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Review of assessment, design, and mitigation of multiple hazards

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A Review on Assessment, Design, and Mitigation of Multiple Hazards

By:

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A REPORT

Submitted in partial fulfillment of the requirements for the degree of

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This report, "Assessment, Design and Mitigation of Multiple Hazards," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN CIVIL ENGINEERING.

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ABSTRACT

Large parts of the world are subjected to one or more natural hazards, such as earthquakes, tsunamis, landslides, tropical storms (hurricanes, cyclones and typhoons), costal inundation and flooding. Virtually the entire world is at risk of man-made hazards. In recent decades, rapid population growth and economic development in hazard-prone areas have greatly increased the potential of multiple hazards to cause damage and destruction of buildings, bridges, power plants, and other infrastructure; thus posing a grave danger to the community and disruption of economic and societal activities. Although an individual hazard is significant in many parts of the United States (U.S.), in certain areas more than one hazard may pose a threat to the constructed environment. In such areas, structural design and construction practices should address multiple hazards in an integrated manner to achieve structural performance that is consistent with owner expectations and general societal objectives. The growing interest and importance of multiple-hazard engineering has been recognized recently. This has spurred the evolution of multiple-hazard risk-assessment frameworks and development of design approaches which have paved way for future research towards sustainable construction of new and improved structures and retrofitting of the existing structures. This report provides a review of literature and the current state of practice for assessment, design and mitigation of the impact of multiple hazards on structural infrastructure. It also presents an overview of future research needs related to multiple-hazard performance of constructed facilities.

1 INTRODUCTION

Many areas of the world are subjected to one or more natural hazards, such as earthquakes, tsunamis, landslides, tropical storms (hurricanes, cyclones and typhoons), snow storms, wildfires, costal inundation and flooding. Human or man-made hazards can be intentional (terrorist attacks), or unintentional, which can be due to industrial mishaps (chemical plants, oil and natural gas plants, nuclear power plants, etc.), vehicle collision or a crash. With the ever increasing population (due to migration) and rapid economic growth and development, especially concentrated to hazard-prone areas (coastal areas with high storm potential and high seismic activity areas), make them even more vulnerable to multiple hazards and the losses are only expected to grow in the future (Perry and Mackun 2001; RPA 2005). For example coastal areas of the U.S. possess a population of approximately 153 million people (over half the country's population), who live in the 673 coastal counties (Crossett et al. 2004).

During 1984–2003, more than 4.1 billion people were affected by natural disasters across the world. The affected people were 1.6 billion in the first half of that period (1984–93) which increased to almost 2.6 billion in the second half (1994-2003), and has continued to increase since then (World Bank IEG 2006). Furthermore, a global condition in which climate change influences sea level elevation, storm frequency and intensity may continue to increase the vulnerability of structural infrastructure (IPCC 2007; USDOT 2007; White House 2009). While not all weather-related events are directly affected by climate change, some climatic variations may dramatically increase the vulnerability of the structural infrastructure and their impacts on the society as a whole (Allianz Group 2006).

In recent years, widespread social, economic and environmental destruction have resulted from floods due to typhoons and cyclones in many countries across the world, including Bangladesh, India, Thailand, and from earthquakes in Japan, Haiti, Chile, New Zealand, China and India and the hurricanes in the U.S. and the Caribbean. Between 1990 and 1999 natural hazards cost ($652 billion in 1998 values) in losses across the world, which are 15 times higher than they were between 1950 and 1959 ($38 billion at 1998 values) (World Bank IEG 2006). National Institute of Standards and Technology (NIST 2007) estimated that natural hazards cause an estimated $55 billion in average annual costs in terms of direct and indirect loss in the U.S. Claims paid for weather-related losses totaled more than $320 billion between1980-2005. According to the Federal Emergency Management Agency (FEMA), in the U.S. alone direct economic losses average about $5.4 billion annually from hurricanes and about $4.4 billion dollars a year from earthquakes (FEMA 366 2008). Table 1.1 illustrates some of the worst hazards in the history of the world and the U.S., and estimated damages and losses caused by these hazards.

Table 1.1: Damages Caused by Various Hazards in the World & U.S.

Hazard	World	U.S.
Hurricanes and Typhoons	• Typhoon Durian (2006) killed 800 people in Phillippines and Typhoon Shanshan (2006) caused damages of more than $1.2 billion in Japan (Munich Re Group 2007).	• The 1900 hurricane of Galveston, Texas killed around 6000 people. Hurricane Katrina (2005) in caused damages worth $200 billion and killed around 1570 people (Burton 2010).
Flood	• The Saguenay flood damaged over 1350 houses and around $1.5 billion (Canadian) were paid in insurance claims (Geographical Survey of Canada 2008). • The 1997 Red River Basin flood led to losses worth $300 million (Canadian) (Etkin and Haque 2003).	• The Great Midwest flood of 1993 along the Mississippi river killed 48 people and caused $15 to 20 billion in damages (US Department of Commerce 1994). • The 2008 Cedar Rapids, Iowa floods damaged two power plants and over 20 substations (Graham et al. 2009).
Earthquake	• Haiti earthquake of 2010 killed 250,000 people, 300,000 were injured and 7.804 billion worth of losses (Haiti PDNA 2010).	• The Northridge earthquake of 1994 in San Francisco valley killed 61 people and damaged about 45,000 residential buildings (Fairweather 1994).
Tsunami following Earthquake	• The 2004 Indian ocean Tsunami killed 283,000 people and displaced more than 1.1 million (Tang et al. 2008). • Tsunami in Chile in 2010 killed 521 people and caused $30 billion in losses (Elnashai et al. 2011). • Tsunami in Japan in 2011 killed 11,600 people and around 63,000 buildings were damaged (The New York Times 2011).	• The effects of the 2011 Japan Tsunami were felt in Hawaii islands and at some places along the coast of California.
Terrorist Attacks	• Train bombings of Spain in 2004 Killed 191 people (Global Security 2005) and train bombings in India killed around 176 people (CNN 2006). • The 11/26 terrorist attacks in Mumbai, India also referred to as the Indian 9/11 killed more than 172 people (RAND 2009).	• World Trade Center attacks in 2001 led to the collapse of the twin towers killed more than 2,800 people and caused losses of around $109 billion (FEMA 2010; Rose and Blomberg 2011). • A total of 598,000 people lost their jobs after the WTC attacks (Roberts 2009).

The above events highlight the need for a multiple-hazard resilient world. Assessment and design for multiple hazards is a vast area of research, which has attracted much interest from lawmakers, stake holders, engineers and general public to prepare and to mitigate adverse consequences from multiple hazards.

This report provides a summary of the evolving literature and state of practice related to multiple-hazard engineering, which has emerged as a critical topic in last few decades. The summary is intended to highlight the breadth of work related to characterizing the importance of multiple-hazard. The report summarizes a number of individual hazards, their combinations, different perspectives and consequences. Furthermore, different hazard assessment strategies including post-disaster surveys, numerical models and experiment testing related to multiple hazards are presented. Figure 1.1 illustrates a multiple-hazard approach, which includes the occurrences and the corresponding consequences of individual and a combination of hazards, followed by a set of different assessment and design strategies for mitigation of multiple hazards. Finally, the report provides an insight into the potential impact of climate change aggravating the risks from multiple hazards and the future work that is needed to be done to create a multiple-hazard resilient constructed environment.

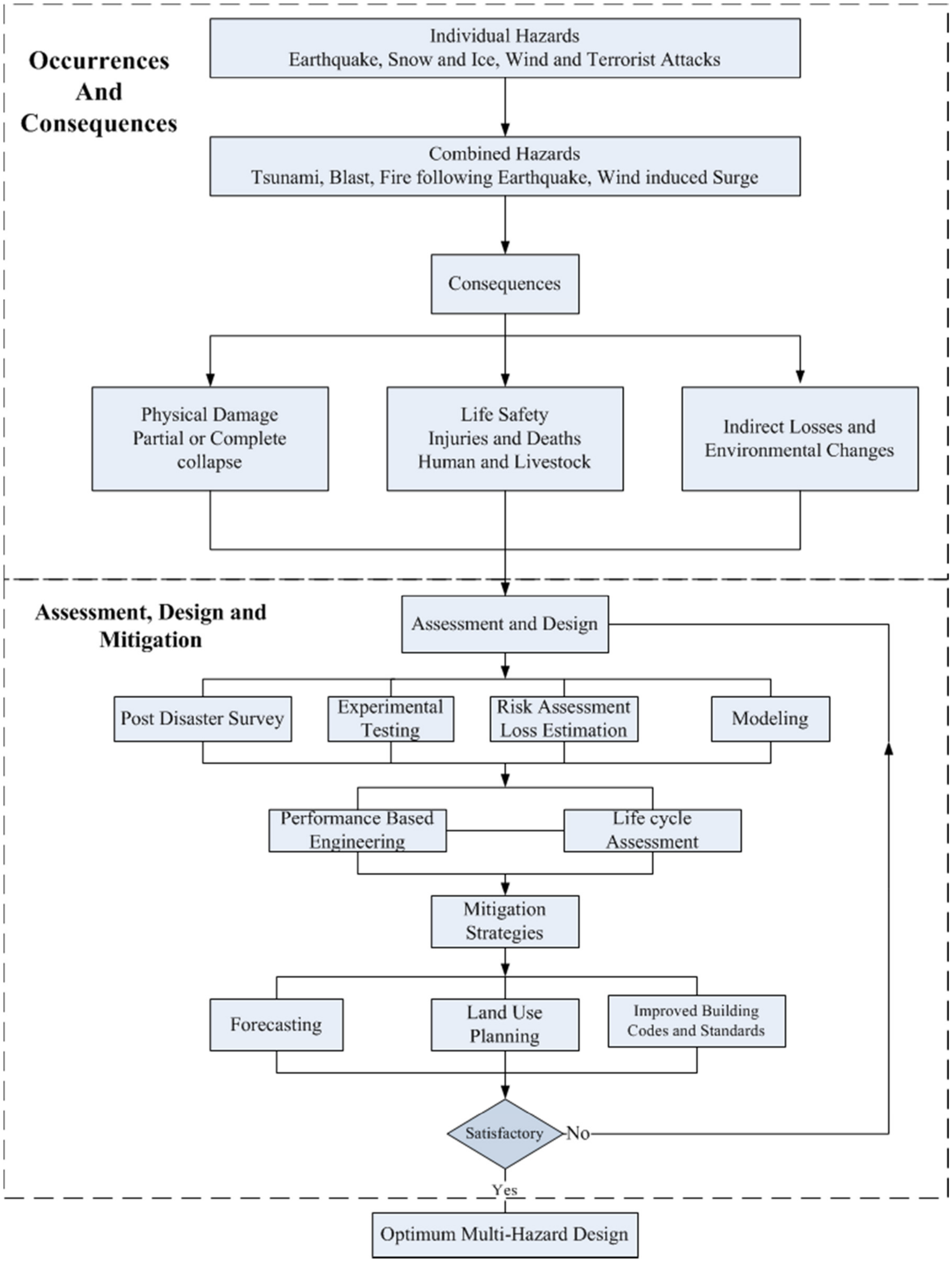

Figure 1.1: Assessment, Design, and Mitigation of Multiple Hazards

2 MULTIPLE-HAZARD PERSPECTIVE AND EXAMPLES

Hazards are different in terms of their nature, frequency of occurrence and associated return period for design. Additional differences include hazard-resistant design philosophies, consequences, and mitigation strategies. The following discussion presents different perspective of multiple hazards and a few examples of damages and losses caused by major multiple hazards over the years.

2.1 Different perspective in multiple hazards

Management of risks due to multiple hazards through proper design, construction practices, occupancy and code enforcement presents a challenge to the structural engineering community as well as the owners and the policy makers. For all natural and man-made hazards, the disruption and downtime of the local businesses, as well as the need for certain essential facilities to maintain their integrity for post-disaster recovery, must factor into any comparative risk assessment.

The economic impact of damage to a structure's components and contents from wind and earthquake are most significant. The lack of advanced warning systems makes life safety the paramount objective for earthquakes. The design wind speed in ASCE Standard 7-05 is based on a 50-year return period for areas in the central U.S. and corresponds roughly to a 100-year return period (ASD design basis) or 700-year return period (LRFD design basis) peak 3-second gust wind speeds along the coast (Li and Ellingwood 2009). Until recently, the ground motion intensity for seismic design was set as the intensity with a return period of 475 years; current seismic hazard maps stipulate a 2% probability of exceedence in 50 years (abbreviated in the sequel as a 2%/50-yr event, termed the “maximum considered earthquake, or MCE”), spectral acceleration with a 2,475-year return period, and the design spectral acceleration is 2/3 of the stipulated seismic intensity (Li et al. 2010). In comparison, the return periods for flood and snow loads are 100 years and 50 years, respectively (ASCE7-10 2010).

In some cases, mitigating risks against an individual hazard may reduce the structure’s vulnerability to another hazard. For example the use of more ductile design details and enhancing connections between components (e.g. roof-to-wall, wall-to-foundation) may reduce damage from both hurricane and earthquake loading. Installation of seismic shear wall anchors will be beneficial for buildings to resist horizontal wind loads as well. However, in other cases mitigating one hazard may increase vulnerability to other hazards. A lighter structure, such as a glass wall or light roof system, may reduce the impact of seismic forces, but the potential damages due to wind would increase. Construction standards and practices should aim at optimizing overall costs and risks, and to do this effectively, the relative risks associated with a structure’s performance under a spectrum of multiple hazards must be well understood.

2.2 Damage and Losses from multiple hazards

When high speed winds combine with moisture evaporated from warm ocean waters at low pressure, they form into a tropical storm, which continues to grow stronger and larger before making a landfall. In Fig.2.1 we can see considerable wind damage to the roof with missing shingles from Hurricane Katrina's high speed winds. A part of the roof is missing and there is visible damage to the trusses inside the roof. The rest of the building envelope is damaged by the impact of high speed wave and due to the buildup of storm surge. An earthquake causes large scale damage and destruction due to ground vibration. When an earthquake strikes an oil rig, a chemical plant, a nuclear power plant or damages oil and gas pipelines (leakage) and power transmission lines (electric sparks), a blast and fire can occur. If fires started from the impact of an earthquake are not controlled in time they may take the form of a conflagration, which is more dangerous than the earthquake itself. Fig. 2.2 displays the fire that started from the damaged natural gas pipelines due to the Northridge earthquake. Table 2.1 outlines different examples of multiple hazards, their modes of damage, occurrences in the past, and the extent of damages caused by the hazards.

Figure 2.1: Wind and Storm Surge Damage

© Jordon and Paulius (2006) ®

When a hazard strikes and leads to the failure of a particular infrastructure, it starts a chain reaction which is a one by one failure of dependent infrastructures. This is also known as cascading (Chang et al. 2009). The Kobe earthquake (Tokyo) of 1995 disrupted the power supply causing a city wide blackout, which led to the failure of 90% of the traffic signal resulting in chaos on streets and delayed the response of emergency services to the calls of the victims (Savage et al. 2006; McDaniels et al. 2007). In addition gas and phone connections of thousands of households were cut off. About 531 fires broke out in different parts of the city, most of them because of the natural gas leaks and electric sparks from damaged electrical power lines (Selvaduray 2003).

Figure 2.2: Fire from Damage to Gas Pipelines from Northridge Earthquake in 1994
© Dr. Kerry Sieh (1994), Earth Observatory of Singapore, Nanyang Technological University ®

Table 2.1 Multiple Hazards

Multiple Hazards	Mode of Damage	Occurrences	Examples of Multi-Hazard Damage
Hurricane (Wind and Rain)	High speed winds damage doors and windows and when followed by heavy rainfall, causing interior property damage to the structure.	• Hurricane Ike (2008) • Hurricanes Katrina and Rita (2005) • Hurricane Andrew (1992)	• During Katrina complete structural damage was observed when the roofs were blown away by high speed winds and the interior damaged by heavy rainfall that followed.
Hurricane (Wind, Wave and Storm Surge)	Waves cause extensive damage when they strike coastal structures after wind has caused external structural damages.	• Hurricane Ike (2008) • Hurricanes Katrina and Rita (2005) • Hurricane Andrew (1992) • Hurricane Opal (1995)	• Waves as high as 25 ft. were observed during Katrina, which caused large scale structural damage (buildings, bridges, etc.).
Earthquake and Tsunami	Tsunamis are high speed and height waves triggered by an underwater earthquake. The combined damages are caused first by ground shaking followed impact of high speed waves	• Indian Ocean Tsunami (2004) • Japan Tsunami (2011)	•Indian Ocean Tsunami killed about 283,000 and displaced more than 1.1 million people. •The Japanese tsunami damaged the electrical power lines of Fukushima Daiichi nuclear power plant creating a meltdown threat.
Fire following an Earthquake	Fires caused after damages to oil and gas pipelines and to electrical power transmission lines damaged by an earthquake	• San Francisco (1906) • Tokyo (1923) • Kobe (1995) • Northridge (1994) • Japan (2011)	•Around 3000 people were killed in the 1906 San Francisco (Varnes and Pielke Jr. 2009) and around 142,000 people were killed in Tokyo in 1923 from fires following an earthquake (James 2002). •The cities of Kesennuma and Sendai of Japan were under heavy fires after the earthquake of 2011 (Reuters 2011).
Landslides caused by earthquakes, heavy rainfall and flood.	Landslides can be caused by heavy rainfall, earthquake ground shaking, water level change, storm waves or erosion. Large scale deforestation, cutting of slopes for roads and settlement can also trigger a landslide.	• Brazil (2011) • California (2005) • Philippines (2006) • Indonesia (2006) • Venezuela (1998)	• In the U.S., landslides cause about 25-50 deaths and $2 billion in damages each year (FEMA 2004). • The 1962 Peru landslides killed about 5,000 people and again in1970 about 18,000 people were killed. • The 2006 Indonesia and Philippines landslides buried almost entire villages overnight.
Terrorist Attacks	Blasts and fires mostly due to detonation of a charge or impact of collision. The damages are caused by the impact of the blast, consequent fires and the flying debris.	• Oklahoma City Bombings (1995) • WTC Attacks (2001) • Train Bombings in Spain (2004) and India (2006)	• The 2006 train bombings in India killed more than 209 people. • The bombing of Alfred P. Murrah building in Oklahoma City in 1995 killed 168 people and caused damages worth more than $80 million (BBC News 2001).

3 ASSESSMENT OF THE IMPACTS OF MULTIPLE HAZARDS

Assessment of the impact of multiple hazards on constructed environment is carried out to aid researchers and policy makers to make decisions regarding future design of new, and retrofitting of existing structures. One of the ways of assessment of impact of multiple hazards is the post disaster survey. The data collected from post disaster surveys help in conducting experimental tests, risk assessment, modeling and numerical analysis for developing retrofitting, and new design procedures.

3.1 Post disaster survey and investigation

A post disaster survey is often conducted after the disastrous event to collect data on the hazards and their consequences, such as modes of structural failure, infrastructure performance and capacity for resilience. The qualitative lessons learned from such events often either help to validate or to shape changes in design and construction practices, offer empirical data for model calibration and validation, and future risk assessment, management, mitigation and planning for individual and multiple hazards. The data collected is typically in the form of visual inspections, field surveys, photographs, survey forms, shop drawings (recreation of pre-hazard original condition) and samples of structural components, and building or infrastructure owner's quarries about the status of their facilities, or service level that will be provided to their constituents. Post disaster survey forms are used not only for determining number of casualties and extent of damage and loss assessment, but also to monitor medical health of the victims, clean water supply and sanitation conditions, condition of lifeline utilities, requirement and availability of food, damage to crops and livestock, etc. (EMA 2001; Franco et al. 2010).

As an example, Robertson et al. (2007) visited Biloxi, Mississippi to survey damage to bridges, barges, buildings and other infrastructure, and researchers from Technical Council on Lifeline Earthquake Engineering (TCLEE) evaluated performance of the gulf coast's bridges, railroads, and roadways following Hurricane Katrina (DesRoches 2006). FEMA's Mitigation Assessment Team (MAT) surveyed Katrina's landfall sites to evaluate building performances, practices and materials used, to assess flood and wind damages (FEMA 549 2006). FEMA's Building Performance Assessment Team (BPAT) (FEMA 1992) post Hurricane Andrew, and MAT surveyed the effected sites post Hurricane Ivan and post the mid-west floods in Iowa and Wisconsin, respectively. The teams assessed structural performances and provided recommendations for future construction practices in those areas (FEMA 489 2005; FEMA p-765 2008).

International Tsunami Survey Team surveyed post tsunami coasts of Sumatra and off shore Aceh Province islands to analyze structural damage, injuries and deaths, scouring, erosion caused by the 2004 Indian Ocean Tsunami (Prasetya et al. 2008). Similar surveys for damage and loss estimation were carried out over southern India and Sri Lanka (Yeh et al. 2007; Tanaka et al. 2007). FEMA's BPAT surveyed the site of 9/11 attacks on the World Trade Center to estimate losses and to identify areas of further research (NIST 2005; FEMA 2010). NIST investigated the collapse of WTC 7 due to falling debris from the collapse of WTC 1 tower (NIST 2008). FEMA's BPAT surveyed the area around

Alfred P. Murrah building to collect data from damages from a car bomb explosion in the Oklahoma City in 1995 (Corley et al. 1998).

A post disaster survey team consisting of members from The Word Bank, the Government of Haiti and other organizations from around the world, surveyed post 2010 earthquake Haiti for damage assessment and future risk management needs (Haiti PDNA 2010). Earthquake Engineering Research Institute's (EERI) reconnaissance team investigated the after effects of the earthquake at Chile in 2010 to assess nonstructural (ceiling tiles, equipment, piping, etc.) damage to hospitals and other important buildings (MCEER 2010). EERI (2011) research team travelled to New Zealand post 2011 Christchurch earthquake to study the performance of engineered structures, eccentrically braced steel frame structures, nonstructural building components, hospitals and other structures.

Post disaster surveys in the past have led to significant changes in the design codes as well as modeling and numerical analysis. Van de Lindt et al. (2007) gathered wind damage data post Katrina for design codes development. Padgett et al. (2009) evaluated hazard intensities and bridge characteristics important in predicting the level of bridge damage by performing a multivariate regression analysis using data collected from post Katrina surveys. SAC steel project (a joint venture between the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and Consortium of Universities for Research in Earthquake Engineering (CUREE)) provided interim guidelines for evaluation, repair and rehabilitation of moment-resisting steel frame buildings based on analytical studies and physical tests conducted from the data collected from post Northridge earthquake surveys (Song and Ellingwood 1998). Data collected from the post disaster surveys for Loma Prieta (1989) and Northridge (1994) earthquakes, led to the 1997 American Institute of Steel Construction's (AISC) seismic specifications for improved connection details for steel moment-frame structures and stricter requirements for wood frame shear walls in International Building Code (IBC) 2006, respectively (Ratay 2011). The data collected by post disaster surveys not only used for record keeping, experimental tests conducted can also use the collected data to test the impacts of multiple hazards.

3.2 Experimental Testing

NIST's (2010) Building and Fire Research Lab (BFRL) provides FASTData, a collection of results of over 450 real time fire experiments at single assemblies and single as well as multiple apartments conducted in the labs. Network for Earthquake Engineering Simulation (NEES 2009) has test facilities across many universities in the U.S. to assess seismic performance of wood, steel and concrete structures using shake tables, field mounted actuator assemblies, centrifuges and field equipment. Though a number of tests have been conducted for individual hazards very less number of experiments have been conducted for multiple hazards, as experimental testing is difficult and is not possible for every hazard. Some of the experimental tests conducted to validate new designs and to assess the impact of multiple hazards, are discussed in the next section.

Example 1: Earthquake and Blast

A blast may be a result of an accident, detonation of a charge or impact of a collision done on purpose. A large magnitude earthquake can easily trigger a blast, however majority of blasts are caused by terrorist attacks. Bruneau et al. (2006) experimentally tested a multiple-hazard bridge pier concept. The bridge pier system provided satisfactory protection from collapse under seismic and blast loading but not a combination of both. Fig. 3.1 displays the experimental setup of bent frames which had Concrete Filled Circular Steel Columns (CFCSC) and were subjected to a series of successive blasts. No significant damage was observed to the bents and the piers showed ductile behavior.

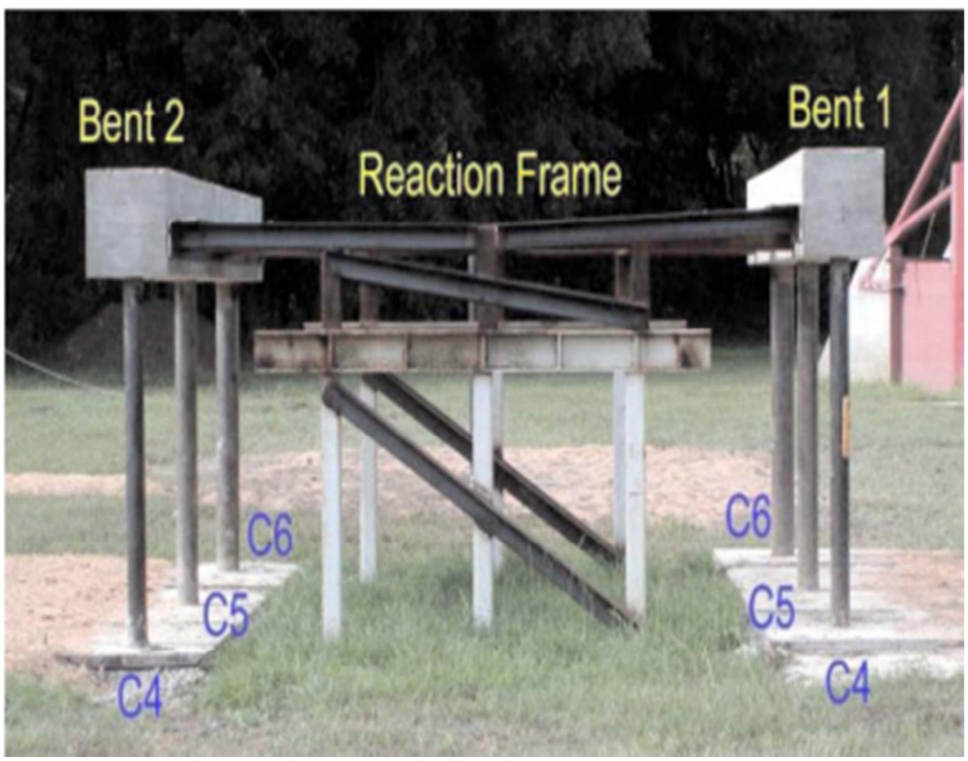

Figure 3.1: Test setup showing CFCS Columns subjected to a blast loading © Fujikura et al. (2008) ®

Example 2: Hurricane (Wind, Rain, Wave and Storm Surge)

During a hurricane, high speed winds cause initial damage by damaging building envelope and in some cases complete upliftment of the roof and the remaining damage is caused by heavy rains and surge/flood. Florida International University built a portable hurricane machine "Wall of Wind" to simulate high speed winds and wind driven rain from a hurricane (Fig.3.2). The 6 fan machine generates winds up to 130 mph along with a water-injection system for simulating horizontal wind-driven rain for destructive testing on several structures (Florida International University 2011).

Figure 3.2: Wind Driven Rain Testing at FIU Wall of Wind

© Dr. Arindam Chowdhury, Florida International University ®

Oregon State University's Tsunami Wave Basin provides test facilities and experimental data for tsunami research (NEES 2009). Testing was performed on a 1/6th scaled model of a 2-story wood-framed residential structure at the Tsunami Basin of Oregon State University using alternate wave heights from 10 to 60cm. This research was successful in developing experimental setup test surge wave forces (overturning moments and upliftment forces) due to wave loading (Wilson et al. 2009). The results from experimental testing provide basis for risk assessment of real world structures from multiple hazards. A number of experimental tests have been conducted for individual hazards. In the future advanced test equipment and facilities are required which would be able to test the impacts of multiple hazards simultaneously.

3.3 Risk assessment, modeling and numerical analysis

The following section defines the process of risk assessment and discusses the current risk assessment approaches and tools being used. A risk can be viewed as the summation of the expected number of deaths, injuries, damage to infrastructure and socio-economic disruption specific or combination of threats. Faber and Stewart (2003) defined risk (R) as the product of the probability that an event with potential consequences will occur (P) and its consequences (C) given the event occurs

$$R = P \ X \ C \tag{3.1}$$

Petak and Atkinson (1982) defined risk as the combination of a probability of the occurrence of a hazard or the probability of exceedence of the intensity of the hazard and the vulnerability of a region and its people to the hazards and the losses that it would inflict on them.

A number of studies have been carried out in recent decades for hazard risk and impact assessment of structural infrastructure. Ellingwood and Ang (1975) carried out quantitative analysis of design uncertainties, to show the effect of these uncertainties on the level of risk to the structures. Cornell (1968) presented a method for seismic risk evaluation due to uncertainties from number, size and locations of future earthquakes. Ang (1973) developed methods for risk assessment in terms of probability of failure or survival of a structure. Corotis and Nafday (1990) developed a model to assess reliability of complex structural systems from random loads and resistances. Chang et al. (2000) developed a probabilistic risk analysis method to assess seismic risks to lifeline systems in Los Angeles area.

Structural infrastructure (bridges, buildings, etc.) are at a continuous risk from structural deterioration and eventual collapse from aging by the impacts of corrosion, chemical attack, etc. (Ellingwood 2005). Li and Ellingwood (2007) assessed the overall risk due to hurricane and earthquake. The damage states considered are as follows; minor (loss of one roof panel from wind and 1% lateral drift in earthquake), medium (failure of two or more windows or loss of multiple roof panels from wind and 2% lateral drift in earthquake) and severe (failure of the roof to wall connections leading to roof uplift and collapse of the wall from wind and 3% lateral drift in earthquake). Fig.3.3 shows the probability of damage due to different levels of earthquakes and hurricanes intensities as a function of their return period for a building in Charleston, SC. The two hazards may strike the same site at different times. However, the probability of their simultaneous occurrence at a site is very low.

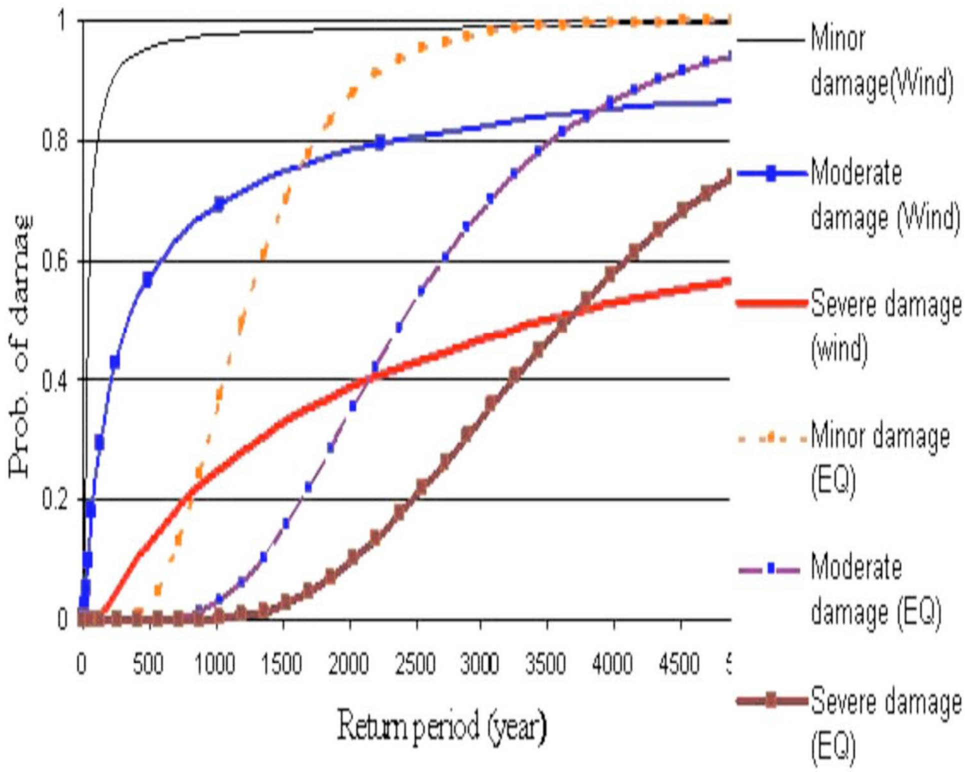

Figure 3.3: Probability of Hurricane and Earthquake Damage

© Li and Ellingwood (2007) ®

The risk assessment approach called the SAMUG (Kepner and Trego 1981) and AS/NZA 4360:1999 are used by the Australian Emergency Agencies to identify hazards that cause maximum damage. The structural information (location, type of material used, etc.) and risk level from multiple hazards are stored in a database for future use (Standards Australia 1999; Middleman and Granger 2000). Novelo-Casanova and Suarez (2010) carried out risk and vulnerability assessment for Cayman Islands for multiple natural and man-made hazards by identifying different hazards and then categorizing them according to both the severity and vulnerability of the region.

Various risk assessment tools are available to assess risks and potential losses from multiple hazards. HAZUS-MH, a risk assessment tool developed by FEMA analyzes potential losses from floods, hurricane winds and earthquakes (FEMA 2011). Risk and vulnerability Assessment Tool (RVAT) assesses risk and vulnerability to help identify people, property, and resources that are at risk of injury, damage, or losses from natural and other hazards (NOAA 2003).

The effect of climate change has been incorporated into risk assessment over the years, however significant amount of research needs to be done in this area. Tools that consider policy or planning requirements while considering both physical impacts and predictions, and keeping in mind both stakeholders and policy makers interests need to be developed in the future (Alkhaled et al. 2007).

Numerical models for predicting risks and losses, performance assessment, and design are developed using data from experimental testing. When experimental data is not available modeling and numerical analysis can be carried out using data collected from the post disaster surveys, and the models can then be validated through experimental testing. This section discusses numerical models developed for prediction of failure, risk assessment, performance and design for multiple hazards. Examples of modeling and analysis for a combination of hazards are discussed later in the section.

Javanbarg et al. (2009) proposed the following numerical model to predict the probability of failure of a lifeline network from multiple hazards, to analyze large scale lifeline network failures.

$$P_F = \sum_{i=1}^{2^m} [\, \Pr(F \,|\, CCE_i) \cdot \Pr(CCE_i) \,] \tag{3.2}$$

where m is a set of common cause events, $\Pr(CCE_i)$ is the probability of occurrence of a common cause or a hazard event and $\Pr(F \,|\, CCE_i)$ is the conditional probability of failure of a lifeline network under the occurrence a hazard event. A study was carried out to evaluate the model (Eq.3.2) using Xing's (2008) ROBDD method for flood. Burneau et al. (2003) developed a quality function to describe structural performance of power transmission networks for earthquakes. The same function was used by Reed for wind (Reed 2007).

Greimann et al. (1999) carried out a 3D finite element analysis of the AP600 nuclear power plant's shield building roof under a combination of dead, snow, wind and seismic loads. Alampalli and Ettouney (MCEER 2007) introduced the SHCE (Sensing, structural identification, damage identification and decision-making) bridge management approach to multiple hazards. Internal Atomic Energy Agency's (IAEA 2006) carried out a survey of its member countries' nuclear power plants for design methods currently in used to protect nuclear power plants from multiple hazards. This information can be used to upgrade existing or for construction of new plants.

Example 1: Earthquake and Wind

Earthquake and tsunami, earthquake and blast, fire following earthquake, earthquake and wind are a few examples of combinations of earthquakes with other hazards that have to be considered by designers and risk managers. Potra and Simiu (2009) set forth a numerical method for optimization of multiple-hazard design using inter point method by optimizing design variables for loads generated by earthquake and winds for sites subjected to both the hazards individually and simultaneously. Kostarev et al. (2003) proposed a design method for decreasing the floor response spectra considering interconnection of main building structures inside nuclear power plant containment, using high viscous dampers. This would increase the resistance of the power plant towards seismic, wind and blast loads. Padgett et al. (2010) evaluated a multi-span simply supported concrete girder bridge for seismic and hurricane induced wave and storm surge loading, and conducted a sensitivity analysis to determine aging parameters that significantly affect the dynamic response of the bridge to both the hazards.

Example 2: Wind, Wave and Surge/Floods

Hurricanes cause damage by the combined effects of wind, waves and storm surge/flood. Li et al. (2011) calculated the losses due to combined effect of wind and storm surge, on a single story wooden residential building. Fig. 3.4 displays the combined losses caused by hurricane wind and surge as a percentage of the total cost of the building. Kim and Yamashita (2004) developed a wind-wave-surge model to simulate storm surge caused by Typhoon Bart in the Yatsushiro Sea, Japan. The model consists of a WW3 model for wind waves, meso-scale meteorological model for wind, and coastal ocean model (POM) for storm surge simulations. Ataei et al. (2010) studied the combined effects of storm surge and wind waves caused by hurricanes on the dynamic response of bridges, using a 3D non-linear finite element model to identify statistically significant bridge parameters (upliftment of deck, ultimate dowel strength, initial stiffness of elastomeric pads, etc.) through a sensitivity analysis.

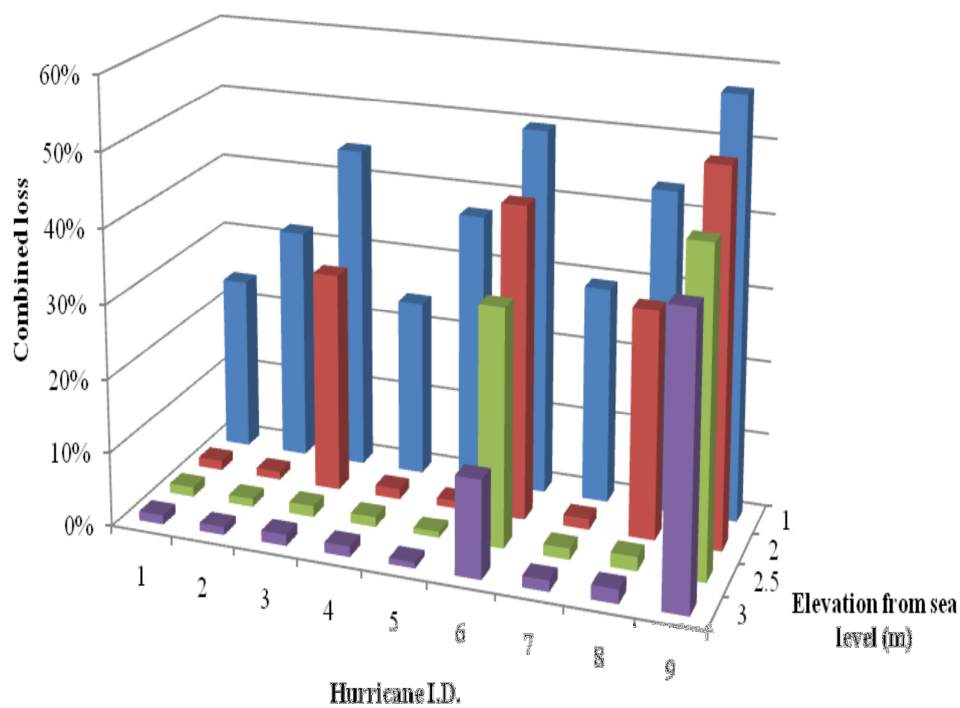

Figure 3.4: Combined Losses from Hurricane Wind and Surge Damage © Li et al. (2011) ®

Case Study

A case study was conducted to estimate combined losses due to hurricane wind and storm surge flooding of single story wooden frame residential building. Hurricane Katrina caused widespread damages to buildings located across the coast line through wind, wave and storm surge flooding. Although wave action causes considerable damage to the buildings, the study here is limited to damages caused by storm surge floods. The estimation methodology of Taggart and van de Lindt (2009) was used. Table 3.1 displays the general information about the building. It contains the information about total cost of the house, the count and height of the components and. Figure 3.5 shows a typical one story residential building.

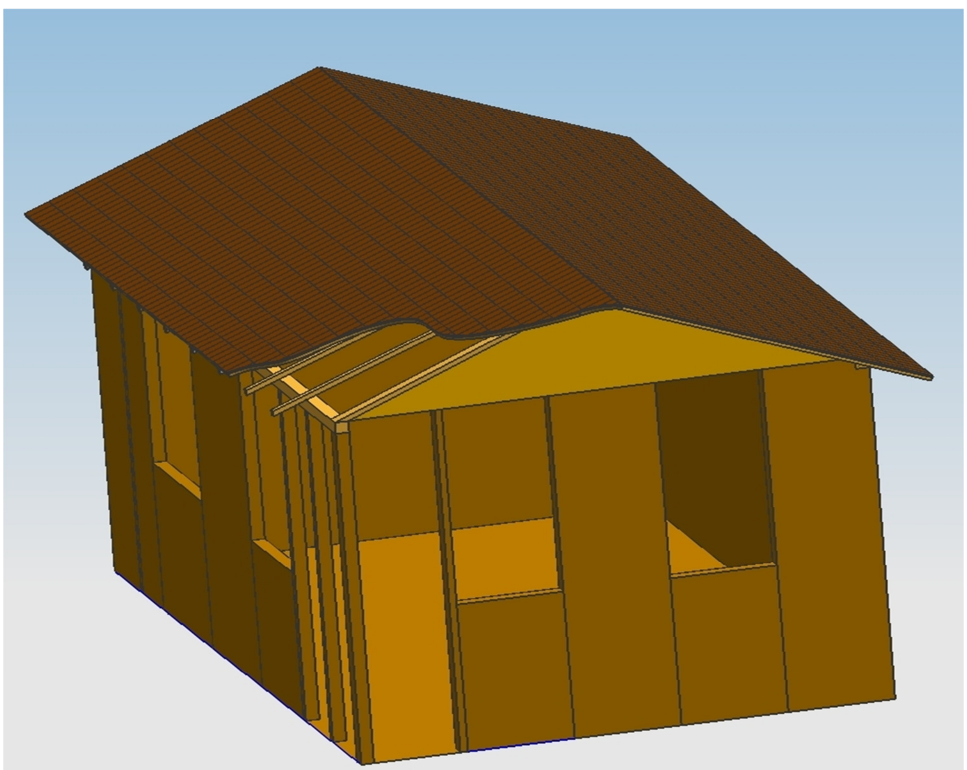

Figure 3.5: Single Story Building

Table 3.1: General Information of a Single Story Building

General Information Of the Building	
Total floor area	1800
Finished floor area	1800
Total floor area covered with carpet	1230
Total floor area covered with tile	570
Total floor area covered with decorative wood flooring	0
Total floor area covered with vinyl	0
Total length of lower cabinets	33
Total length of upper cabinets	18
Total length of baseboard trim	206
Total length of trim not including baseboards	0
Total length of interior walls	116
Total length of exterior walls which are covered on the interior surface	180
Total length of exterior walls which are covered on the exterior surface	180
Number of windows	7
Number of interior doors	5
Number of exterior doors	1
Number of closet doors	0
Number of garage doors	0
Number of staircases	0
Number of electrical outlets	52
Number of electrical switches	16
Number of light fixtures	21

Table 3.1: Continued

Total floor area	1800
Value of home	200000
Number of stories	1
Any basement	0
Floor on which appliances are located	1
Furnace location	0
Air conditioning compressor location	1
Water heater location	0
Washer and dryer location	1
Range location	1
Refrigerator location	1
Garbage disposal location	1
Dishwasher location	1
Vented hood location	1
Electrical panel box location	1
Heights for each story	144
Height from floor to ceiling	132
Height from floor of current story to floor of story above	0
Height of electrical outlets	12
Height of electrical switches	48

Loss due to Storm Surge Floods

The losses were estimated for 9 different hurricanes as a percent of the replacement value of the damaged components of the building. Due to the uncertainties, the damage percentage is given for the mean, 5^{th} and the 95^{th} percentiles. Figure 3.6 displays the storm surge build up across a coast and the flooding of a building located along the coast. Table 3.2 displays the losses due to storm surge floods. The values were calculated using Matlab, from the historical data of the hurricane wind velocity (V_{max}), the radius of the eye (R_{max}) and the height of the storm surge.

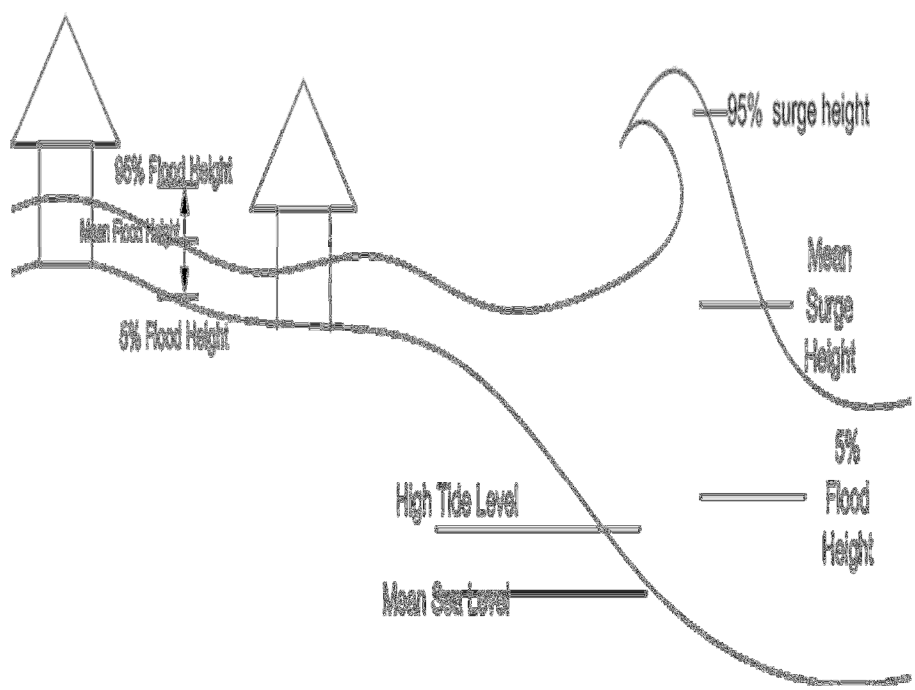

Figure 3.6: Storm Surge Floods

Table 3.2: Losses due to Storm Surge Flood

Hurricane ID	V_{max} m/s	R_{max} Km	Surge height m	Total Cost (Ratio to house value) mean	5th percentile	95th percentile
1	43.5	20	1.20	0.230	0.199	0.247
2	54.4	11	1.59	0.312	0.291	0.336
3	66.0	19	2.65	0.443	0.407	0.455
4	43.5	26.5	1.26	0.230	0.229	0.284
5	54.4	43	2.02	0.370	0.340	0.396
6	66.0	40.3	2.68	0.456	0.436	0.482
7	43.5	33	1.32	0.283	0.229	0.289
8	54.4	74	2.40	0.431	0.386	0.457
9	66.0	56	2.91	0.481	0.457	0.501

Hurricanes 1, 2 and 3 are category 1 hurricanes, hurricanes 4, 5 and 6 are category 2 hurricanes and hurricanes 7, 8 and 9 are category 3 hurricanes. The losses for hurricane 3 are the maximum with the Hurricane 9 causing maximum (0.481) loss.

Combined Loss due to Wind and Surge

When combined loss due to storm surge and wind were determined, certain components were counted for twice. The damage to the overlapping components were established and subtracted from the total loss percentage. The overlapping components in the building (Table 3.3) consists of a computer, a television set, and a bed in each bedroom. The living room consists of a television and the damageable items in the kitchen are the kitchen closets. In addition the floor and the walls of each room are considered damageable.

Table 3.3: Overlapping Components

Bed room #1	Bed room #2	Living room	Kitchen
Computer	Computer		
TV	TV	TV	
Floor	Floor	Floor	Floor
Wall	Wall	Wall	Wall
Bed	Bed		Kitchen Closet

The floor is assumed to be damaged for all surge heights. Most of the parts of the floor can be restored to the initial condition by drying for some time including the carpeted areas (Algan et al. 2004). Therefore 25% of the total replacement cost of the entire floor is considered as a loss. The wall coverings are assumed to take the maximum impact of the surge floods and the wooden frames and insulation can be restored (original strength and no mold growth) to their initial conditions when dried adequately (Algan et al. 2004; Wingfeild et al. 2005). Therefore 50% of the total replacement value is considered to be the loss. The computer and the TV sets are assumed to be at a height of 1.3 m from the floor and are completely damaged if the surge height crosses 1.3 m. The bed was assumed to sustain 100% damage if the surge height is higher than 1.5 m, 50% damage if the surge height is between 1.0 m and 1.5 m, and 20% damage if the surge height is less than 1.0 m. The kitchen cabinets are assumed to be located 0.3 m above the ground and suffer 50% damage if the surge height is greater than 1.0 m, 25% damage if the surge is between 0.3 m and 1.0 m, and no damage if the surge height is less than 0.3 m.

Table 3.4 presents losses for wind, surge, and the combined losses. The surge loss is the mean surge loss from table 3.2. The combined losses were determined by combining the loss due to wind and surge, after subtracting the overlap, and therefore will always be less than the direct sum of the losses. These values for combined loss represent nine different hurricane scenarios. Such results could be used effectively in detailed land use planning or in design code updates.

Table 3.4: Combined loss from wind and storm surge flood

Hurricane ID	V_{max}	R_{max}	Surge Height	Wind Loss	Surge Loss	Combined Loss
	m/s	Km	m	Total Cost (Ratio to house value)		
1	43.5	20	1.20	0.013	0.230	0.238
2	54.4	11	1.59	0.011	0.312	0.318
3	66.0	19	2.65	0.015	0.443	0.444
4	43.5	26.5	1.26	0.014	0.230	0.239
5	54.4	43	2.02	0.008	0.370	0.372
6	66.0	40.3	2.68	0.131	0.456	0.492
7	43.5	33	1.32	0.015	0.283	0.292
8	54.4	74	2.40	0.019	0.431	0.436
9	66.0	56	2.91	0.182	0.481	0.567

Example 3: Fire Following Earthquake

Usually fire follows a significant earthquake. Fires following San Francisco (1906), Tokyo (1923) and Loma Pareta (1989) earthquakes caused more damages than the earthquake itself. Zhao et al. (2006) set forth a numerical model in which a random poisson event and Weibull distribution were used to construct the spatial–temporal probability distribution of fire outbreaks following an earthquake using a geographical information system (GIS) based stochastic simulation schema. The model was applied for simulating fire outbreaks in Xiamen city. Davidson (2006) used generalized linear and generalized linear mixed models to statistically model post-earthquake fire ignitions and to collect data for such modeling, and applied it to late 20th century California. Rin and Xie (2004) developed a mathematical model that predicts the place where fire outbreaks may occur after an earthquake and also simulated dynamic fire spreading using data from past fires following earthquakes in America, Japan, and China. Yassin et al. (2008) developed a framework for studying the effects of post-earthquake fire on wooden structures. A finite element model for assessing the performance of the wood frame system tested at the National Fire laboratory of National Research Council Canada was created using ANSYS 3D modeling software .

The data collected through post disaster surveys, experimental tests conducted, risk assessment and loss estimation, and numerical models developed are then combined together to aid in the development of multiple hazards resistant design.

4 DESIGN AND MITIGATION FOR MULTIPLE HAZARDS

4.1Design for multiple hazards

It is physically impossible and economically not feasible to design structures for worst possible or most extreme event. There always exists a tradeoff, whether structures should be redesigned or retrofitted for multiple hazards. Therefore economically viable and socially acceptable structural design and retrofitting techniques should be developed with careful consideration of design constraints or minimum design requirements, for structures at risk or located in hazard prone areas using results of experimental tests verified by numerical models and vice-versa.

Keller and Bruneau (2009) proposed the concept of Steel Plate Shear Wall (SPSW) Design of bridge piers. SPSW are ductile, resistant to multiple hazards and easy to repair when damaged. A four column box SPSW pier was developed, that offered seismic resistance in all directions depending upon the plate thickness, which also resisted the impacts of hurricane induced surge, tsunami waves and blast. ABAQUS (3D modeling software) was used to carry out an advanced finite element analysis of a SPSW pier bridge model under the effect of multiple hazards and performed satisfactorily to resist them. Teich and Gebbeken (2009) designed a new structural system containing a reinforced concrete sacrificial wall with reinforced and protective sand cladding, for both seismic and blast load resistance. The design (fig. 4.1) also replaces the traditional stone foundation with a deep and stiff strip foundation with a reinforced concrete slab.

With increasing demand for stakeholder or owner's participation in residential building design and performance, performance-based design has gained considerable attention not only from researchers and engineers, but also from individuals and policy makers.

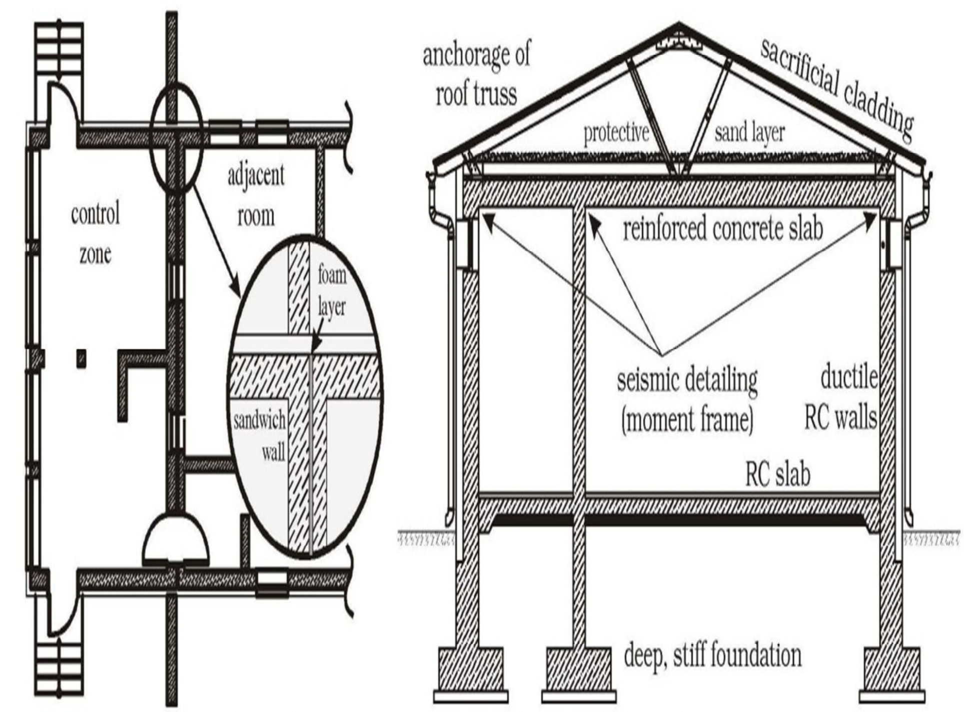

Figure 4.1. Design of a Single Storey Building for Earthquake & Blast © Teich and Gebbekken (2009) ®

4.2 Performance-based design (PBD) for multiple hazards

There is a recent trend, for residents to remain in their homes during a high speed wind event due to difficulties associated with large scale evacuation and a desire to protect their property from vandalism during the aftermath of a large-scale natural disaster. With the move towards PBD, it should become feasible to achieve residential building performance that is consistent with both individual and societal needs. In PBD, the performance objectives of a structure are decided by the owners and then the best design is selected after going through a series of designs that incorporate risks from multiple hazards. PBD is the integration of design, construction practices, operation and maintenance of a structure for the intended life time. Fig. 4.2 describes a performance based engineering approach for multiple hazards.

The Applied Technology Council (ATC) and FEMA's Project ATC-58 developed performance-based seismic design guidelines. The project includes a series of resource documents that define procedures to design new or upgrade (retrofit) existing structures to achieve desired performance goals, and to assist stakeholders in selecting best suited reliable design performance goals for buildings economically (ATC 2009). The guidelines developed could also be used for other hazards such as blast, fire and hurricanes. Taggart and Van De Lindt (2009) developed a PBD approach to calculate monetary losses due to flood damage for various buildings and site design. The cost of construction, operation, maintenance, repair etc. over the lifetime of a structure plays an important role in designing the new structure or for retrofitting of existing structures.

Incorporation of life cycle cost analysis would help home owners to apply cost effective multiple hazard mitigation techniques into their design.

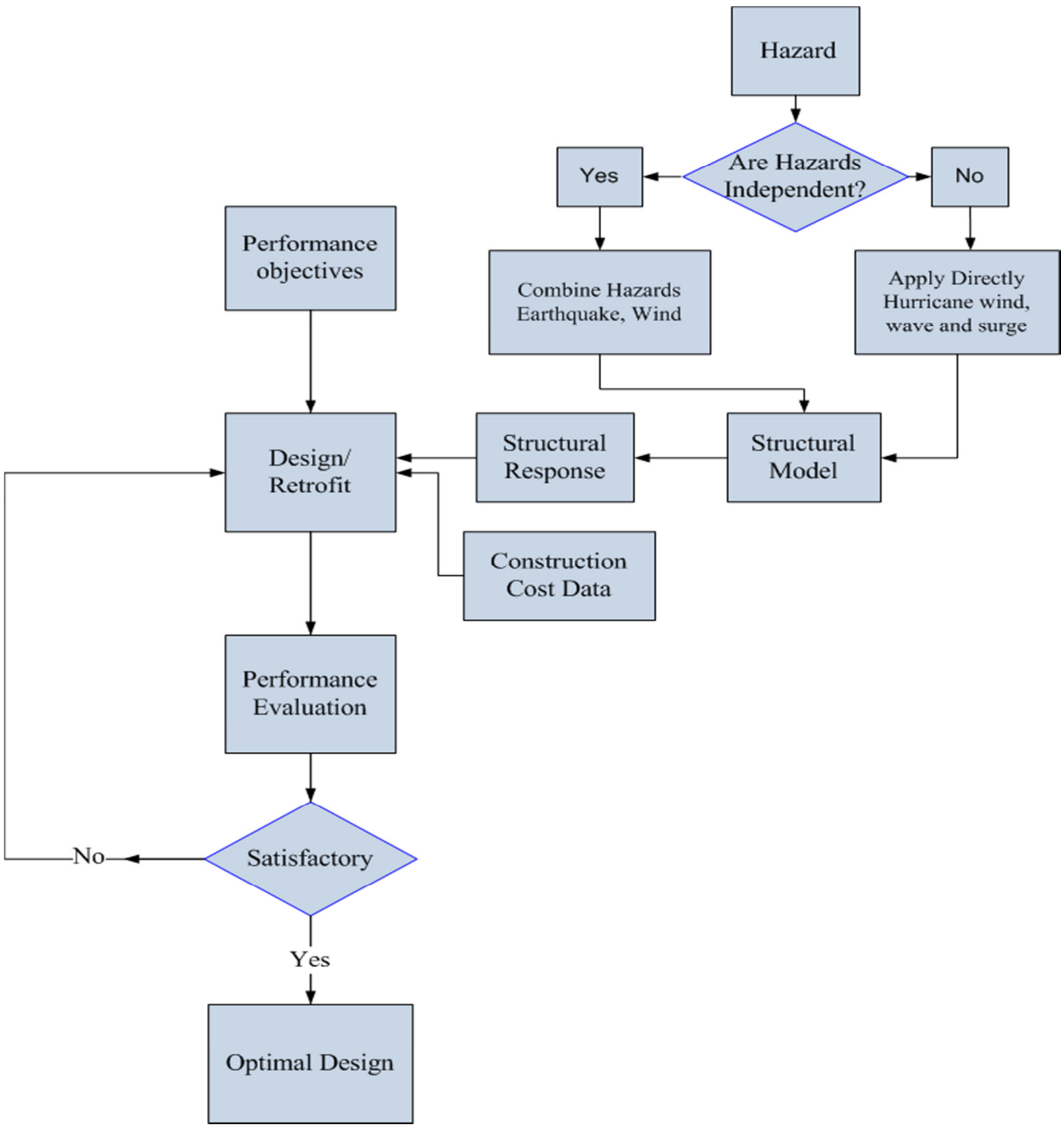

Figure 4.2: Performance-Based Design Approach for Multiple Hazards

4.3 Life cycle analysis

Life cycle analysis is carried out to determine whether it is economically feasible to retrofit a structure using mitigation strategies incorporated into design or to rebuild from start. Life cycle analysis is also used to determine the best retrofitting design from a number of available design options and potential losses to the structure from multiple hazards during its lifetime. Bruneau (Multi Hazard Mitigation Council 2005) stated that spending every $1 towards multiple hazard mitigation would save $4 in the future from losses. Wen and Kang (2001a) developed a mathematical model (Eq.4.1) to calculate the expected total cost of new or retrofitted structure over its life time for a single or multiple hazards using an optimum design method.

$$E[C\ (t, X)] = C_o + C_F \frac{\left(1 - e^{-\lambda t}\right)}{\lambda} + \frac{C_m}{\lambda}(1 - e^{-\lambda t}) \tag{4.1}$$

where E[C (t,X)] is the expected cost, C_F is the expected cost, C_o is the initial cost of new or retrofitted facility, C_m is the operation and maintenance cost per year and λ is the discount rate per year for inflation. The result of the analysis demonstrates that the structure should not be designed only for the dominating hazard as the lesser hazard may also contribute significantly (Wen and Kang 2001b).

Jalayer et al. (2010) developed a model (Eq. 4.2) to calculate the expected life cycle cost of a structure for multiple hazards involving uncertainties both type of loading and the modeling parameters.

$$E[L; T_{max}] = C_o + C_R + C_M \tag{4.2}$$

where $E[L; T_{max}]$ is the expected life cycle cost is over a time period T_{max}, C_o is the initial construction cost, C_R is the repair or replacement cost taking into account the loss of revenue during time and C_M is the annual maintenance costs. Ettouney and Alampalli (2006) developed a model (Eq. 4.3) which performs life cycle analysis for a structure affected by multiple hazards

$$C_j = \sum_{k=1}^{k=NH} \sum_{i=1}^{i=NH} H_{ik}\, C_{aijk} \tag{4.3}$$

where C_j is the total cost because of a hazard H_{ik} is the hazard intensity of the i^{th} hazard, NH are the number of sub divisions of the hazard intensity space x, and C_{aijk} is the corresponding cost.

Developing design methods alone may not be enough to mitigate the impacts of multiple hazards, the designs need to be included into building codes, which should be implemented strictly. In Australia minimum design requirements of structures for earthquake, floods, winds and storm have been set and every structure has to meet these requirements (Middlemann and Granger 2000). In Japan the strict implementation of the building design codes saved many lives during the 2011 tsunami and earthquake. Furthermore, designs should be combined with a number of other mitigation strategies (land use planning, risk communication, etc.) for effective mitigation of multiple hazards.

4.4 Mitigation strategies and considerations

NIST's disaster resilience report (2006) provides detailed insight into types of hazards, vulnerability and risk assessment using forecasting, risk management, loss estimation, retrofitting and mitigation strategies, and provides steps to be taken to be prepared in future. FEMA 543 (2007) design guide recommends incorporating wind and flood hazard mitigation measures into all stages and at all levels of critical structural planning and design. FEMA 530 (2005) Earthquake Design Guide provides a number of methods for identification of retrofitting areas for homeowners, which would also mitigate threats from fires and floods. MCEER and other institutions are currently working towards the establishment of a framework to systematically expand the current AASHTO LRFD into a multiple-hazard (MH)-LRFD for multiple-hazards design of highway bridges (MCEER 2009). Table 4.1 illustrates a summary of current mitigation strategies employed for multiple hazards in the U.S.

Table 4.1. Current Mitigation Strategies for Multiple-Hazards

Mitigation Strategies	Description	Examples
Forecasting	Forecasting specifies in advance the location, size and time of occurrence of a natural hazard.	• SLOSH is used to estimate storm surge heights and wind intensities resulting from historical, hypothetical, or predicted hurricanes (NHC 2003).
Land Use Planning	An effective tool for development of hazard prone areas.	• Coastal Barrier Resources Act (CBRA) protects coastal areas from development and thus limits property damage (FEMA 2010). • Disaster mitigation Act, 2000 makes it mandatory for public sector organizations to prepare multi hazard mitigation plans to eligible for federal funding.
Improved Building codes and standards	Provide minimum design specifications and instructions necessary for new construction and retrofitting.	• International Building Code includes instructions for designing structures for wave and wind load simultaneously (ASCE-7 2010). • National Flood Insurance program (NFIP) has created performance standards for structures in the coastal areas.
Risk Communication and loss estimation	Creating public awareness about the ways a hazard can affect people.	• Building trust among people so that every warning (flood, tsunami, winds) is treated as a real threat. • Local hazard information centers to educate people about multi-hazard risks and mitigation strategies.

Countries around the world that do not have strong economic infrastructure as the U.S. have also realized the need to incorporate the impacts of multiple hazards into mitigation strategies. China, India and Bangladesh have the maximum number of deaths occurring each year from natural disasters in Asia (Office for the Coordination of Humanitarian Affairs 2009). The countries of India and Bangladesh are pestered with cyclones and floods every year which leads to the deaths of a large number of people and other direct and indirect losses. According to Resource Management Strategies Inc. (RMSI), in India, the limited availability of data from past losses makes it difficult to estimate risk and potential losses from hazards of the future. The data that is available is sparse and is not easily accessible. The Vulnerability Atlas of India includes hazard maps and has been successful in helping individuals to take action to reduce risk and also enabling local governments to reduce the community risk through land use planning (RMSI 2009).

Billions of dollars have been spent by developing nations of Asia for disaster risk reduction. From 1960 to 2000 China spent $3.15 billion on flood mitigation which resulted in savings of approximately $12 billion by averting losses. Disaster mitigation and preparedness strategies in cyclone prone Andhra Pradesh, India yielded a cost/benefit ratio of 13.38, and the mitigation strategy of planting mangroves (1994-2001) to protect coastal population in Vietnam from typhoons and storms with an estimated cost/benefit ratio of 52 (International Strategy for Disaster Reduction 2008).

Bangladesh has a total of 2139 miles in coastline\, and 1695 flood control/regulating structures e.g. dykes, embankments, etc. have been constructed. These structural measures included building of bottom vanes screens, cut-offs, intelligent dredging at critical locations, etc. (Hossain 2007). Under the Asia Flood network (AFN), NOAA and USGS have conducted workshops, in 2005, for flash flood forecasting and warning systems, different communication systems, and satellite-based forecasting (U.S. Agency for International Development 2006).

The percentage of number of non-engineered (nonstandard materials and low construction quality standards) structures is almost 80% in developing countries like India, and almost 50% of the current structures under construction do not follow building codes (Government of India 1998). In Vietnam, Mekong Delta Redevelopment Ordinance emphasized design techniques and skills to help train village builders and communities built and retrofit structures against coastal hazards, which included strengthening to keep the roof elements attached together, holding down roof coverings, providing shutters, doors and tying the structure together (ADPC 2002).

A number of research institutes in India, including the Central Building Research Institute (CBRI), have developed cost effective construction technologies through rigorous research. These technologies include traditional methods using traditional materials (mud, stone, bamboo and timber) and also the latest technological methods using professional designers and materials like steel, concrete, etc. (ADPC 2002). Fig. 6.1 shows a typical concrete masonry construction in developing countries of Asia. It shows how the buildings constructed do not adhere to the building codes, and the building has poor construction quality and poor quality materials were used for construction. This increases the vulnerability of the building to hazards or a disaster waiting to happen.

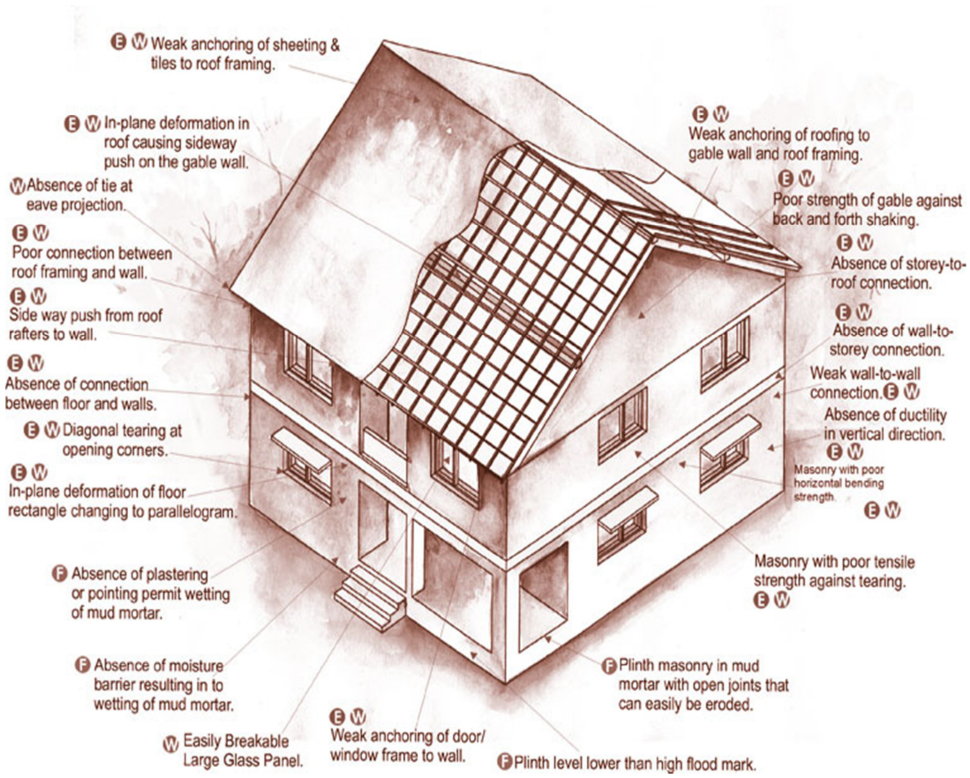

Figure 6.1: Typical Masonry Construction in Asia

© UNDP (2008) ®

Land Use Planning

Land use planning is an effective tool for development of hazard prone areas to reduce the losses caused by the hazards. Land use planning uses technical and scientific data and incorporate them with hazard mitigation techniques to develop design criteria for land in hazardous areas. Fact based hazard assessment is an important part of land use planning. Hazard assessment consist of three which include identification of a potential hazard followed by identification of the regions most vulnerable to the hazard and in the end, risk analysis for the damage that can be incurred to both life and property from the hazard.

To investigate the effectiveness of land use planning on mitigating loss and the same building is considered and now is constructed further off the coast to increase the elevation by 1m, 1.5m, and 2m, or that it is raised from the original elevation of 1m. These increases are in addition to the assumption that the structure is constructed at 1m above the sea level at high tide which was used throughout this report. Table 5.2 presents the loss estimation (wind, surge, and combined) for various increases in elevation and for the original elevation. From the table it can be seen that increasing the elevation has a significant impact on the loss estimations, as the 3m elevation has the lowest combined loss, as one would expect. The information provided in the table 4.2 can be used by homeowners to decide the height to which they want their building to be raised or to be rebuilt at. Thus incorporating land use planning with design considerably reduces losses from hurricane and can be used in actual practice.

Table 4.2: Combined Loss from wind and surge for the various building elevations

Elevation from sea level	1m (original structure)			2m			2.5m			3m		
Hurricane ID	Wind Loss	Surge Loss	Combined Loss	Wind Loss	Surge Loss	Combined Loss	Wind Loss	Surge Loss	Combined Loss	Wind Loss	Surge Loss	Combined Loss
	Total Cost (Ratio to house value)			Total Cost (Ratio to house value)			Total Cost (Ratio to house value)			Total Cost (Ratio to house value)		
1	0.013	0.230	0.239	0.013	0	0.013	0.013	0	0.013	0.013	0	0.013
2	0.011	0.312	0.319	0.011	0	0.011	0.011	0	0.011	0.011	0	0.011
3	0.015	0.443	0.444	0.015	0.291	0.299	0.015	0	0.015	0.015	0	0.015
4	0.014	0.230	0.241	0.014	0	0.014	0.014	0	0.014	0.014	0	0.014
5	0.008	0.370	0.372	0.008	0.004	0.010	0.008	0	0.008	0.008	0	0.008
6	0.131	0.456	0.498	0.131	0.334	0.424	0.131	0.225	0.320	0.131	0	0.131
7	0.015	0.282	0.294	0.015	0	0.015	0.015	0	0.015	0.015	0	0.015
8	0.019	0.431	0.436	0.019	0.295	0.307	0.019	0	0.019	0.019	0	0.019
9	0.182	0.481	0.571	0.182	0.365	0.504	0.182	0.291	0.435	0.182	0.226	0.385

5 POTENTIAL IMPACT OF CLIMATE CHANGE

The current design and mitigation strategies address the impacts of nature as a stationary process. However, it is evident from numerous global warming and climate change studies that the constructed environment may be affected by climate change through a rising sea level and altered patterns of natural hazards due to enhanced greenhouse conditions in the future (IPCC 2007; Olsen et al. 1998; Schiermeier 2006; Wilbanks 2003). Over the last century the earth has become 0.74 degree Celsius warmer (Carius et al. 2008). Zhang et al. (2010) displayed the trends of increasing frequency and intensity of typhoons due to change in hydrological cycle as a result of global warming, which would continue to increase in the future (Nordhaus 2007). Hazards such as hurricanes, snowfall and heavy precipitation, and floods, are expected to change in magnitude with even a small increase in temperature as a result of climate change (IPCC 2007; CBO 2009). Current design and construction practices may not meet current or proposed building performance requirements warranted by plausible climate change scenarios (AGO 2007; Larsson 2003; Liso et al. 2003), therefore design of new buildings and retrofitting existing facilities should consider this impact. Understanding of the physical climate system has progressed rapidly in the U.S., but the use of this knowledge to support decision making, manage risks, and engage stakeholders is inadequate (National Research Council 2007).

This has led to a growing interest in the potential impacts of climate change on building and infrastructure damage (Stewart et al. 2011; Bjarnadottir et al. 2011; Association of British Insurers 2005; Hansen 2008; McCarthy et al. 2001). A number of risk assessment tools are available to incorporate the climate change effects into development plans, land use plans for the policy makers to create a balance between protection against hazards, structural construction costs and impacts from these costs. Community based Risk Screening Tool for Adaptation and Livelihoods is a tool to help integrate climate change adaptation and risk reduction into community level projects (International Institute for Sustainable Development 2007). SimCLIM is another computer model system used for examining the effects of climate variability and change, over time by describing baseline climates, examines current climate changes and assesses risks at present and in the future (CLIM 2007).

6 FUTURE WORK AND NEEDS FOR RESEARCH

In the past, design and mitigation strategies were often limited to an emphasis on mitigating the impacts of individual hazards. However, such measures may improve the structure's performance to specific hazards, but in some cases may make the structure more vulnerable to other hazards. Therefore, there often exists a trade-off in designing a structure for an individual hazard and leveraging limited resources to optimize design and construction practices. In recent decades a shift towards developing methods to assess and mitigate the impacts of multiple hazards has occurred. This transition has been propelled by the occurrence of rare and extreme events revealing the susceptibility of structures and infrastructure to multiple hazards (either concurrent or independent throughout a structure's lifetime); an evolution in understanding of the hazard exposure of different regions of the country and increased awareness of the potential impacts of a changing climate; as well as a paradigm shift toward performance-based or consequence-based engineering of structures which implicitly necessitates consideration of multiple hazards to which a structure is exposed.

The National Science Foundation (NSF 2008) stated that developing performance-based design approaches for multiple hazards would be a large step toward building a resilient and sustainable civil infrastructure. Although there have been some advancements in the field of performance-based design, there exists a gap between development and actual implementation of the designs. For example, most of the developed performance-based design models and strategies remain qualitative and are never actually used in quantitative terms or along with conventional design (Aktan et al. 2007).

The MCEER (2007) symposium emphasized the need for resilience towards multiple hazards in the future and identified needs. Bruneau proposed a 4R (Robustness, Redundancy, Resourcefulness and Rapidity) approach towards enhancing the disaster resilience of the communities through multi-hazard engineering (MCEER 2007). King (MCEER 2007) discussed the need to develop methods that incorporate changing probabilities of occurrences of the multiple hazards and their consequences. Additionally, the Consequence Based Engineering approach concentrates on the consequences of the hazard and the mitigation strategies employed (Abrams 2002), emphasizing impacts ranging from damage to socio-economic effects. This framework offers an alternative lens through which multi-hazard mitigation can be evaluated, yet its application to integrating different hazards has been limited to date.

Even with the recent advance of performance-based engineering approaches and complementary multi-hazard perspectives, improvement of building codes and development of new mitigation strategies, constructed facilities remain vulnerable to threats from multiple hazards at large. Changing climate and natural degradation (deforestation), population growth and excessive land use, has exacerbated the impact of hazards and is only expected to rise in the future (Oberoi and Thakur 2005; IPCC 2007). Future research to address the aforementioned knowledge gaps and promote a transition to practical implementation is central to mitigate the effects of multiple hazards in regions susceptible to exposure and damage from different threats.

7 CONCLUSIONS

This report provides examples of damages realized from multiple hazards, and provides an overview on the different perspectives of multiple hazards. Experimental tests performed to assess damages, to validate new designs and to evaluate the performance of structures are discussed. A review of current risk assessment methods, design and mitigation strategies for multiple hazards are summarized. In addition, potential impacts of climate change on natural hazard patterns and building/infrastructure damages are presented.

Despite the stringent building codes and advanced warning systems, the 2011 earthquake and tsunami in Japan caused unprecedented damages, deaths and economic and societal losses. This type of event underscores the importance of multi-hazard mitigation and the challenge of designing and building structures capable of withstanding the impact of such an event in a technically sound and cost-effective manner.

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