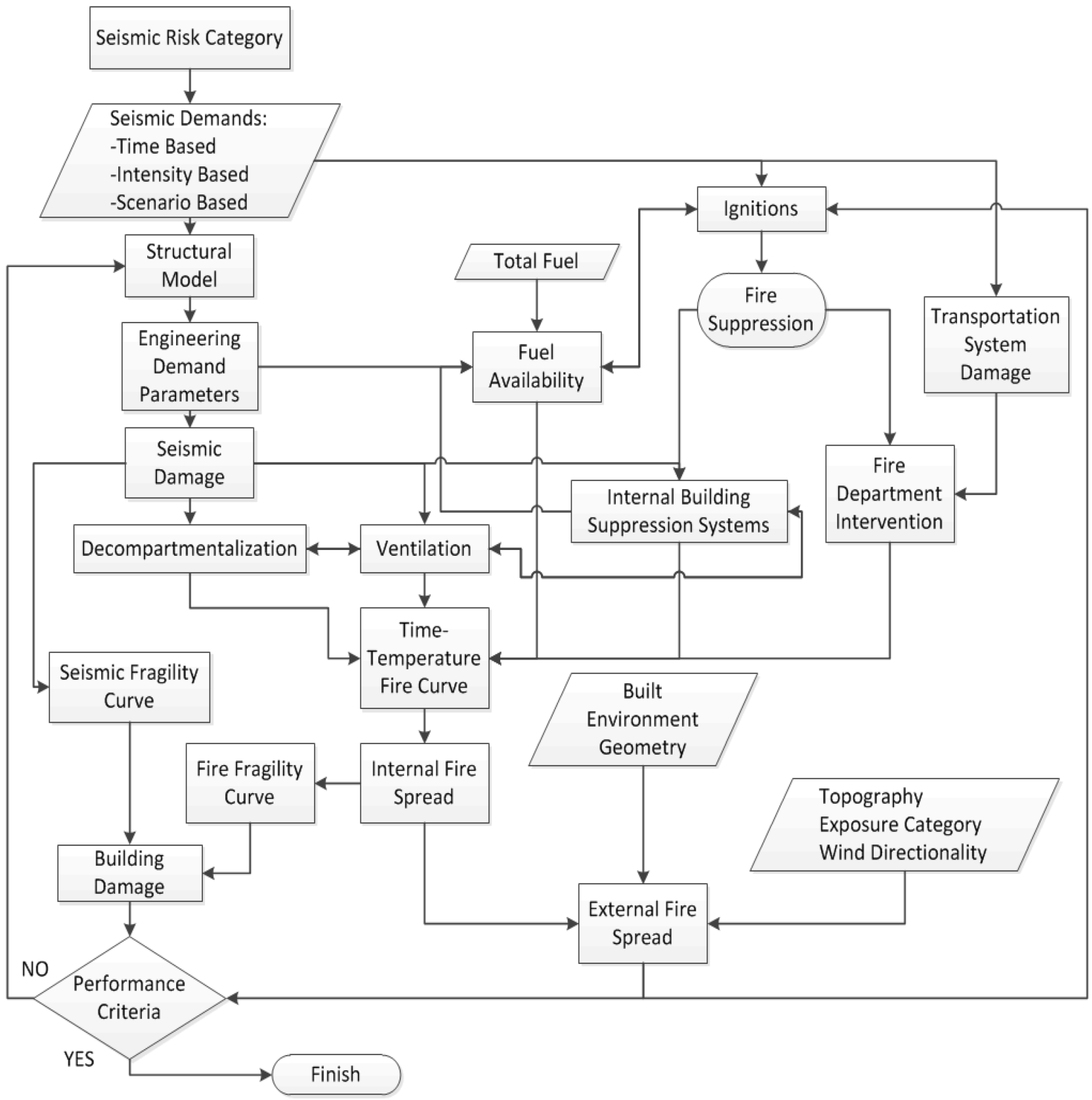

Figure 8: PBE Earthquake and Fire Following Earthquake Framework

The PBE evaluation of a given structure begins with the seismic risk category which can be determined from ASCE 7 dependent upon the building site location, the proximity to geologic faults and the site soil properties. A seismic demand must be defined and introduced to a structural model of the building to be evaluated. Seismic demand can be defined via three different methods outlined from the Performance-Based Earthquake Engineering procedure: time-based, intensity-based, or scenario-based. There may be advantages and disadvantages to each seismic demand type, which will need further investigation to determine which demand type is most beneficial to EQ and FFE evaluation. The seismic demand has direct consequences for building response, ignition, and transportation system functionality (which influence Fire Department intervention).

From the structural model the building response can be determined using engineering demand parameters such as drift, acceleration, and velocity. Note, that from seismic risk category through seismic damage there is no deviation from Performance-Based Earthquake Engineering (PBEE). The seismic damage includes elements such as cracking within fire compartments, exterior barrier breakage (such as windows), and fire suppression system damage (such as sprinkler systems and HVAC ventilation stops), which begins the interrelation effects of seismic and fire behavior. The seismic damage is then evaluated against the seismic fragility curve for the given structure which later is interrelated with the overall building damage. Careful consideration must be given to the overlap between EQ induced damage and FFE induced damage such that structural damage is not counted twice.

From the seismic demands the direct influence is seen in the probability of ignition. Scawthorn et al. (2005) utilizes an approximate ignition rate in relation to the Modified Mercalli Intensity scale. Table 2, below, exhibits the findings, however may or may not be the best way to evaluate ignitions from seismic demand. Zolfaghari et al. (2009) illustrated a drastic discrepancy between the total number of ignitions and *HAZUS*' ignition number which is based upon the Scawthorn et al. (2005) approximation (Table 2).

Table 2: Modified Mercalli Intensity to Approximate Number of Ignitions

Modified Mercalli Intensity:	**VII**	**VIII**	**IX**	**X**
Number of Ignitions per one million sq. ft. of Building Floor Area	18	10.5	4.5	1.5
Note: Table 2 is developed from Scawthorn et al. (2005), and is specified as only ignitions requiring Fire Department intervention to extinguish.				

The ignitions initialize the fire suppression protocols for the given structure via detectors and human recognition. fire suppression can be classified into two categories: internal building suppression systems and external or fire department intervention. The internal systems should include: fire sprinkler systems, fire detection systems, fire brakes, HVAC ventilation shut down, automated fire door systems, and other more difficult to define human behaviors. Human intervention can range from fire suppression system use like building fire-hose, or fire-extinguisher, use to leaving windows and doors open. The interrelation between internal building suppression systems, ventilation, and decompartmentalization is unknown, but could prove to be important in accurately defining fire behavior and damage uncertainty.

The time-temperature fire curve is typically utilized to describe a single compartment fire behavior, is influenced by decompartmentalization, ventilation, internal building suppression systems, fuel availability, and fire department intervention. As described in the section, Introduction to Fire Behavior, the time-temperature fire curve significantly changes depending upon fire development period, ventilation, and fuel availability within a compartment. The time-temperature fire curve influences, along with decompartmentalization, suppression, and ventilation, the internal fire spread. These parameters dictate the speed and direction of the fire spread within the structure from the compartment of initial ignition to the surround compartments (whether room to hall, room to room, room to stairwell, or any combination thereof).

Once the internal fire spread is evaluated, the damage can be assessed via a fire fragility curve and combined with the results of the seismic fragility curve to define the overall combined EQ and FFE building damage. Again, care must be taken to avoid double counted damage to obtain an accurate estimation of the total building damage. The internal fire spread also influences the external fire spread along with the built environment geometry and the building site: topography, exposure category, and wind directionality. The external fire spread will then influence additional ignitions creating a feedback loop, initiating the fire protocol for additional buildings within the immediate area.

From the building damage and external fire spread, the structure's performance must be evaluated to an established performance criterion. If the criteria are met successfully the evaluation is completed, and if not, a return to the structural model must be made. Within the loop back to the structural model, an expectation of design changes to mitigate the unmet performance criteria should be understood.

There are methods for evaluating pieces of the total as has been discussed in the Introduction and State-of-the-art review sections, and the problematic issues inherent in the process were outlined in the Critical Appraisal section. As a result, the implementation of this framework will require additional assumptions, empirical data, and probability analysis to accurately and functionally flesh-out the details within the framework.

As an example, reviewing the building damage evaluation of the framework the need for probabilistic interrelation between the seismic and fire damage must be determined. Building upon the equation of loss estimation from the methods of Baker et al. (2008) and Wen et al. (2003), where P denotes the probability of occurrence, is an illustration of the basis for the proposed probabilistic analysis necessary to complete computation proposed by the framework.

$$P(Loss) = \iiint \int P(Damage|Response)P(Response|Spec.Dis.)P(Spec.Dis.|EQ)P(FFE|EQ)P(EQ) \quad \text{(EQ. 6)}$$

Where P(EQ) indicates the probability of Earthquake hazard, P(FFE|EQ) indicates the probability of Fire Following Earthquake given the probability of Earthquake, P(Spec.Dis.|EQ) indicates the probability of spectral displacement of the structure (similar to those illustrated in Figure 3) given the Earthquake hazard, P(Response|Sec.Dis.) is the probability of building response given the spectral displacement, P(Damage|Response) is the probability of damage for the structure given the structural response, and P(Loss) is the probability of loss for the proposed framework. The response and damage are key areas in need of further definition as fire suppression system functionality, decompartmentalization, ventilation, etc. are encompassed and are defining parameters for adequate fire behavior characterization. The damage parameter must be carefully described to avoid double counting of structural damage from EQ and FFE.

Within each of these basic probability descriptions are interrelated probability distributions for the interaction between Earthquake hazard and subsequent Fire Following Earthquake. Each of these probabilistic requirements will require testing similar to the work Worchester Polytechnic Institute completed at the University of California - San Diego in 2012 (Meacham et al. 2013). Monte Carlo simulation will be necessary to determine the probability distributions and development of conditional probabilities will play key roles in the probability analysis development yielding equations and values to the proposed base equation above.

The inherent uncertainty of fire behavior and fire modeling illustrates the necessity of the PBE approach and the necessary probabilistic analyses. With additional testing, the uncertainty can most certainly be accurately described and will increase the understanding and modeling capabilities of engineers to design safer, sustainable, resilient, and cost effective buildings.

Table 3: Variables Necessary for Framework Implementation

Variable	Earthquake	Fire	Human
Structural Stability	X	/	
Window Breakage	X	/	-
Compartment Wall Break-Through	X	/	-
Door and Window Openings	/	-	X
Manual Suppression	/		X
Automatic Suppression	X	-	
Fire Fighter Intervention Activities	/	/	X
Building Geometry			
Fuel Availability	X		X
Key: X denotes primary influence, / denotes secondary influence, - denotes tertiary influence.			

Table 3 lists the variables which need to be defined to begin the implementation of the proposed PBE framework for EQ and FFE. Experiments similar to what Mecham et al. (2013) outlined will be necessary to establish the necessary parameters and probability distributions of the variables listed in Table 3. Only after data collection and analysis, will the proposed framework be applicable.

The structural stability needs to be defined in relation to the sustained EQ hazard and redefined as fire develops in the structure. As an example, the seismic structural damage can negatively impact the performance of fire retardant on steel members making the members more susceptible to fire overload. Window breakage must be initially defined as a function of seismic response and again as fire develops. Exterior windows influence the ventilation situation available to the fire during initiation affecting compartment temperatures. As the fire develops, a maximum allowable temperature is reached that exceeds the thermal capacity of the external windows in a compartment causing additional breakages.

Compartment wall break-through or fire compartment cracking will be directly influenced by the seismic demand and building response, and has greatest influence on how the heated gases, smoke, and thermal energy will transfer from the interior of a fire compartment to the compartment exterior (hallway, adjacent room, etc.). The compartment wall break-through parameter may also influence and be closely related to the structural stability. Door and window openings and manual suppression are functions related to human intervention, a highly randomized variable which depends upon the actions of the persons within the structure during the hazard events. There may not be an adequate way to quantify this parameter, and may be reduced to a probabilistic assumption.

Automatic suppression involves the systems installed within the structure to combat fire development and spread and largely will be influenced by the structural seismic response. The suppression systems have the ability to mitigate the risk from fire, and effectively reduce the necessity of fire fighter response. Fire fighter intervention is dependent upon the state of the local transportation system and human response time to notify fire fighters.

Building geometry is a constant which is easily defined for a given structure, but much more difficult to describe on a city scale (as is needed for software programs like *HAZUS*). Adequate simplifications to building geometry must be developed to yield adequate models for city-scale emergency planning. Keep in mind that building geometry includes not only intra-structural geometry, but also inter-structural geometry. Fuel availability influences the way that fire can ignite and develop and should be highly directed by the seismic response of the structure. A room of scattered paper and books facilitates faster fire growth and spread as opposed to a room with neatly grouped books on shelves and file cabinets.

5 Future Research Needed

The proposed Performance-Based Engineering (PBE) framework illustrates the interconnectedness between seismic and fire hazards. The damage sustained from a seismic event and the ignition, development, and suppression of fire are closely related, but the interaction is not well understood. The Engineering Demand Parameters can affect fuel dispersion throughout the structure, decompartmentalization, and ventilation which all effect the possibility of ignition, compartmental fire growth, and fire spread throughout the structure. To adequately quantify the way seismic building response affects fire behavior, empirical testing must be completed.

The building nonstructural components and systems (BNCS) project conducted full scale testing on the largest US shake table at the University California, San Diego with students from Worchester Polytechnic Institute in April and May 2012 to assess fire behavior affected by seismic structural damage (Meacham et al. 2013). To date, only the executive summary of the testing has been released, and the focus of the project was largely towards fire suppression systems: sprinkler components, fire stop components, fire doors, elevator shaft doors, and stairwell performance. The BNCS project methodology included effects on compartmentalization from seismic damage, which is the first step in the process to adequately model decompartmentalization.

Probability distributions are needed for exterior ventilation barrier loss (exterior window breakage with relation to increased ventilation area), fire compartment damage, and fuel distribution as functions of seismic hazard effects to the structure. These distributions may be developed from story drift, story acceleration, and/or story velocity in relation to the dispersion of fire fuel within a given compartment and material limits of exterior window systems and fire compartments.

Also, additional work needs to be completed to gain a better understanding of the likelihood of ignition. The current standard for ignition is the Scawthorn et al. 2005 method relating Modified Mercalli Index to number of ignitions per million square feet of building floor area (see Table 2). *HAZUS*, a current state-of-the-art software plug-in for *ArcGIS*, utilizes an ignition equation based upon the last forty years of fire following earthquake records, but only manages an R-squared value of 0.08.

The fire spread models also need additional research and model development. The current *HAZUS* fire spread equation utilizes an elliptical spread pattern with the long axis corresponding to the wind direction and speed. Structures are labeled as total loss based upon time corresponding to the standard fire curve. The *HAZUS* model is a simplified way to gain estimates for natural disasters. Detailed information regarding structural geometry for compartmentalization, fire suppression systems, and proximity to adjacent structures is difficult to incorporate due to the limited availability of data as well as the means to calculate fire spread through each individual structure. However, additional rigor for fire spread is needed, which could include topographic effects, exposure category, natural fire barriers such as street widths, and adjacent building exterior flammability.

The relationship between seismic damage and fire damage also needs additional investigation to gain a better understanding of the ways each type of damage affects the other. Building response to a seismic event can induce fire ignition and influence fire development, growth, and spread, while the fire damage can induce thermal stress and strain into the structural members increasing damage.

6 Summary Conclusion

The movement of structural design methodologies toward implementing increasing elements of Performance-Based Engineering (PBE) necessitates further study in all aspects of hazard analysis. Ellingwood (2008) stated that a more rigorous PBE design has been in development for nearly thirty years and appears, at this point, to be inevitable because of the increased confidence PBE provides when quantifying uncertainty. The quantification of uncertainty makes adequate risk management possible. Buchanan (1994) summarized the code developments within New Zealand, largely decrying the deficiencies of prescriptive codes as: slowly evolving, having no statement of objectives, providing no input from engineers, and illustrating no flexibility to adapt to unusual situations. Buchanan (1994) stated that the US currently lags behind a large portion of the world namely: Japan, Canada, New Zealand, and the United Kingdom regarding fire safety. This lag is largely due to the inaction of the fire safety community to establish a Performance-Based code. The historical perspective Hadjisophocleous et al. (1998) has outlined illustrates a consistent call over decades for a PBE approach to fire safety engineering.

The minimal existing evaluations for Earthquake (EQ) and Fire Following Earthquake (FFE) have left a void in an essential aspect to make the coming structural design code changes. The deficiencies in the current software packages give validity to the proposed research to develop a flexible framework for the establishment of EQ and FFE loss with quantified uncertainty. Adequate description of fire dynamics within buildings and the effects on the structural integrity of the building has been a difficult task. The unpredictable nature of ignition, the origination point of ignition, proximity between the ignition point and fuel, the availability and type of fuel, compartment size, compartment ventilation, effectiveness of code prescribed suppression systems (e.g., fire sprinklers and HVAC system fire cutoff), and human behavior such as use of fire extinguishers and closing doors have made the attempts to quantify and model fire behavior in buildings a daunting task. As a result of the very nature of fire, the use of probability analysis and probabilistic estimation will always dominate fire models (Hadjisophocleous et al. 1998, Kodur et al. 2007).

This thesis has presented a generalized Performance-Based Engineering (PBE) framework to evaluate structural performance, damage, and loss associated with the multiple hazards of Earthquake (EQ) and Fire Following Earthquake (FFE). The framework was presented as an outline of the interaction between EQ and FFE and a guide for future research pursuits. After gains in probabilistic data are made for the necessary elements to fully implement the proposed framework, various design and/or retrofit options for cost effective hazard mitigation strategies are expected. By individualizing the sources of unnecessary costs over the building life cycle, adequate and specific retrofit options will become apparent and available to mitigate loss. Various sources of uncertainty in fire behavior modeling and structural response can be quantified within the fully developed framework. The inclusion of uncertainty is what bestows longevity and significance to the framework. The models used to evaluate damage and loss become available for optimization. The uncertainty, therefore, can directly indicate which materials should be improved, which codes need to be more stringently enforced or updated, and even which portions of accepted models relate deficiencies to the overall characterized behavior.

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