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Overcoming Barriers to High Performance Seismic Design Using Lessons Learned from the Green Building Industry

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OVERCOMING BARRIERS TO HIGH PERFORMANCE SEISMIC DESIGN USING LESSONS LEARNED FROM THE GREEN BUILDING INDUSTRY

by

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written by Dorothy Glezil
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Dr. Abbie Liel

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Dr. John McCartney

Date_______________

The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.

ABSTRACT

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Overcoming Barriers to High Performance Seismic Design Using Lessons Learned from the Green Building Industry

Thesis directed by Associate Professor Abbie Liel

Earthquakes are one of the most destructive natural hazards. A large moment magnitude earthquake may last only a few seconds, but leave communities and economies recovering for decades or longer after its occurrence. A movement toward seismically resistant design began to emerge in the early 20th century, NEHRP's Provisions today currently governing conventional seismic resistant design. These provisions, though they ensure the life-safety of building occupants, extensive damage and economic losses may still occur in the structures. This minimum performance can be enhanced using the Performance-Based Earthquake Engineering methodology and passive control systems like base isolations and energy dissipation systems. It has been shown that, with an enhanced performance, the cost of damage repair, loss of lives, and building downtime are reduced.

Even though these technologies and the PBEE methodology are effective reducing economic losses and fatalities during earthquakes, getting them implemented into seismic resistant design has been challenging. One of the many barriers to their implementation has been their upfront costs. The green building community has faced some of the same challenges that the high performance seismic design community currently faces. Even with all the many market barriers that green development has faced since its inception, the industry has seen an exponential growth in the number of LEED building registrations.

The goal of this thesis is to draw on the success of the green building industry to provide recommendations that may be used overcome the barriers that high performance seismic design (HPSD) is currently facing. The assumption is, since the solutions used to diffuse the innovation of the high performance green buildings have been shown as effective, and since both industries face the similar implementation barriers, if these solutions have worked for the green industry, they may work for the earthquake community as well.

DEDICATION

I dedicate this thesis to God; my parents, Denise and Adrien, who have always supported my choices and encouraged me to be the best that I can be; my siblings, Rachel, Pierre, Adrien, Caroline, who have kept their hands at my back, pushing me forward; and my two friends, Dan and Mike, who have taught me so much.

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I would like to also acknowledge Dan, Mike, and Bianca, my three friends. Without their support, I may not have been able to complete this degree. In my times of frustration, they have lent me their ears, and have been my advisors and tutors.

I would like to recognize and thank Mr. Sam Johnson from the StarSeismic Corporation. He has given me great insight into the industry of buckling-restrained braces (BRB) and how clients view the LEED rating system. He has also provided the data that was used to create the graph of the rate of use and current market for these BRBs.

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PREFACE

Since the establishment of the U.S. Green Building Council in 1993 and LEED in 2000, the emergence of environmental sustainability through green building design has been effective in capturing both the public and the media's attention (ATC-71, 2009; Mayes, et al., 2011). The green building revolution has been instrumental at getting state legislatures to require that steps be taken toward reducing building energy consumptions and sustainable use of resources, reducing construction waste generated by the built environment, and promoting the use of local materials in construction. The green building movement is seen as a "significant force of change in the building design process" (ATC-71, 2009), "fostering a new ethic for developers, consumers, and building suppliers" (May, 2007). As a result of this new ethic, a new market for green construction has emerged (May, 2007) and the general public is conversant in the idea of green buildings.

Although a case could be made that green building designs could do even more to achieve environmental sustainability and create a greater impact on conventional construction, it is clear that, in a relatively short time, the green building movement has brought significant changes to design and construction practices. These changes have occurred despite barriers in the form of high initial upfront costs, lack of information about costs and benefits of green buildings, and lack of incentives.

At the same time, tools have been developed to promote high performance seismic design (HPSD). In HPSD, building designs are directly related to their expected or predicted performance when subjected to seismic forces; in other words, these buildings meet or exceed seismic code requirements in creative ways. Various techniques and technologies are presently used to accomplish a higher performance in seismic resistant design of buildings. The performance-based earthquake engineering methodology, seismic isolation, and passive dissipation systems are techniques and technologies used to enhance building performance. The identified barriers to high performance seismic design are comparable to those that the green industry has faced, with the same challenges with the high initial first costs, and the public perception of that the risks are not as significant as they may actually be, and the associated consequences. In the instance of green design, these risk and consequences are associated with the built environment and its effect on the natural environment. In the case of seismic design, these risks and consequences are related to earthquake events and their consequences on local economy and life-safety.

This research aims to draw on the successes of the green building industry to understand what lessons learned may be applicable to the high performance seismic design industry. Given that these barriers in both cases are fundamentally based on upfront costs, risks and perception of risks, the goal of this comparison is to draw on the success of the green building industry and use the solutions that have been used to overcome some of the similar challenges that high performance seismic design currently faces, and present some recommendations that may be used as solutions to these challenges.

One of the purposes of this thesis is to document the many successes of the green building industry. At the inception of the LEED rating system in 2000, there were only 50 known sustainable buildings built and rated in the U.S. 13 years later, there are over 16,000 rated green buildings worldwide, with over 14,000 located in the US (USGBC , 2013). This growth has been particularly strong since the development of various incentives programs in many states in the US, which has contributed to a yearly increase of 15% to 44% across the US. Despite the many barriers to high performance green buildings, the primary one being the real and perceived upfront premium of green construction, these incentives, along with the USGBC's aggressive advocacy and coalition programs to disseminate information about LEED to the public, the industry has and continues to thrive.

Another goal of this thesis is to compare and recommend solutions that could be used to diffuse the innovations of high performance seismic resistant design (HPSD) using the green industry as a model. One of the main lessons learned from the green industry is its coalition efforts. The green building industry has strong ties to many states, local and federal governments, one of latter being the US Department of Energy. The industry has partnered with high ranking organizations in both the private and public sectors. With these ties, policy implementations in favor of green buildings have received strong backing from government officials. The earthquake community needs similar partnerships. With strong government backing and public/private partnership, as is seen with the green industry, implementing the PBEE methodology into mainstream seismic resistant design could be achieved. The use of PBEE will tend to promote the high performance techniques and technologies.

The contents of this thesis are divided in two parts. In Part 1, the green building industry, its successes, challenges, and solutions used to overcome these challenges, is presented. Chapter 1 and 2 in Part 1 in this report seeks to illustrate the trajectory of the green building evolution; high performance green building designs; the emergence of the US Green Building Council and the LEED rating system; and the present market for green building across the US. Chapter 3 provides costs and benefits of green buildings, the challenges to the green building innovations, and the solutions that are presently used to overcome these barriers.

The current state of high performance seismic resistant design and its challenges are described in Part 2. Chapters 4 and 5 outline the evolution of seismic design, the limitations of the current practices, and the current HPSD techniques and technologies. In Chapter 6, the barriers to HPSD are described, along with some industry leaders’ and the author’s recommendations on methods of overcoming these barriers. Chapter 7 provides a systematic comparison of the green and earthquake industries, and further lists a series of recommendations based on the lessons learned from the green industry.

CHAPTER 1: INTRODUCTION TO GREEN BUILDING DESIGN

1.1 THE GREEN BUILDING REVOLUTION

At the inception of the animated tale *The Lorax*, the walled city, Thneedville, was depicted as a city where everything therein was plastic. The city contained no living trees, plants or shrubs. The plants that populated the city were battery operated. The level of energy consumption and contaminants emitted into the atmosphere for all the structures in the city was incredibly high. As a result, the government began manufacturing and selling clean air in bottles to the citizens of Thneedville. As could be imagined, the more factories that were erected to provide clean air, the more contaminants were emitted into the atmosphere, worsening the existing conditions. The world's environmental problems of today, as a result of the built environment's contribution to the depletion of earth's non-renewable resources, could be compared to those in the fictionalized tale of Thneedville. This chapter will aim to outline the existing environmental problems caused by the built environment, and the spur of the green revolution and the emergence of high performance green building designs.

The built environment has a direct and long-lasting impact on the biosphere. In the United States, the design, construction and management of structures uses 6 billion tons of materials extracted from the Earth annually. Although the construction industry only represents 8% of the US gross domestic product, that sector uses over 40% of all raw materials and consumes approximately 30% of the national energy for its operation (Kilbert, 2008). Ninety percent of all materials extracted from the earth currently reside within the built structures of today (Kilbert, 2008).[1]

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[1] The remaining 10% of materials ever extracted from the earth reside in other man-made items such as automobiles, electric rail cars, jewelry, and other items that their mention herein are outside the scope of this report.

The built environment, due to its enormous scale, requires that it occupies a significant portion of the earth's available surface, and in certain cases, the oceans. The built environment, during its lifetime, typically measured over a period of 100 years, "consumes energy, water and other materials" exhumed from the earth, and "emits solids, liquid, and gas contaminants" (Kilbert, 2008). In many instances, the existing natural systems are replaced by man-made landscapes which never truly resemble the natural systems which were there before. In the end, these built structures impart large amounts of contaminated matter to the environment, about "0.4 to 0.5 tons per capita per year in industrialized countries" (Kilbert, 2008).

The World Meteorological Organization (WMO) in a 1988 assessment concluded that human activities have induced a change in the global atmosphere resulting in climate changes. The average climate changes observed globally varies between 1.2 plus or minus 0.4 degrees Fahrenheit from 1900 to 1988 (Garman, 2011). The sudden shifts in temperatures have resulted in violent and destructive storms, glaciers melting, destructive earthquakes (EPA, 2002). In some cases, those natural disasters often impact the local, national and global economies, thus altering and reducing the quality of life.

Furthermore, building construction and operation materials and chemicals have been observed to reduce the ozone layer (Kilbert, 2008). The layer has been gradually depleting during the past 100 years. This is caused primarily to gases emitted into the environment like the gases chlorofluorocarbons (CFCs) used in refrigeration. In addition to climate changes and ozone layer depletion, deforestation and soil erosion have become a concern. The forests, covering 1/3 of the earth surface, have been now reduced to about 50% of that amount. In the US alone, only about 2% percent of "original forest cover" remains (Kilbert, 2008). Without the aid of forest, climate changes and other global warming effects are accelerated.

In short, the human race has put a strain on earth’s natural ecosystems and is now considered hazardous to many other species on the planet. There are doubts as to the planet’s ecosystems’ ability to sustain life for the future generations. Many of the wetlands, forests, sea and plant lives, as well as other habitats which are able to recycle air and water have been deemed “irreparably” damaged (Radford, 2005). Robert Watson, British Chief Scientist at the World Bank, stated that, because of the many needs of the current world population for nutrition, water, fuel, more than 24% of earth’s surface has been claimed for agriculture and other forms of material harvesting (Radford, 2005). Watson’s study shows that that percentage has exponential increased by 60% since the 18th and 19th centuries (Radford, 2005).

With 6.7 Billion people presently living on earth, a number that is predicted to increase to over nine billion by the year 2050, the natural resources will continue to be depleted. It is imperative that a transition to a “new order of things that can be sustained within the limits of the natural systems” (Kilbert, 2008); the built environment represents an opportunity to make this transition. The green revolution, the systematic, global shift in tendencies and actions toward sustainability, relies on the analysis and management of the Earth’s natural resources. This transition requires that, not only the end results, the structures, are addressed accordingly, but all the interrelated parts, such as the design, construction and maintenance are considered as well.

1.2 DEFINING GREEN BUILDINGS

Since the built environment has negative impacts on the natural environment, enhancing modern structures will improve the environment while benefiting humans and the community. High performance green buildings are structures whose designs are tailored to the "local climate, site conditions, culture and community in order to reduce resource consumption, augment resource supply and enhance the quality and diversity of life (Karolides, 2011)."

By developing the built environment such that the structures are self-sustaining, humanity ensures that the needs of the current generations are met without precluding the future generations from meeting theirs. Consequently, the design of green buildings is not an application of better design intentions, nor an assembly of environmental components. It is however a process through which designers and owners consider the built environment and the natural ecologies not as unrelated parts. Green Building design is an "integrated conversation involving programming intentions, locality, energy systems, controls, materials, water and form" (Kilbert, 2002). The former requires the analysis of issues such as "site and climate considerations, building orientation and form, lighting and thermal comfort, systems and materials, and optimizing all these aspects into an integrated design" (Karolides, 2011). The integrated design approach, important in the conception of the green buildings, requires the cooperation of the clients, designers and construction team in order to achieve the sustainable goals. The green measures cannot be added as an afterthought, but must be integrated within the building design from the inception of the design process. Attempting to add sustainable design components after the structure's initial design has already been drafted is usually the source of a significant cost increase. A high performance building, derived from an integrated design, seeks to:

i. Reduce consumption of and reuses natural resources
ii. Strive for energy efficiency via the use of renewable energy systems
iii. Efficiently use water
iv. Enhance its design
v. Offer health comfort to its occupants

1.2.1 Selection of Building Materials

One step in the achievement of high performance building is resource efficiency. By definition, resources are any items used in the generation of another. In green building design, some resources are building materials, energy and water. Effective resource production and usage involves using the natural resources in such a way that the impact on existing ecological systems is minimized. Effective resource management is used to eliminate the solid, gas or liquid toxic emission into the atmosphere. With building materials, green buildings are designed with materials that are able to be reused, reduced, and recycled (Kilbert, 2008):

- Reduce materials: This approach involves using the least amount possible of materials when designing structures. Though this approach can seldom be carried out in a structure, because "dematerialize" options may be few due to the building codes mandating a certain minimum for building design.
- Reuse materials: When modifying existing structures, materials removed from the structural or non-structural systems may be salvaged and reused so as to minimize the use or acquisition of new materials. Salvaging materials from existing structures will require systematic deconstruction in lieu of demolition. Once salvaged, some material's reuse can only be in lower applications. For instance,

the reuse of concrete aggregates from recycled sources can only be used as sub-base material, and cannot be reused, in the US, in the generation of new concrete.

- Recycle materials: certain materials in the built environment can be recycled; these include materials that have been recycled by manufacturing plants such as plastic lumber, and materials that have been recycled by consumers in their home applications.
- Local Materials: This approach involves using materials locally available to minimize and eliminate the need for material transportation and its associated toxic emissions. High performance buildings with a LEED rating, detailed in chapter 2 of this report, consider materials local if their points of origin do not exceed a radius of 500 miles.

1.2.2 Renewable Energy Sources as Technologies used in Green Buildings

Fossil and nuclear fuels are considered to be today's primary sources of energy. Since the modern society depends heavily on energy, with the rise in global population, global energy demand has exponentially increased. The global need for energy has increased by 44% over a time period of 40 years, from 1970 to 2010 (Karolides, 2011). This has been primarily due to the increase in the world population and the economic prosperity of countries around the world. With an exponential increase in energy demand, the accompanying environmental effects have also grown at an accelerated pace.

According to a 2002 study, the 80 million buildings in the US emitted 47% percent of all the sulfur dioxide in the US, 22 percent of nitrogen oxide and 38.1 percent of carbon dioxide (EPA, 2002;Kilbert, 2008). Table 1 depicts the non-renewable resource consumptions and resulting CO2 emissions of residential and commercial buildings in the U.S in 2002. The total

39.4 percent of energy consumption reported for both residential and commercial buildings in 2002 resulted in approximately 38% of all the CO_2 emissions, which is close to 50% of all pollutants released into the atmosphere. It can be seen that the built environment is in large part responsible for the current environmental problems; therefore, in order for the world to be able to meet its future energy needs, methods must be developed to minimize non-renewable energy consumptions in buildings. Some methods that could be used in buildings to reduce reliance on fossil and nuclear fuel sources are to begin using renewable energy sources.

Table 1: Green Building Statistics in 2002 (EPA, 2002)

% Total	**39.4%**	**67.9%**	**38.1%**	**12.2%**
Building Types	U.S. Energy Consumption	U.S. Electricity Consumption	U.S. CO2 Emissions	U. S. Water Consumption
Residential	21.5%	34.8%	20.6%	3.12%
Commercial	17.9%	33.1%	17.5%	9.08%

There are many benefits to using renewable energy, one being that the pollution embodied in the operation of the renewable energy forms is less than that of the non-renewable fossil fuels (Dover, 1994). Additionally, many of the sustainable energy sources are based on natural systems, such as wind, solar radiation and water (Dover, 1994). Energy can be generated on site by harnessing and converting power from water, wind and the solar radiation. The energy generated using these technologies are used in green buildings to minimize their use of non-renewable energy consumption. These technologies enable greens buildings to become more energy efficient, develop self-reliance, and minimize the level of pollutants emitted into the atmosphere. Some of these renewable energy technologies are detailed below.

1.2.2.1 Wind Power

Similar to the technique used in sails, wind energy can be captured, and converted into electricity. The vanes of a turbine are linked to a generator; the wind that passes over the blade of the turbine are first converted into a type of mechanical power whose transmission into an electric generator produces electricity. The latter, once generated, may be used directly or stored for later use.

There are two types of wind turbines, horizontal and vertical axis; the most common are the horizontal axis turbines. Horizontal axis turbines are capable of producing 350 kW of electricity, and typically are set up on a wind farm, a large farm with multiple turbines (Michaelides, 2009). Since wind speed increases with elevation, the most effective wind turbines are usually located at the top of the structure which it provides power for; however, due to the current material production available for wind turbines, the height limit which the latter can be installed is 98 feet (Michaelides, 2009). Wind turbines work most effectively in wind speeds greater than 14 miles per hour, and can generate enough to power 600 residences (Michaelides, 2009). The power generated on wind farms can be purchased as "green power". The latter refers to electricity generated by renewable energy sources like wind turbines. Wind turbines belong to a network of possible renewable energy sources that can be purchased by consumers. Approximately 45% of green buildings today purchase green power in lieu of using energy generated onsite (Yudelson, 2008).[2] Data that conveys what percent of these buildings buy electricity generated by wind turbines is currently unavailable.

1.2.2.2 Solar Power

Earth receives an average of 1.73×10^{14} kW of solar radiation power which yields a total annual solar insolation of 5.46×10^{21} MJ. A common method of harvesting solar energy to generate electricity is by means of photovoltaic systems (PV).

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[2] The percentages presented in this section are based on a 2007 study conducted on 2000 green projects, and are used herein to illustrate the market for these green measures.

A photovoltaic system uses cells to convert the solar radiation collected directly into electricity. A photovoltaic cell is made up of two semi-conducting materials. When a photon of energy from the sun strikes an electron near the boundary of these two materials, a “charge separation (Michaelides, 2009)” occurs. Once the electron moves from the photovoltaic cell and into the building, “an electric current in the circuit is produced” thereby generating electricity (Michaelides, 2009). PVs are set up using grid-connected systems, with each panel able to generate a certain amount of kW hour of electricity. Based on a review of commercial and industrial PV grid-connected applications in the US in 2006, 140 megawatt hour of electricity was reported as being generated over a period of 12 months (Yudelson, 2008). PV systems can be used onsite, or in power plants and purchased as green power. Approximately 5% of green buildings use PV systems to generate electricity onsite, and an unknown percentage of the previously mentioned 45% of green buildings purchase green power from PV plants (Yudelson, 2008).

1.2.2.3 Water efficiency

Water is an essential resource. The 80 billion buildings that comprise the built environment worldwide is the cause of over 12 percent of all the water withdrawals from rivers (EPA, 2002). Efficient planning of building hydrology is needed to address the increasing problem of water scarcity. Below are some common methods by which water consumption may be reduced in buildings. In general, inclusion of these techniques in green building design has been seen to provide a 30% water reduction as compared to conventional buildings (Kats, 2003).

One method of conserving water in buildings is by using low-flow rate plumbing fixtures throughout the structure. Since toilets account for approximately one half of all water consumed in a building, replacing all existing toilets with 1.6 gallon per flush models can reduce water consumption by 5,500 gallons of water per person per year (Kilbert, 2008). Similar to toilets, faucets and shower heads can be enhanced, either via electrical controls, or their design, to provide the same quality of flow while using far less water. These green water conservation measures, achieved by means of low-water-use fixtures, are used in nearly 33% of green projects today (Yudelson, 2008).[3] Another method of reducing potable water consumption is by rainwater harvesting. In building applications, rainwater is typically collected at the roof level into storage tanks or cistern, and then used in various building systems such as irrigation, household sinks, and toilet flushing (Kilbert, 2008). These types of water conservation measures are used in approximately 40% of today's green buildings (Yudelson, 2008).

1.2.3 Building Design

In designing a green building, local climates, site conditions, building aspect ratio, orientation, massing, usage and building envelope should be designed such that energy costs of heating, cooling and lighting are reduced. Passive Design is "the design of the building's heating, cooling, lighting, and ventilation systems [by] relying on sunlight, wind, vegetation, and other naturally occurring resources on the building site" (Kilbert, 2008). When designed using the passive design strategy, a green building can be "disconnected" from the actual energy sources, and still be functional because of the daylighting, passive heating and cooling systems, and cross- ventilation. Although passive design is considered climate responsive, it is complex because it depends on many factors such as solar isolation, patterns in humidity, wind strength and direction, the site landscape and vegetation as well the presence of other structures on the site. Passive building design techniques have different applications into different green buildings. For instance, one building may integrate one technique, and none of the others. Conversely,

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[3] The percentages presented in this section are based on a 2007 study conducted on 2000 green projects, and are used herein to illustrate the market for these green measures.

another green building may have all of the techniques integrated into its design. The table bellows lists each technique, and the percent of green buildings that are designed using them.[4] As shown in the table below, the application of each measure varies.

Table 2: Percentage of Use of Passive Design Measures (Yudelson, 2008)

Passive Design Measures	**% of Projects**
High Efficiency Ventilation	35
Daylighting	41
Site Selection (environmentally sensitive areas avoided)	67
Reduction of Heat Island	63
Views to the Outdoors	59

1.2.3.1 Shape and Orientation

When designing using the passive strategy, building should be oriented on an East-West axis such that solar loads received by the building are minimized during the summer months and maximized during the winter months. Consequently, the building will be cool during the hot summer days and warmer during the colder winter months. Additionally, limiting the aspect ratio of the building length to width to 1.0, particularly in North America, will limit the amount of surface area through which temperature can be transferred to building occupants. With an aspect ratio of 1.0, the building geometry resembles a square. In hotter climates, building aspect ratio should increase to create a longer and narrower building. With a narrower building, the designer seeks to reduce the amount of surface area that gets impacted by the heavier east and west solar loads. Thus, the opening on those east and west facades are smaller in sizes whereas the south-facing windows, which receive a varying degree of sun, are covered and or protected by overhangs, shading devices or simply are recessed in the walls (Kilbert, 2008).

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[4] The percentages presented in this section are based on a 2007 study conducted on 2000 green projects, and are used herein to illustrate the market for these green measures.

Changing the aspect ratio and building orientation affects the heating and cooling energy demands in the building. In a 2000 study, five building designs, located in five different cities in Turkey, were simulated to uncover the optimal aspect ratio and building orientation. During the simulation, various building ratios and orientations were analyzed and compared based on their resulting energy demands during the winter and summer months. The energy demand was calculated based on different configurations of the openings in the walls oriented to the north, east, west and south facades. Five ratios were compared against the 1:1 building aspect ratio. The results of the energy differentials between all six ratios ranged from 3.16% to 6.3%. For instance, the building located in Ankara, Turkey, when the aspect ratio of 1:1:2 was compared to the 1:1 ratio, the energy demands decreased by 3.7%. Conversely, the energy demand increased by 3.17%, when the ratio was changed from 1:1 to 1:2 (Inanici & Demirbilek, 2000). The energy demands were seen to have a greater change when the orientation and window sizes were changed. On average the energy demands were seen to decrease in the summer months by 50% with the larger windows oriented to the north and to the south during the winter months (Inanici & Demirbilek, 2000).

1.2.3.2 Daylighting

High performance buildings usually utilize daylighting as natural sources of lights. Using the natural light provided by the sun has many benefits: it is free and has been seen to provide physical and psychological benefits to building occupants. Through many studies, daylighting in commercial buildings like stores has been proven to increase sales from 30 to 50 percent, and in schools, the learning rate per student has been shown to increase from 20 to 26 percent (Kilbert, Sustainable construction : green building design and delivery, 2008). Compared to artificial lighting, using natural light is proven to help reduce energy costs by 30% (Kats, 2003) and improve productivity in building occupants.

1.2.3.3 Building Envelope

In passive design, the building envelope is used to control heat gain, conduction, infiltration, and transmission. A building thermal resistance is comprised of the walls, the floor and roof systems. The northern climate zones generally require that walls have a higher thermal resistance than climates in the southern parts of the world. When designing and considering wall systems, the type of wall and insulation should be selected based on the thermal mass received by the building surfaces because of the latter’s orientation. In warmer climates where the building wall systems are light and insulated, shading the facades such that energy is reflected or cross ventilated is important.

In addition to wall systems, windows play an important part in the building envelope in that they admit light into the building, they allow the building occupants the freedom to admit and control how much air enters their space, and they provide resistance to thermal loads. Windows are selected such that the amount of light admitted is balanced with the amount of solar heat gain. There are many types of windows available. Some have low emissivity capability which reduces the amount of heat transferred from the outside to the inside of a building. Other types of windows available may be comprised of a set of double pane glazing with an air cavity. Each window is able to deliver a certain combination of light and solar radiation. It is up to the designer to designate which combination will achieve the highest level of daylighting while balance the amount of radiation received. The roof of a green building is important because of its high surface area and constant exposure to the sun. In certain commercial buildings, roof temperatures have been seen to reach 150°F during the summer. Roof surface materials that have the ability to reflect the sun’s rays are necessary to provide a better interior environment.

1.2.3.4 Occupant health comfort and productivity

Building indoor environment may become contaminated by chemical, organic and particulates come from the outside or as a result of machinery and or materials used within the building. While high performance buildings seek to reduce energy consumption by lowering ventilation rates, the latter may increase exposure to the contaminants produced indoors. Without proper ventilation, these contaminants will remain concentrated within the building envelope. In addition to pollutants, dampness caused by water infiltration may encourage biological growth of mold and other bacteria, which subsequently leads to harsh chemical emissions. Extreme indoor temperatures may have adverse health effects on building occupants, especially the elderly. Improperly designed buildings may have a poor indoor environment. The latter may be harmful to building occupants and may impair their abilities to work and learn. It is important to choose non-toxic materials such that no chemical emission affects the health of those inhabiting the spaces, design the space such that a greater amount of daylighting is received, and provide a balanced thermal environment.

CHAPTER 2: GREEN BUILDING STANDARDS AND CERTIFICATION

2.1 THE U.S. GREEN BUILDING COUNCIL

2.1.1 History of the U.S. Green Building Movement

In the United States, the green building movement traces its roots back to the late nineteenth century (Kilbert, 2008). The 1970's oil crisis and other environmental concerns began to pique public interest in sustainable development. With interest in sustainable development on the rise, the federal government began to encourage green practices by providing tax credits for any solar energy investments and developments, and testing of innovative technologies involving sustainable development. By the end of 1970s, new energy efficient standards were seen in many state energy codes (Kilbert, 2002).

From the 1970s onward, many events were seen to have either directly or indirectly formally shaped the green building industry. In 1987, a group of architects from the American Institute of Architects (AIA) created the Committee on the Environment. That committee was said to have aided in steering professionals within that field toward sustainable design (Yudelson, 2008). The 20th anniversary of the U.S. Earth Day in 1990 and the U.N.'s Earth Summit held in Brazil in 1992 were both seen as contributors to the development of the U.S. Green Building Council (USGBC). These two events indirectly triggered the USGBC's formation in 1993 (Yudelson, 2008).The USGBC, described in the 2.1.2 section of this chapter, developed the one of the green building assessment standards that articulates the parameters for all green building evaluations in the U.S. as well as abroad.

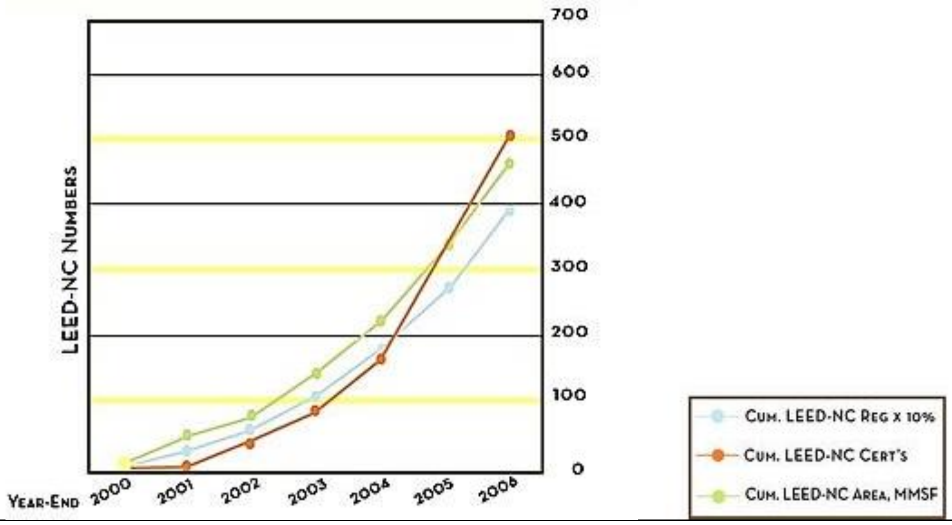
2.1.2 The emergence of USGB Council and the LEED Rating System

Presently, many private and public organizations such as, the USGBC, The Green Building Initiative, the U.S. Department of Energy, the U.S. Environmental Protection Agency, are all actively involved in promoting the implementation of green building principles in modern construction practices. The USGBC, whose main purpose is to transform the build environment into a “more environmentally responsible activity,” (Kilbert, 2008) is comprised of member organizations, not individuals. These members include federal, state and local government agencies; colleges and universities; architects, engineers and construction companies; and companies representing a number of other disciplines that are involved in the building industry (Yudelson, 2008). The USGBC saw a rapid growth from its original 100 member companies to an exponential rise in membership to about 7,700 companies in 2007. With members from all the various disciplines that make up the building industry and the environmental community, the USGBC was able to “craft a consensus standard for evaluating the environmental attributes of buildings and developments (Kilbert, 2008).”

With the endorsement of the US Department of Energy, the USGBC began the development of a rating system that could be used to evaluate green buildings and to help define what a green building represented. In 1995, the first rating system, Leadership in Energy and Environmental Design (LEED), was introduced to evaluate new construction and major renovations. The LEED system was tested through a pilot program in 1998 and 1999 on approximately fifty projects in the United States. The first version of the LEED system was systematically updated and replaced with the second version in March of 2000.

Figure 1 shows the growth of the LEED rated certifications issued between 2000 and 2006. By the end of 2006, the LEED registrations were seen to increase by 67 percent, with a 50 percent increase from the previous year. The graph is evidence that there has been an upward trend in the registrations of LEED projects since 2000. Since its inception, the LEED rated projects grew from the original 50 pilot projects to 16,144 projects throughout the US as of 2013. The number of projects has increased exponentially from the year 2000 to 2013 (USGBC , 2013).

Figure 1: LEED-NC Project Growth from 2000 to 2006 (Yudelson, 2008)



2.2 LEED RATING SYSTEM

2.2.1 LEED and the Green Building Certification Institute

LEED is the green building standard and rating system used by the USGBC to evaluate US commercial, institutional, mid-rise to high-rise residential buildings. LEED is a point-based rating system used to award a Platinum, Gold, Silver and Certified rating to a building based on how many of the predefined criteria in several different categories that the building successfully addresses. This assessment system rates a building's design, construction and operation, environmental impacts, resources consumption, indoor air quality, and occupant health and productivity. Each category has several different units of measurement and is applied at different scales. For instance, environmental impacts are measured on a local, regional, national or global scale, whereas resource conservation and management is measured in terms of mass, volume, energy, parts per million, density, and area.

The LEED rating system is self-assessed, where each design team estimates how many points the building will receive, and submits the documentation for verification to the USGBC. USGBC then assigns it to a third party reviewer that verifies the points and awards the points based on whether the reviewer agrees or disagrees with the points claimed. The first version of the LEED rating system was the LEED Version 1 introduced in 2000. There have been three revisions to the rating system since that date, with LEED 2009 being the version currently in use. LEED version 3 (v3) was introduced by USGBC in April 2009 and requires that all projects seeking registration after that date be verified and rated under the new system. The changes incorporated into the new system are mostly to enhance performance. The credit requirements remained unchanged; however, the point allocations have changed to emphasize the focus on emission reductions and to reflect the modern advancement in green technologies. Another main change that was incorporated into the new system is the Green Building Certification Institute (GBCI). The GBCI is a third-party body and "credentialing authority" (Taylor, 2011) appointed by the USGBC to oversee the certification of LEED projects in 2008.

Since the GBCI took over administering the certifications for LEED 2009, the institute has attempted to improve the LEED certification process. The GBCI has been able to streamline the process to minimize the wait for certification reviews. Prior to the launch of the GBCI, it was common for project teams to wait 3 to 4 months for the return of certification reviews. Additionally, prior to the introduction of LEED 2009 and the GBCI, the certification process was said to be "somewhat subjective" (Thomas, 2011). The USGBC used to hire consultants from the various fields of construction, architecture and engineering to act as third-party reviewers during the LEED certification processes. Biases were often seen from these design and engineering experts when performing the reviews. Since GBCI gained control of the LEED administration, the institute became responsible for selecting and hiring the consultants who would be reviewing the applications. The consultants recruited by the GBCI to perform the reviews are "ISO-certified organizations" that have experience in certifying individual products (Taylor, 2011). These consultants may or may not be professionals in the design and construction of buildings. This change has allowed for greatly improved consistency and quality of the certification reviews.

2.2.2 LEED Rating Procedures

The first steps in earing a LEED certification are to form of a LEED Project Team and to register the project online. The person registering the project with USGBC is automatically appointed the Project Administrator (PA) by the LEED ratings office at USGBC. The PA may be any member of the design team or be a consultant or a firm with experience in LEED registration processes. All PAs must be LEED Accredited Professionals (LEED-AP). The PA is responsible for reviewing and submitting all the project documentations to LEED and to ensuring compliance to all LEED guidelines and specifications. Once the project is registered, the PA then assigns each team member a role; the typical roles are architect, landscape architect, civil engineer, owner, developer and so on. New roles unique to each project may be created at the PA's discretion. Once roles have been given, the PA then develops a project description, and monitors the submission and evaluation process. Since there are certain LEED requirements that must be met prior to a project being certified, projects are only given a rating once the building construction is complete and the building is fully furnished. Once all the technical reviews are performed and points are tabulated, a LEED notification of certification is sent out. The project team has thirty days to accept the certification or file an appeal.

2.2.3 LEED Impact Categories and Point Allocations

Based on the types of construction, all the projects seeking registration are rated using eight different rating systems, four of which are emphasized in this section. The most common rating systems are the LEED for New Constructions (NC), Commercial Interiors (CI), Core and Shell (CS) and Existing Buildings (EB). The dominant rating system is the LEED-NC for new constructions, with 77% of all LEED certified projects falling in that category (Yudelson, 2008). Table 3 describes the type of buildings are typically considered under each rating system.

Table 3: Four Major LEED Rating Systems (Yudelson, 2008)

Rating System	**Coverage**
LEED for New Construction (NC)	New Buildings and major renovations; housing of more than three stories
LEED for Commercial Interiors (CI)	Tenant improvements and remodels that do not involve building shell and structure
LEED for Core and Shell (CS)	New buildings in which the developer or owner controls less than 50% of the improvements
LEED for Existing Buildings (EB)	Buildings more than 2 years old in which no major renovations are contemplated

Each of the LEED rating systems have a different number of points that a project can be awarded. Thus, projects receiving scores from each of these systems can only compared other projects within the same system. Although the total number of points differs for each system, the level of difficulty to attain a LEED rating is the same for all the rating systems. For instance a attaining a Gold rating within the LEED-NC is the "same level of achievement" as attaining the same rating level within LEED-CI (Yudelson, 2008). Since the LEED-NC is the most widely used rating system, it will be used to illustrate the workings of the various components of LEED in this section.

LEED-NC is divided into two sections, the prerequisites and the optional credits. Prerequisites are conditions that must be satisfied for a building to be eligible to certification. These prerequisites are not counted as points. These prerequisites are (Thomas, 2011):

1. Construction Activity Pollution Prevention: This requirement is a construction phase submittal. Proof of compliance for this prerequisite is submitted by the contractor during the building construction. This pollution prevention is governed by the Environmental Protection Agency or the local code requirements, whichever is more stringent.
2. Water Use Reduction Projects: This is a requirement that all projects achieve a 20% reduction in potable water use as compared to conventional buildings.
3. Fundamental Commissioning of the Building Energy Systems: A "commissioning authority" is required to provide the commissioning services on the project.
4. Minimum Energy Performance: All the projects must meet the energy requirement standard 90.1-2007 of the American National Standards Institute (ANSI), American

Society of Heating, Refrigerating, And Air-Conditioning Engineers (ASHRAE), and the Illuminating Engineering Society of North America (IESNA).

5. Fundamental Refrigerant Management: The equipment on the projects must not use chlorofluorocarbon (CFC)-based refrigerants.
6. Storage and Collection of Recyclables: A recycling system for paper, glass, plastics and metals must be established on site for every project during the operation of the building.
7. Minimum Indoor Air Quality Performance: All projects must meet ASHRAE Standard 62.1-2007.
8. Environmental Tobacco Smoke (ETS) Control: Projects must ensure that non-smokers are not exposed to ETS.

Once the project is registered and compliance to all prerequisites is demonstrated, LEED performs various technical reviews to ascertain the project receives the merited point from each of the seven categories in Table 4. The optional credits are dispersed among seven categories yielding a maximum of 71 points; these points may be earned in addition to the prerequisites.

Table 4: LEED-NC Categories (Optional Credits)

LEED-NC 3.0

Categories	**Maximum Points**
1. Sustainable Sites (SS)	14
2. Water Efficiency (WE)	5
3. Energy and Atmosphere (EA)	17
4. Materials and Resources (MR)	13
5. Indoor Environmental Quality (IEQ)	15
6. Innovation in Design (ID)	5
7. Regional Priority (RP)	4
Total Possible Points	**71**

The categories in Table 4 are "impact categories." The USGBC's process of assigning value to each of these categories is by allocating points "to assign to credits that have an association with each impact category" (USGBC , 2013). The USGBC uses a weighting tool to rank and allocate points to each category. The impact categories are ranked based on their "severity, scope and scale, reversibility, contribution of the built environment to the problem, and extent to which LEED currently addresses solutions to the problems associated" with each of the categories (USGBC , 2013). The maximum points shown in Table 4 are the scores received from the weighting tool. The scores provided are always rounded and normalized for the differences in the input factors for each category. The total scores received from the categories determine which level of rating a building receives, as outlined in Table 5.

Table 5: LEED-NC Points Required for Ratings

LEED-NC Ratings	Points Required
Platinum	52-71
Gold	39-51
Silver	33-38
Certified	26-32
No Rating	<25

The points, prerequisites and the submittal phases for each category are shown below. Once the final construction phases have been reviewed, USGBC and the GBCI offer a rating level that, if accepted, will allow the building to receive the LEED "eco-label" (Yudelson, 2008).

1. Sustainable Sites: This category addresses how the designer successful solved the issue of the building environmental footprint using various site strategies such as public transportation access to where building is located, bike storage, parking capacity, maximizing open space, the building storm water design and so forth.

Table 6: LEED-NC Sustainable Sites (Thomas, 2011)		
Description	**Points**	**Submittal Phase**
Prerequisite 1: Construction Activity Pollution Prevention	Required	Construction
Credit 1: Site Selection	1	Design
Credit 2: Development Density and Community Connectivity	5	Design
Credit 3: Brownfield Redevelopment	1	Design
Credit 4.1: Alternative Transportation: Public Transportation Access	6	Design
Credit 4.2: Alternative Transportation: Bicycle Storage and Changing Rooms	1	Design
Credit 4.3: Alternative Transportation: Low-Emitting and Fuel Efficient Vehicles	3	Design
Credit 4.4: Alternative Transportation: Parking Capacity	2	Design
Credit 5.1: Site Development: Protect and Restore Habitat	1	Construction
Credit 5.2: Site Development: Maximize Open Space	1	Design
Credit 6.1: Stormwater Design: Quantity Control	1	Design
Credit 6.2: Stormwater Design: Quality Control	1	Design
Credit 7.1: Heat Island Effect: Non-Roof	1	Construction
Credit 7.2: Heat Island Effect: Roof	1	Design
Credit 8: Light Pollution Reduction	1	Design
Section Total	**26**	

2. Energy and Atmosphere: This category mainly evaluates the building's reduction in energy usage and CO_2 emissions.

Table 7: LEED-NC Energy and Atmosphere (Thomas, 2011)		
Description	**Points**	**Submittal Phase**
Prerequisite 1: Construction Activity Pollution Prevention	Required	Construction
Prerequisite 2: Minimum Energy Performance	Required	Design
Prerequisite 3: Fundamental Refrigerant Management	Required	Design
Credit 1: Optimize Energy Performance	1-19	Design
Credit 2: On-Site Renewable Energy	1-7	Design
Credit 3: Enhanced Commission	2	Construction
Credit 4: Enhanced Refrigerant Management	2	Design
Credit 5: Measurement and Verification	3	Construction
Credit 6: Green Power	2	Construction
Section Total	**35**	

3. Water Efficiency: This category evaluates the building design based on its methods of water conservation and management.

Table 8: LEED-NC Water Efficiency (Thomas, 2011)

Description	**Points**	**Submittal Phase**
Prerequisite 1: Water Use reduction	Required	Design
Credit 1: Water efficient landscaping	2-4	Design
Credit 2: Innovative Wastewater Technologies	2	Design
Credit 3: Water Use Reduction	2-4	Design
Section Total	**10**	

4. Materials and Resources: This category measures the material reuse, recycled content, regional materials and rapidly renewable materials used in the building. Submission for this category is mainly fulfilled by the contractor. The latter is responsible to "plan, procure, demonstrate, document, and submit evidence to support" (Thomas, 2011) the credits received in this category.

Table 9: LEED-NC Materials and Resources (Thomas, 2011)

Description	**Points**	**Submittal Phase**
Prerequisite 1: Storage and Collection of Recyclables	Required	Design
Credit 1.1: Building Reuse-Maintain existing walls, floors and roof	1-3	Construction
Credit 1.2: Building Reuse-Maintain interior non-structural elements	1	Construction
Credit 2: Construction Waste Management	1-2	Construction
Credit 3: Material Reuse	1-2	Construction
Credit 4: Recycled Content	1-2	Construction
Credit 5: Regional Materials	1-2	Construction
Credit 6: Rapidly Renewable Materials	1	Construction
Credit 7: Certified Wood	1	Construction
Section Total	**14**	

5. Innovation in Design: This category evaluates the building on innovative design strategies and performance.

Table 10: LEED-NC Innovation in Design (Thomas, 2011)

Description	**Points**	**Submittal Phase**
Credit 1: Innovation in Design	1-5	Design/Const
Credit 2: LEED Accredited Professional	1	Design/Const
Section Total	**6**	

6. Regional Priority: This category awards points to a project based on its location and are not available for projects outside the United States. For any given project zip code, a total of four point can be awarded as extra credit

Table 11: LEED-NC Regional Priority (Thomas, 2011)

Description	**Points**	**Submittal Phase**
Credit 1: Regional Priority	1-4	Design/Const
Section Total	**4**	

7. Indoor Environment Quality: This category evaluates how a building design addresses indoor environment. The EIQ evaluates a building's air quality, daylighting, thermal comforts and views to the outside.

Table 12: : LEED-NC Indoor Air Quality (Thomas, 2011)

Description	**Points**	**Submittal Phase**
Prerequisite 1: Minimum Indoor Air Quality Performance	Required	Design
Prerequisite 2: Environmental Tobacco Smoke (ETS) Control	Required	Design
Credit 1: Outdoor Air Delivery Monitoring	1	Design
Credit 2: Increased Ventilation	1	Design
Credit 3.1: Construction Indoor Air Quality Management Plan During Construction	1	Construction
Credit 3.2: Construction Indoor Air Quality Management Plan Before Occupancy	1	Construction
Credit 4.1: Low Emitting Materials-Adhesives and Sealants	1	Construction
Credit 4.2: Low Emitting Materials-Paints and Coating	1	Construction
Credit 4.3: Low Emitting Materials-Flooring Systems	1	Construction
Credit 4.4: Low Emitting Materials- Composite Wood and Agrifiber Products	1	Construction
Credit 5: Indoor Chemical and Pollutant Source Control	1	Design
Credit 6.1: Controllability of Systems-Lighting	1	Design
Credit 6.2: Controllability of Systems-Thermal Comfort	1	Design
Credit 7.1: Thermal Control-Design	1	Design
Credit 7.2: Thermal Control-Verification	1	Design
Credit 8.1: Daylight and Views-Daylight	1	Design
Credit 8.1: Daylight and Views-Views	1	Design
Section Total	**15**	

2.3 THE MARKET FOR GREEN BUILDINGS IN THE US

2.3.1 Adoption of Green Building Technologies in the US

The green building industry has seen a “significant expansion” (Yudelson, 2008) since 2000. By the end of 2006, the LEED-New Construction (LEED-NC) registered projects comprised approximately 10% of all the new commercial and institution market with close to 4000 registered projects. As seen in the table below, at the beginning of 2007, the total number of LEED –NC registered projects reached 1,100, representing over 130 million gross square feet of new commercial construction, the highest number ever registered in a single year.

Even with this rapid growth, influenced by the changing public perceptions, the expansion has not been evenly distributed across the U.S. Most of the projects registered with LEED are found on the West Coast, the Mid Atlantic and Northeast. The leading six states where LEED registrations are prominent are California, New York, Washington, Pennsylvania, Illinois and Florida (Table 13). The West Coast states, California, Washington and Oregon, as shown below, has 1.25 times the national average of registered projects per capita (based on the study of 708 projects). These states have over 1/3 of all the LEED registered projects even though they only have about 16% of the US population. This growth for the West Coast states continued through 2013. Table 14 lists the top eight states and their current number of LEED rated projects; the remaining states and their corresponding projects can be found in Appendix A.[5] As shown in Table 14, the state of California LEED projects account for 13.9% of all the projects currently

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[5] The data for these tables was reviewed and tabulated from the USGBC’s 2013 LEED Project Profiles. Since the USGBC lists the LEED projects under more than one project and owner type, in effort to remain consistent, the project and owner type that is listed first for each project was chosen as the principal category. For instance, a project may be listed as being a commercial office, an assembly and a retail space. For simplification purposes, the project was chosen as being a commercial office since that is the type which is listed first. The same method was used in the cases where multiple ownership types appeared in the data columns. Additionally, the project located in Canada and those abroad were not included in the number of US projects.

registered in the US and abroad. Together with Washington, the West Coast states make up 18% of all the LEED Projects.

Although 90.8% of all the current LEED projects are registered here in the US, LEED projects can be seen all over the world, particularly in Canada, Europe, Japan, China, Dubai and Australia. Apart from Canada, the international projects (including Mexico) comprise 8.4% of the total LEED registrations with 1353 projects. The 130 projects located in Canada make up 0.8% of the total.

Table 13: LEED Registrations (All Systems) Per State, as of April 2007 (Yudelson, 2008)
**Based on 3392 US Registered Projects in 2007*

State	2007 LEED Registrations	Percentage of Total Registered Projects	2006 Population (Millions)	LEED Registration /Mil
Washington	296	9%	6.4	46
Massachusetts	184	5%	6.4	29
Maryland	131	4%	5.6	23
Pennsylvania	285	8%	12.4	23
California	813	24%	36.5	22
Colorado	104	3%	4.8	22
Michigan	193	6%	10.1	19
Arizona	114	3%	6.2	18
Illinois	230	7%	12.8	18
New York	338	10%	19.3	17
New Jersey	149	4%	8.7	17
Georgia	135	4%	9.4	14
Texas	203	6%	22.1	8

Table 14: Total LEED Registrations (All Systems) For the top eight states, as of February 2013

States	# of LEED Projects	% of Total
California	2245	13.9%
Texas	932	5.8%
New York	773	4.8%
Illinois	723	4.5%
Florida	722	4.5%
Washington	624	3.9%
Pennsylvania	600	3.7%
Virginia	569	3.5%

The projects currently LEED registered vary in their building footprints, with the largest registered building measuring over 37 million square feet (USGBC , 2013). All the current LEED projects combined represent approximately 20% of the annual square footage built in the United States (Kilbert, 2008). The project types with the largest numbers of LEED registrations are commercial offices. As shown in Table 15, commercial offices made up over 25 percent of all the 762 registered projects registered in 2007.[6] And based on USGBC's 2013 Project Profiles, the market for commercial offices has continued to grow, and now represents one of largest portion of all the LEED registrations, with over 5000 registered projects worldwide (Appendix B).

Table 15: LEED Registrations by project type (All Systems) as of April 2007 (Yudelson, 2008)
**Based on 762 Registered Projects in 2007*

Project Type	**Gross Sq. ft. (Millions)**	**Number of Projects ***	**% of Total Projects**
Commercial	23.9	203	26.6
Multi-Use	24.2	195	25.6
Industrial/Public Works	5.6	28	3.7
Higher Education	4.0	51	6.7
Multi-Unit Residential	3.5	24	3.1
K-12 Education	3.3	32	5.2
Laboratory	2.3	17	2.2
Retail	1.8	19	2.5
Health Care	1.2	14	1.8

The types of ownership for the project types in Table 15 vary from private organizations (for-profit companies), non-profit (universities, colleges, private schools, health care facilities, and many non-governmental organizations), and various government agencies. Table 16 shows a list of LEED certified projected organized by ownership types as of 2007.[7] As evidenced below,

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[6] The same project sampling was used to generate tables 4 and 6.

[7] Although government agencies can own any of the project types shown in Table 15, there are no correlations between tables 15 and 16 where the project types in table 15 correspond in some way to the ownership types in table

although the government-owned projects has been seen to dominate the LEED market since its inception (see Table 17 for more details), representing close to half (44%) of all the LEED-NC projects registered since 2003, in 2007, the government projects only made up 31%, whereas the profit corporations accounted for over 42% of the 762 projects studied. The profit corporations currently account for over 50% of all the projects registered worldwide, with 8832 LEED rated projects (Table 18). Based on the 2012 USGBC tallies, the federal, state and local government involvement in sustainable design has continued decrease, with their projects comprising only 24% of the LEED registered projects in the US and abroad.

Table 16: LEED Registrations by owner type (All Systems) as of April 2007 (Yudelson, 2008)
**Based on 762 Registered Projects in 2007*

Owner Type	**Gross Sq. ft. (Millions)**	**Number of Projects ***	**% of Total Projects**
Profit Corporation	45.3	317	41.6
Nonprofit Corporation	10.6	129	16.9
Local Government	13.4	122	16.0
State Government	9.2	76	10.0
Other	7.2	63	8.3
Federal Government	4.2	40	5.2
Individual	4.9	15	2.0
Total All Projects	**94.9**	**762**	

Table 17: Growth of LEED-NC Registrations by owner type from 2003 to 2007 (Yudelson, 2008)
**Based on USGBC 's April 2007, September 2005, July 2004 and July 2003 Tallies*

Owner Type	**July 2003 Projects**	**July 2004 Projects**	**Sep 2005 Projects**	**Feb 2007 Projects**
Profit Corporation	237	372	579	2532
Nonprofit Corporation	227	345	494	772
Local Government	138	272	441	876
State Government	100	174	260	441
Other	81	142	188	293
Federal Government	51	109	179	324
Individual	7	14	36	129
Total All Projects	**841**	**1428**	**2177**	**5367**

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6. These tables are simply used in this section to illustrate the 2007 trends in LEED registered project types versus project ownership.

Analyzing the data presented in the previous paragraphs in this section, it seems that at the inception of the LEED rating system, the state, federal and local government were actively involved in propagating its support for the system. In light of the consistent growth in the private sector, there are now new potential clients (Yudelson, 2008). The private sector attitude toward sustainable design has changed as can be seen by the rise in LEED registrations for private owners from 26 in 2007 to 55% in 2013 (USGBC , 2013).

Table 18: LEED Registrations by owner type (All LEED rating Systems) as of February 2013
Courtesy of the USGBC

Owner Type		# of Projects	% of Total Projects
Federal Government		1004	6%
State Government		1033	6%
Local Government		1801	11%
Non-Profit Organizations		2200	14%
	Subtotal	*6038*	*37%*
Individual		459	3%
Profit Organizations		8832	55%
Other		815	5%
TOTAL		**16144**	

2.4 LIMITATION OF LEED RATING SYSTEM

Even though there are many benefits to receiving a LEED rating (see section 3.1 of this report), there are however some disadvantages. LEED is viewed by some contractors and designers as being too time consuming. The SunTimes reported that architects and other professionals in the building industry find that LEED registration is too costly. These extra costs, costs to register the projects, extra design and consultation fees to designers and contractors, do not directly add to the building value (Wilson, 2008). In many instances, these designers become too involved in adding on elements to the building design to accumulate more LEED points and obtaining the "green label" (Wilson, 2008). They may or may not care about designing a building that "adds environmental value" (Wilson, 2008).

Another disadvantage is the fact that LEED many view the point allocations in the categories as unequal. For instance, designing bike storage on a project earns the same number of points as installing solar panels (Wilson, 2008). Additionally, some have maintained that LEED points are "skewed toward the ongoing use of fossil fuels" (Lundy Group, 2009). For example, the points allocated to the Energy and Atmosphere category is more than half the total points awarded for the LEED-NC, and half of that number is awarded based on how "efficiently" the building has made use of fossil fuels. Only a total of 9 points are given for using renewable energy sources and technologies (Lundy Group, 2009). The USGBC has shown itself as being very "receptive to change" and has made many changes to LEED. Nevertheless, even with all the changes made, only 2% of individually owned projects are part of the green market (USGBC , 2013). The current data shows that mostly medium to large projects make it to a LEED certification.

CHAPTER 3: COSTS, BENEFITS, AND CHALLENGES TO GREEN BUILDINGS

3.1 COSTS AND BENEFITS OF LEED RATED GREEN BUILDINGS

3.1.1 Up-Front Costs of Green Buildings

Even though there is a general acknowledgement of the environmental benefits associated with green buildings, there is still an issue of high upfront costs as compared to conventional construction. Several studies have compiled data to assess the costs associated with green buildings. Davis Langdon's study and the Capital E 2003 Costs and Benefits Assessment results are two cost-benefit studies detailed in this chapter.

The general consensus on sustainable development is that all green buildings incur a "green building premium" (Kats, 2003). In an attempt to uncover what some perceived this green premium to be, 12 developers were interviewed by the California's Sustainable Building Task Force and reported as part of the Capital E assessment (Kats, 2003). The developers each reported up-front premiums ranging from 10 to 15 percent for green buildings in the state of California (Kats, 2003). Other sources report green premiums to be ranging from 1 to 18 percent (Yudelson, 2008). Despite the many publications by the green building advocates on green buildings, there is little published data on the costs of green buildings as compared to conventional buildings. In a 2006 Building Design and Construction report, 57% of 876 developers surveyed stated that, because of this lack of available data on the costs and benefits of green buildings, this green premium is unjustifiable (Yudelson, 2008). Consequently, with the "market not willing to pay a premium for green buildings," financing this up-front cost becomes a problem for many (Yudelson, 2008). Thus, the issue of a green premium remains the main "prohibitive factor" in implementing green building design throughout the country, as these up-front costs are important to developers (Kats, 2003).

With cost being the main impediment to green development, several studies have been done to prove that there may be no evidence of any cost differences between green and conventional buildings. A 2004 study conducted by Davis Langdon on 138 different building types provided evidence that there is “no statistically significant evidence” that green building initial costs per square footage are more than those of traditional buildings (Langdon, 2004).

The Langdon cost analysis compared the costs per square-foot of 45 LEED-seeking buildings versus 93 non-LEED buildings in the state of California. Each building cost was normalized for location such that when compared to the other buildings the analysis could remain consistent. All the buildings in the analysis were grouped under “LEED-seeking” and “non-LEED” (Langdon, 2004). The difference between the two groups is that the LEED-seeking buildings were designed with the purpose of obtaining LEED certification and the non-LEED buildings were conventionally designed.

Figure 2 shows the results of the analysis. The costs per square foot for all the buildings were ranked from lowest to highest. In Figure 2, the green bars represented the LEED Certified buildings, the blue bars, the non-LEED buildings; the gray lines indicate all the buildings seeking the LEED Silver; and the yellow lines, all the building seeking LEED Gold or Platinum. The ranges of costs for the LEED-Seeking buildings were “scattered throughout the range of costs for all buildings studied, with no apparent pattern to the distribution.” (Langdon, 2004) Using the t-test to analyze the variations among the samples, no significant differences were observed between the LEED and the non-LEED populations. The average costs per square footage estimated are summarized in Table 19.

Figure 2: Cost per Gross Square Footage of All of the Buildings (Langdon, 2004)

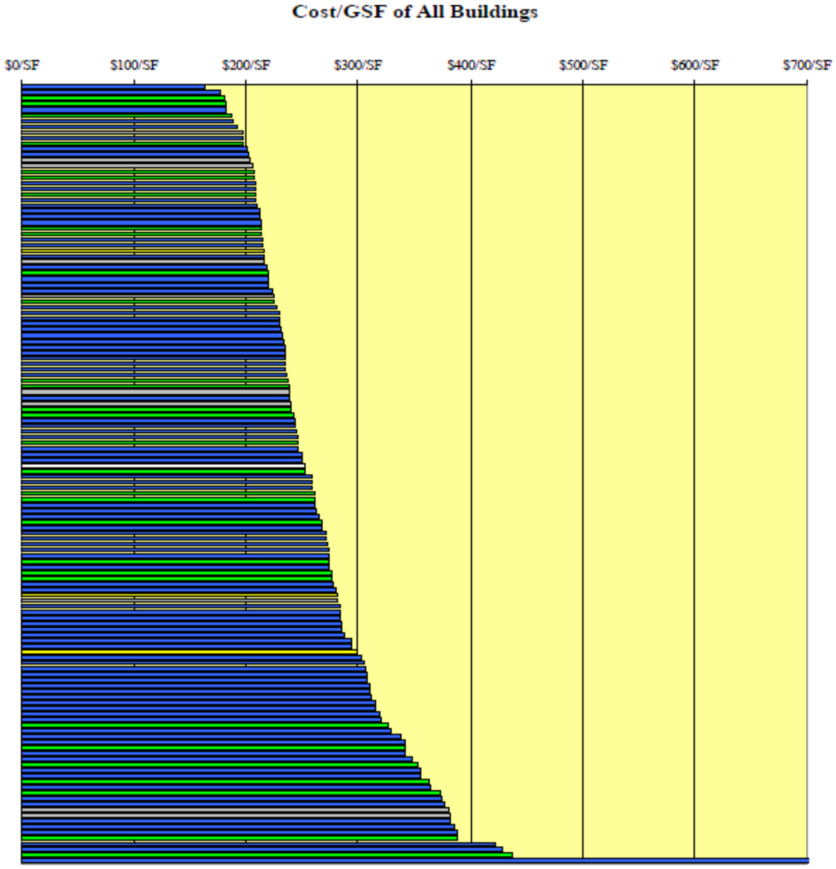


Table 19: Average Costs per Square foot For all 138 buildings (2004 US dollars)

Non-LEED	LEED Certified	LEED Silver	LEED Gold/Platinum
$ 269	$ 282	$ 287	$ 253

After the gross comparison of all 138 buildings, buildings were compared to other buildings of the same type. The university classroom buildings (15 LEED and 37 non-LEED) were analyzed next, with the results shown in Figure 3, and the average costs per square-foot shown in Table 20. The sampling of the academic buildings shown in the figure above did not show the LEED buildings as costing more per square feet than the conventional buildings. No significant differences were observed (Langdon, 2004).

Figure 3: Cost per Gross Square Footage of the Academic Buildings (Langdon, 2004)

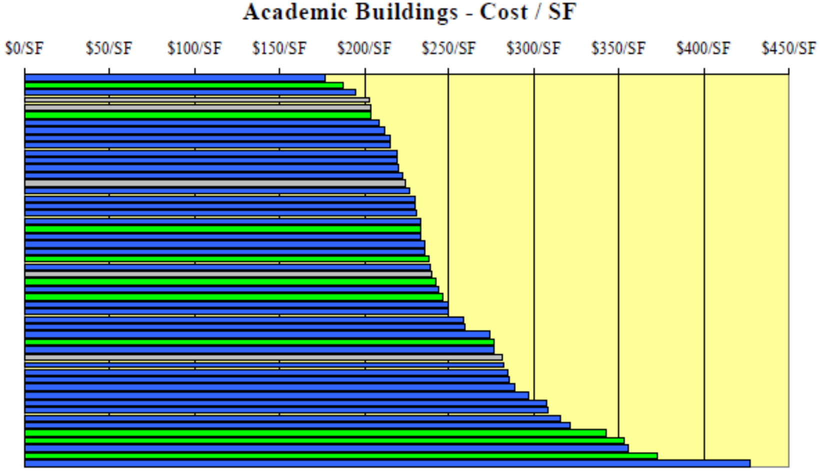
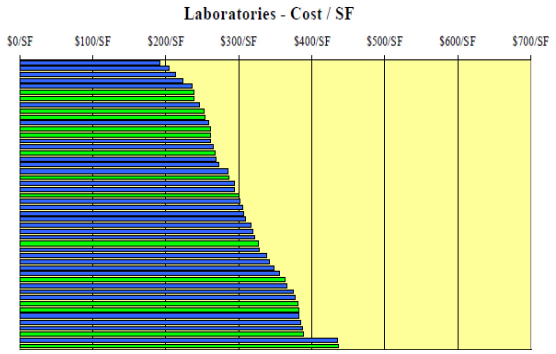
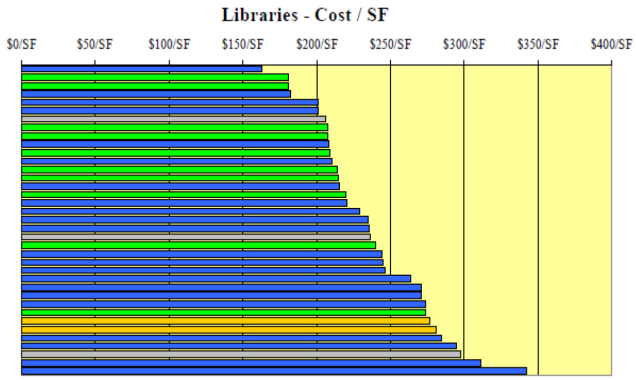


Table 20: Average Costs per Square foot For all Academic buildings (2004 US dollars)

Non-LEED	LEED Certified	LEED Silver
$ 259	$ 269	$ 228

A similar study was made of laboratory (15 LEED, and 34 non-LEED), and library buildings (15 LEED, and 22 non-LEED). Their graphs are shown in Figure 4 and Figure 5. Again, the results showed no significant differences between the buildings studied. In some instances, as seen in the graph for the libraries, some of the conventional buildings examined showed a higher cost per square footage than the LEED buildings within the same sampling.

Cost per Gross Square Footage (Langdon, 2004)	
Figure 4: of Laboratory Buildings (Langdon, 2004)	**Figure 5: Libraries Buildings (Langdon, 2004)**
	

3.1.1.1 Langdon Analysis Conclusions and Limitations

Langdon (2004)'s goal was to disprove the notion that incremental costs associated with green buildings spring from the incorporation of green building technologies and/or principles. The conclusions were that:

1. Many variations in building costs exist, even though the building uses and types are similar. Aside from the program type, the building location, governing design standards, local codes and incentives, climate and building sizes were seen to also affect building costs. The premiums that a building owner would have to pay to upgrade the building in question to the LEED certification level for each one of the factors will increase and decrease accordingly to the building location, climate, and size.
2. Variations in costs were seen for buildings of the same program type and seeking the same LEED rating.
3. Variations in costs were seen for buildings of the same program type for the Non-LEED registered buildings.

The main result of the studies on the 138 different building program types revealed that even without considering sustainability in any building cost assessment, within each building program type, there are vast differences in cost per square footages. Attempting to average the differences in green building costs to compare to those of conventional building cannot be used to "provide any meaningful data…too assess what [the] cost impact might be for incorporating LEED and sustainable design (Langdon, 2004)." Many factors were observed to change the results. Consequently, since no significance differences in costs were observed within each program type sampling, the claim that high performance LEED buildings cost more than conventional buildings could not statistically be substantiated.

Langdon further maintained that the ranges of costs per square footages of the LEED compared to the non-LEED buildings were "within the range to be expected from any random sample of the whole population" (Langdon, 2004). Consequently, Langdon concluded that many of the buildings constructed can achieve the higher performance goals of green buildings within the initially established budget (Langdon, 2004). There are projects, such as the Harvard University Operations Services, a 44,500-square-foot office building, that are able to incorporate sustainable design and achieve LEED-Platinum level with no additional cost (Yudelson, 2008).

Sustainable development does not have to come with an added cost if it is properly integrated into the building design. Therefore, sustainable design should not be an added element in the design of a building but be "embedded in the goals of a project (Yudelson, 2008)." With an integrated sustainable design, many of the buildings that Langdon studied garnered LEED points just from their basic design with no need for additional funding. The few buildings that saw added premium were those utilizing specific green building technologies such as photovoltaics (Yudelson, 2008).

3.1.2 Capital E Green Building Upfront and Life Cycle Cost Assessments

Other cost assessment studies have uncovered that, though there are upfront costs, they can be repaid many times over by the lifecycle cost savings associated with integrating green building technologies and principles in the building design (Yudelson, 2008). In the 2003 Capital E Green Building Cost Assessment completed for the State of California, 33 LEED registered buildings (25 office buildings, and 8 school buildings) were analyzed to assess the ranges of their *upfront* premiums. In the same report, 21 other LEED buildings were analyzed to determine their life cycle cost savings. So the analysis could be comprehensive, the cost per square foot assessment for each building analyzed the costs associated with green buildings by comparing green and conventional designs for the same building. The initial Capital E Cost Assessment sought to prove that the green premiums on those LEED rated building were lower than the perceived 10 to 15%.[8]

Appendix C below lists the 33 buildings used in the Capital E study, the building location, type, date completed, the associated upfront premiums, and the LEED rating sought. (At the time of the study, some of the buildings had not yet acquired the LEED certification level shown). To determine the LEED rating, the architects and engineers of each project did detailed assessments and modeling to predict the resulting LEED standard levels (Kats, 2003).

The analysis showed that, on average, the green building premium does not exceed 2% (Kats, 2003). Table 21 shows a summary of the premiums that each building incurred. The eight Bronze level building premiums from the previous table were averaged to yield a premium that

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[8] Information for this study was collected from interviews with each building architect, and other personnel; communication from California's Sustainable Building Task Force members, USGBC staff, members of the Green Building Valuation Advisory Group; data responses from inquiry in the Environmental Building News.

is less than 1%. The premiums shown in Table 21 are very low cost percentages when compared to the costs of acquiring land and the other building construction costs.

Table 21: Level of Green Standard and Average Upfront Premium Cost (Kats, 2003)

LEED-NC Level	# of Buildings	Premium %
Platinum	1	6.50
Gold	6	1.82
Silver	18	2.11
Certified	8	0.66
AVERAGE PREMIUM	**33**	**1.84**

The conclusions drawn from the Capital E Green Building Cost Assessment were that, though there is an added cost to building green, the premium is much less than is currently perceived and have undergone a “downward trend.” (Kats, 2003) The cost of buildings, because of inflation, rises, however, the upfront premiums associated with sustainable development has been seen to decrease overtime as the building designers acquire more experience. This is evidenced by another analysis done on LEED buildings in Portland and Seattle. The three buildings from Portland, completed in 1995, 1997 and 2000, incurred a green premium of 2%, 1% and 0%. Another recent study shows that, where the Seattle LEED-Silver buildings started at an added premium of 3 to 4%, current LEED-Silver buildings (not included in the Capital E assessment) green premiums have dropped to 2% (Kats, 2003).

Additionally, when compared to the capital building construction costs, this 2 % green premium cost per square-foot, assuming that the cost to build a conventional commercial structure is 150 US dollars per square-foot, is only \$3.00/ft^2. This added cost is minimal especially considering that the amount can be repaid tenfold over the life of the building because of the financial benefits that accompany the green building enhancements as shown in section 3.1.4 of this report (Kats, 2003).

3.1.3 Issues and Limitations in Determining Upfront Costs of Green Buildings

One of the many impediments to green development is the difficulty in determining what these costs are and to quantify them, this may be because there are not many short and long term financial data published about green buildings. This is partly because the USGBC does not require building cost data to be included in the LEED certification submissions; thus, many building owners and developers keep their data unpublished and proprietary. Even with available data, there are many limitations and problems with determining the costs of green buildings (Kats, 2003):

1. Green buildings designed today are often showcase projects. These showcases usually feature costly upgrades and finishes that are not needed for the building to be considered green.
2. Since the green building industry is relatively new, with recent advancements introduced in the last several decades, building designers and firms' projects are often associated with a certain "learning curve costs (Kats, 2003)."
3. The green building technologies in use currently are new; designers use them as conservatively added alternatives. These technologies often can be oversized, superfluous and not properly integrated into the building design.

Moreover, the manner in which building construction costs are reported in recent studies varied for with each source. For instance, certain building owners were reporting fees associated with the designers' fees, consultant, and government fees, as "soft costs," whereas other owners were adding those fees under what they labeled as "Hard costs." With varying methods of allocating expenditures on projects, the final cost results may be inflated and will vary per project (Nalewaik & Venters, 2008). In addition to the cost allocation differences, the data on the cost differences on green buildings compared to conventional buildings vary for each source, as oftentimes, many line items are missing from one report and available in another (Nalewaik & Venters, 2008).

Additionally, the cost assessment methods used to determine the green upfront premiums are sometimes insufficient. These methods often use an average square footage to determine how much impact building green has on the overall building capital costs. With such approach, the actual percentage is inaccurate and may change in value if two different buildings, albeit with the same square footage, were compared. Furthermore, there has been no data gathered on conventional buildings to predict how much such a building would cost if it were constructed using green technologies. Similarly, there is no data available to prove how much a green building would cost as a conventional building. Many of the comparisons made to prove or disprove costs between traditional and green buildings can be manipulated.

3.1.4 Benefits of Incorporating LEED and Sustainability in Building Designs

As shown by studies presented above, sustainability can be achieved with either a small upfront premium or no additional costs if it is integrated into the building design. Whether there are added costs or the project achieved sustainability for the same cost as a conventional building, the improved building designs does offer additional cost savings over the life of the building. The economic and non-economic benefits that building green can provide are summarized in the subsequent sections of this chapter. The Capital E life cycle cost analysis conducted on 21 different LEED rated buildings (also located in California) show evidence that it would be worthwhile to investment in green buildings.

3.1.4.1 Life Cycle Costing

Several studies have revealed that during building design and construction, decisions are usually made from the established budgets and schedules; long term fiscal predictions are seldom examined (Kats, 2003). Consequently, only the short-term costs and benefits are taken into account. Analysis of the initial green premium when compared to the future "recurring, long-term associated benefits and cost by gains in employee productivity, reduction in health and safety costs, and savings from energy, maintenance, and operational costs largely exceed any added initial cost of the green building (Nalewaik & Venters, 2008)."

Those benefits accrued during the life of the building can be estimated using Life Cycle Costing. LCC analyzes the cost and benefits of over the life of a certain system or product, comparing costs and benefits in Net Present Value (NPV) terms. The NPV's represent current and future costs and benefits in "today dollars" that give a Present Value (PV) estimate of future investment values, costs and benefits, less the initial cost of investment. The resulting NPV's are based on benefits accrued over the period of 20 years, an assumption that the benefits will be greatest during the building's first 20 years (Kats, 2003), and on a discount rate of 5%. A 2% rate of inflation was assumed per year.

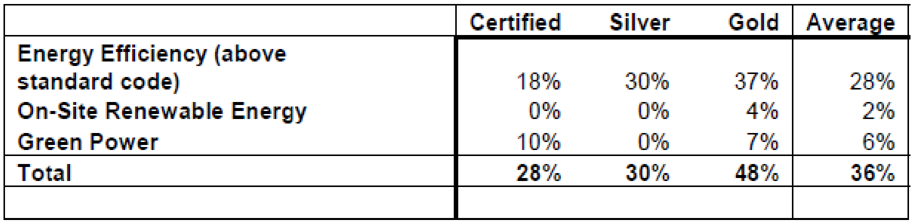
3.1.4.2 Energy Efficiency

As mentioned in section 1.2.2, there are many methods which can be integrated into a building design to reduce the buildings energy consumption and CO_2 emissions. The review of the 21 LEED buildings analyzed compared to conventional buildings revealed that green buildings are more efficient in their energy usage; typically generate renewable energy on site, or purchase "grid power generated from renewable energy sources." (Kats, 2003). Only 2% of the 21 buildings achieved energy efficiency through the integration of on-site renewable energy, and

6%, through the purchase of green power. The remaining buildings were seen to achieve energy efficiency by using energy efficient lighting schemes and systems.

To estimate the net present values of the cost savings associated with being more energy efficient, the study first compared the energy usage of the 21 LEED buildings to conventional buildings of the same program type and size. Based on the result of the initial analysis by the U.S. Green Building Council, it was shown that those 21 LEED rated buildings, on average, use 25 to 30% less energy than conventional buildings. Table 22 shows the results of the energy usage reduction for all 21 buildings. As shown in the figure below, all 21 buildings used an average of 28% less energy than do conventional buildings.

Table 22: Reduced Energy as compared with Conventional Buildings (Kats, 2003)

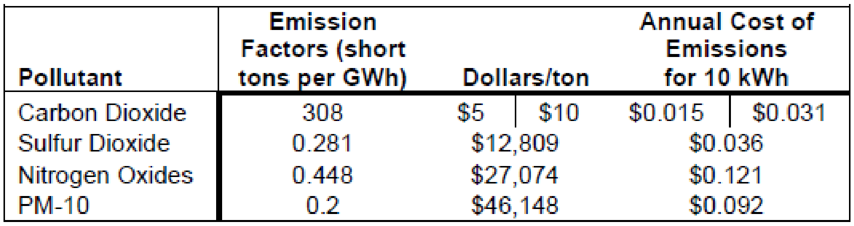


	Certified	Silver	Gold	Average
Energy Efficiency (above standard code)	18%	30%	37%	28%
On-Site Renewable Energy	0%	0%	4%	2%
Green Power	10%	0%	7%	6%
Total	**28%**	**30%**	**48%**	**36%**

With the energy usage percent reductions known, a subsequent analysis was conducted to predict the associated annual cost savings. Using California's utility tariffs and the energy consumption data during and off peak periods, the future energy costs were estimated. Based on the average price per kWh of energy during those times, plus the 5% discount rate, a net present value was calculated to estimate the cost savings of each kWh saved. The LCC present value average energy cost per square-feet per year was estimated to be \$0.44/ft^2/year. This yielded a 20-year PV of \$5.48/ft^2/year. Additionally, since green buildings have also been seen to reduce peak power demands by 15%, an additional cost savings was calculated to be \$0.025/ ft^2/year, with an estimated 20-year PV of \$0.31/ ft^2/year. Together, the total 20-year present value saving is \$5.79/ ft^2/year. The energy savings alone have been seen to offset the initial premium cost, thus rendering building green “cost-effective” (Kats, 2003).

In addition to the economic benefits estimated above, there are non-economic benefits to being energy efficiency. The 30% reduction in energy has been shown to result in a 36% reduction in pollutant emissions (Kats, 2003). In order to quantify the savings associated with this 36% emission reduction, a cost value was assigned to the common pollutants such as nitrogen, sodium and carbon dioxide. The California Board of Energy Efficiency (CBEE), in their 1992 electricity report, developed “damage functions (Kats, 2003)” to measure the impacts of these contaminants on human health, and the environment. Following their analysis, emission market values for these three pollutants were tabulated to yield an estimated annual cost in dollars per ton (Table 23).

Table 23: Estimated Annual Costs of Pollutants Per Square feet (Kats, 2003)

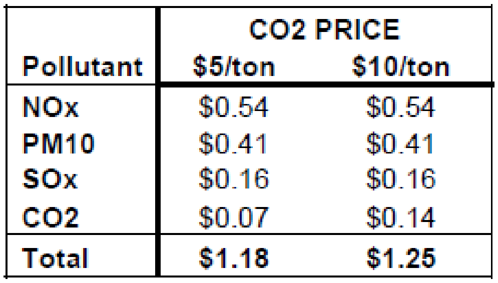


Pollutant	Emission Factors (short tons per GWh)	Dollars/ton		Annual Cost of Emissions for 10 kWh	
Carbon Dioxide	308	\$5	\$10	\$0.015	\$0.031
Sulfur Dioxide	0.281	\$12,809		\$0.036	
Nitrogen Oxides	0.448	\$27,074		\$0.121	
PM-10	0.2	\$46,148		\$0.092	

With the cost in dollars of each of these pollutants known, further analysis was done to determine the resulting cost savings. Several studies have been published attempting to quantify the associated savings, in dollars per ton. It is difficult to know what the “right” price for these pollutants is, especially carbon since the price of carbon pollution is widely perceived to get more expensive as the future market demand grows. In addition to the upward market trend of carbon prices, the range of prices assigned to carbon by many of analysts, policy makers and emissions trading markets vary from $8 to $120 per ton. For the purpose of estimating the NPV's of cost savings, the analysis conservatively assumed a range of $5 to $10 per ton.

Assuming that buildings use electricity at a rate of 10 kWh/ft^2/year, a rate calculated based on the California tariffs, Table 24 shows the 20-year present cost value of the 36% reduction in emissions of the four contaminants shown below (Kats, 2003). With a carbon value of $5 per ton, the $20-year present value saving is $1.18/ft^2/year (Kats, 2003).

Table 24: 20-Year PV of 36% Pollution Reduction per Square-Feet (Kats, 2003)



	CO2 PRICE	
Pollutant	**$5/ton**	**$10/ton**
NOx	$0.54	$0.54
PM10	$0.41	$0.41
SOx	$0.16	$0.16
CO2	$0.07	$0.14
Total	**$1.18**	**$1.25**

3.1.4.3 Water Conservation

Sustainable development can also be achieved through incorporating water efficient design principles. These methods were elaborated at length in chapter one of this report. For convenience, these strategies are repeated here:

- Integrated design and efficient use of potable water
- Graywater collection and use in building plumbing and irrigation
- Storm water collection for use
- Reclaimed water for use

Use of these strategies in green building design have been seen to reduce water by 30% when used indoors only, or over 50% when used for landscaping as well (Kats, 2003). Based on the assessment of the 21 LEED rated buildings aforementioned, 20 of those buildings have water efficient landscaping integrated in their building design. 17 out of the 21 used non-potable water for irrigation. 50% of the 21 buildings examined, through effective water management, were seen to cut indoor water use by 30%.

There have been many studies that have attempted to estimate the cost savings associated with water conservation. Although the Capital E literature reviews done for those studies show that there are costs savings associated with water reductions in buildings, there are many complexities associated with estimating the true marginal cost of water because of all the uncertainties in predicting future water cost, regional differences in water costs and the “unpredictable political landscape” (Kats, 2003). Marginal water costs, to be accurate, would have to be determined through regional assessments per state for a specific period of time.

Several such studies, not mentioned in this report, have been conducted for several regions of California. The 20-year NPV savings of \$0.51/ft^2/year reported in Capital E the analysis was based on the marginal costs calculated for these areas. Since an average cost savings is difficult to be estimated, data from each region of each state has to be analyzed so that a more accurate water cost saving to be determined.

3.1.4.4 Enhanced Productivity and Health

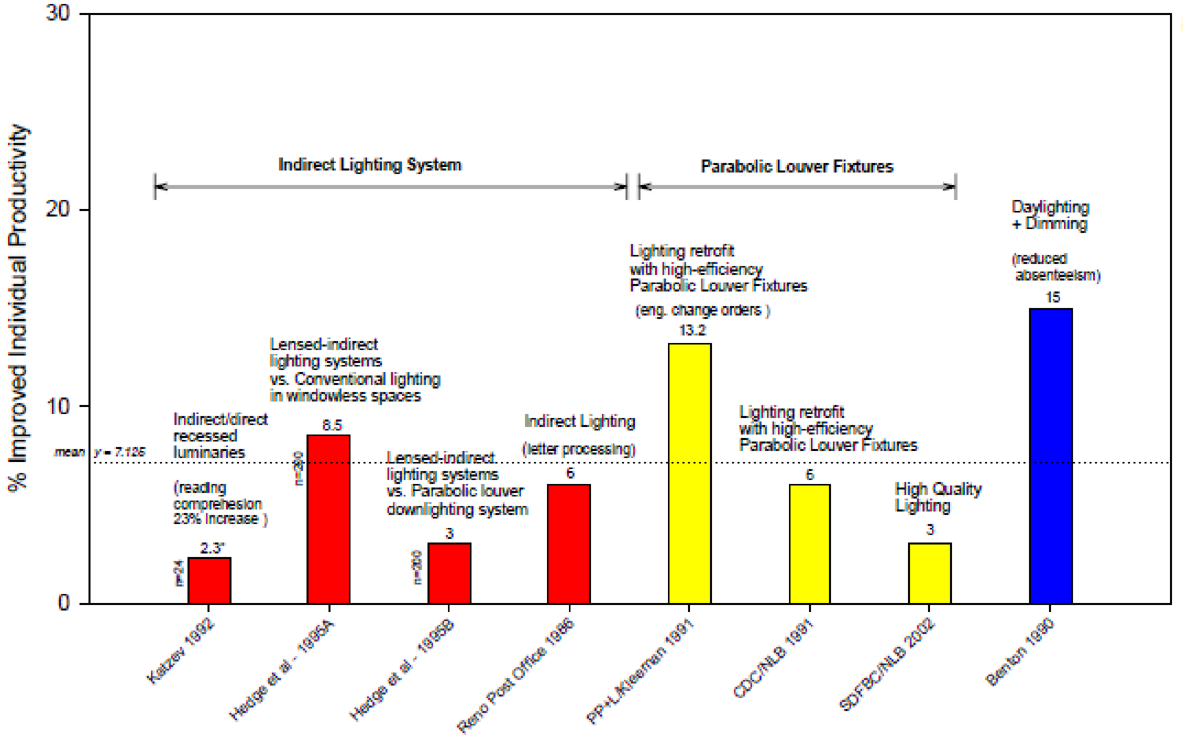
Since green buildings designs differ from one another, there is no set process that can be used to determine the level of productivity and health improvements that each green building can induce. The average percentages of productivity gains reported by the Carnegie Mellon University (CMU) with collaboration with the Center’s Building Investment Decision Support (BIDS) are summarized in this section.

The BIDS has compiled data on several studies done to estimate the percentages of productivity improvement of green buildings and their associated benefits. The BIDS data set included 95 studies which reported the results of several "controlled laboratory studies" that measured the accuracy and speed at which the test subjects completed a set of varying tasks like "typing, addition, proof reading, paragraph completion, reading comprehension, and creative thinking" (Kats, 2003).

The studies observed "measured benefits" ranging from 0.5% to 34% when tenants have increased control over building ventilation, temperature and lighting, (Kats, 2003). These benefits were quantified with various measures of worker productivity that depended on the study, for example, the ability of workers to process engineering change orders quickly. With these benefit percentages, the average annual gain in workforce productivity calculated when tenants have lighting control was 7.1%; productivity gains with an increase in ventilation and thermal control were estimated to be 1.8% and 1.2% respectively (Kats, 2003).

Out of the 95 studies, eight studies measured the correlations between increased control over lighting and productivity gains. The results are summarized in Figure 6. In the graph below, the studies and years are shown on the x-axis and the increase in improvement levels observed in that study is shown on the y-axis; the red bars represent the four studies that measured productivity improvements associated with indirect lighting systems versus conventional lighting; the yellow bars indicated the results of 3 studies that measured the levels of productivity improvement gains from parabolic louver systems; the blue bar represent the level of productivity improvements from daylighting schemes. The first three indirect lighting studies measured the level of productivity improvements observed with reading comprehension; the last study in that category measured improvements in letter processing levels. The three studies in the parabolic louver systems category measured productivity gains while performing engineering change orders. The last study measured how much daylighting reduced absenteeism. The graph shows a positive correlation between increased control of each lighting system and the level of productivity gained. The range of percentages was observed to fall between 3%-34%, with a mean of 7.1% (Kats, 2003).

Figure 6: Case Studies Introducing Improved Performance with Lighting Control Strategies (Kats, 2003)



Seven studies measured the impact of temperature control over worker performance and shown in Figure 7. Six out of the seven studies measured increases in participant performance levels while performing insurance claims processing, typing, creative thinking, and simple mathematical tests. The seventh study, Bauman et al. (1997), measured the overall occupant satisfaction with an increase in temperature control. The average improvement level from these studies with the tenants able to shift room temperatures as needed was reported as being 1.2%.

Figure 7: Case Studies Introducing Improved Performance with Temperature Control (Kats, 2003)

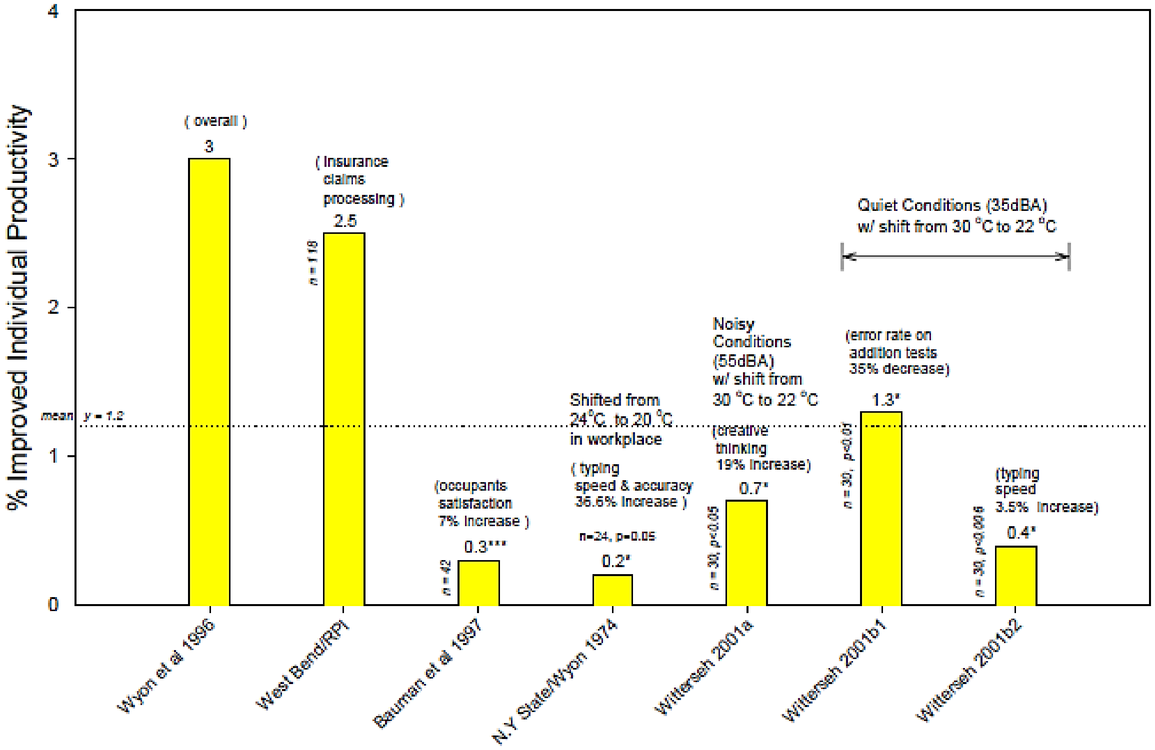


Figure 8 summarizes the result of 13 studies that measured the correlation between an increase of indoor air quality and tenant ventilation control and worker productivity improvements. The first study in the graph below measured an 11% increase in productivity when the tenants have control over the building ventilation. The second two, shown by the yellow bar, measured the improvement levels in tenants' productivity when the ventilation systems help to remove indoor air pollutants. The six studies shown by the red bars measured the productivity levels when outdoor air ventilation is increased in a building. The next five studies measured level improvements from providing "task air;" with the remaining measuring the decrease in absenteeism when ventilation systems have increased filtration capabilities. The improvement levels ranged between 0.5% and 11%, with an average of 1.8%. In addition to the observed direct correlations between increased ventilation, thermal and lighting control and increases in productivity levels of building occupants, there other potential health improvements that may be gained from an improved indoor environmental quality (Table 25).

Figure 8: Case Studies Introducing Improved Performance with Ventilation Control (Kats, 2003)

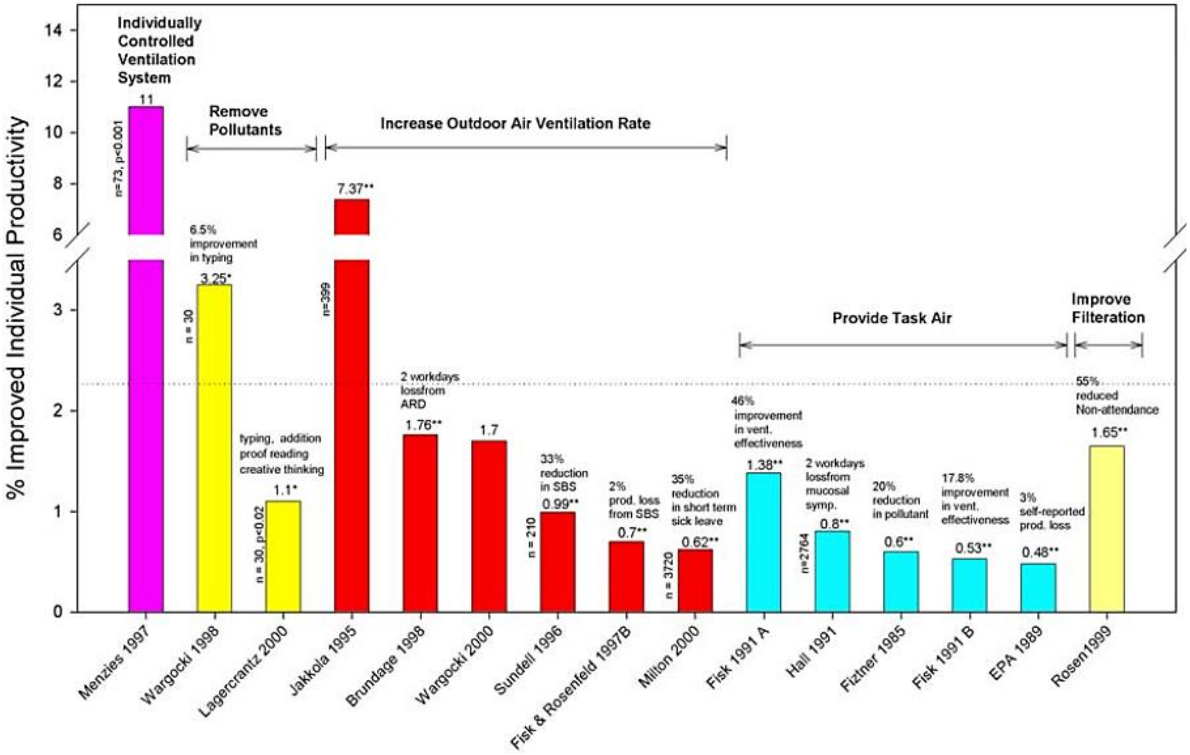
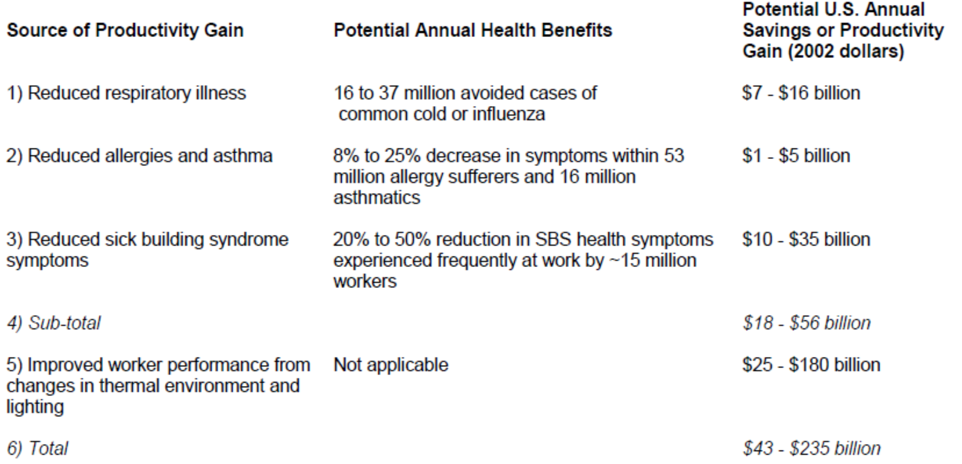


Table 25: Productivity gains from improved Indoor Environmental Quality (Kats, 2003)



Source of Productivity Gain	Potential Annual Health Benefits	Potential U.S. Annual Savings or Productivity Gain (2002 dollars)
1) Reduced respiratory illness	16 to 37 million avoided cases of common cold or influenza	$7 - $16 billion
2) Reduced allergies and asthma	8% to 25% decrease in symptoms within 53 million allergy sufferers and 16 million asthmatics	$1 - $5 billion
3) Reduced sick building syndrome symptoms	20% to 50% reduction in SBS health symptoms experienced frequently at work by ~15 million workers	$10 - $35 billion
4) Sub-total		*$18 - $56 billion*
5) Improved worker performance from changes in thermal environment and lighting	Not applicable	$25 - $180 billion
6) Total		*$43 - $235 billion*

The studies summarized above all observed productivity benefits “across a large population of worker and multiple green buildings.” The conclusion drawn from these studies is such that green buildings are designed to be healthier than conventional buildings because all the buildings studied in those reports have consistently provided ranges of “material, design and operation measures” that help in reducing indoor pollutants that affect occupant health and thereby increase building operation costs; “improve quality of lighting; and increase tenant control and comfort (Kats, 2003).”

The Capital E assessment of the 21 LEED rated buildings did not conduct studies to estimate the ranges of improvement in productivity that these buildings provide, but assumed that a 1% productivity and health improvement gain be attributed to Certified and Silver level buildings, and a 1.5% improvement level gain be attributed to all Gold and Platinum level buildings. With a 1% increase in productivity, the translated cost per square foot is approximately $2.96. Similarly, a 1.5% increase is approximately $4.44 per square foot per year. The 20-year present value of these savings, with the 5% discount rate, are predicted to have present values benefits of $36.89/ft^2 for the Certified and Silver rated buildings and a $55.33/ft^2 for the Gold and Platinum buildings (Kats, 2003).

3.1.4.5 Risk management

In addition to the economic benefits elaborated upon in the previous sections of this chapter, there are other non-economic benefits, like risk management, associated with LEED rated green buildings (Yudelson, The Green Building Revolution, 2008):

- Lawsuit protection because of LEED certification and verification of improvements made to provide better indoor environment.
- LEED certified green buildings get through permitting more quickly upon proof of LEED certification.
- Green buildings are also seen as less risky to insurance companies, and can on occasion receive lower insurance premiums (Yudelson, 2008).

3.1.4.6 Marketing Benefits

Developers, nationally, have become aware of the competitiveness of green buildings in certain markets. Because of their low operating and maintenance costs, green buildings have become more “attractive” to corporate and individual buyers and tenants as more people become educated on green building benefits (Yudelson, 2008). With a LEED certification, the building’s rating is displayed as a public statement of the building’s performance. A high building green building rating typically creates a higher market value due to the building’s low operating costs and enhanced indoor environment (Yudelson, 2008).

3.1.4.7 Capital E Assessment Conclusions and LCC Results

Green buildings have many financial benefits and many market barriers impeding the industry's development, some of which will be discussed in the following section. The 21 green buildings examined were observed to feature lower energy usage, and water costs. They also provided savings from an increase in tenant productivity and health. These two have large impacts on building operation costs as they are directly related to the costs associated with employees. As shown in Figure 10, productivity and health account for approximately 70% of the economic benefits associated with green buildings. Given that employee costs represent 89% of the building operation costs (Figure 9), small increases in productivity and decreases in health-related costs will result in large benefits (Kats, 2003).

Figure 9: Cost of Employee Occupied Office Buildings and Potential Productivity gains (Kats, 2003)

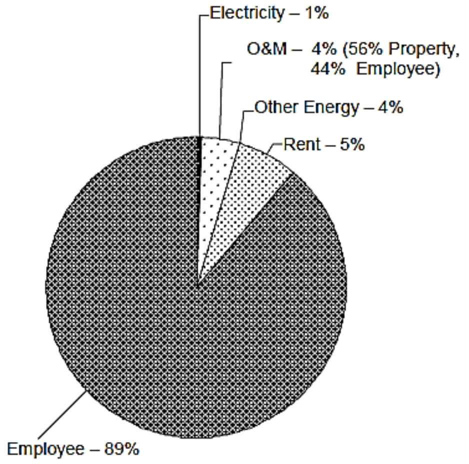
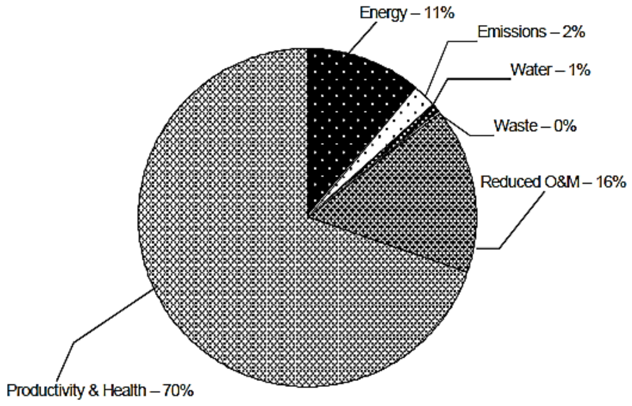


Figure 10: Percentage Breakdown of Green Building Financial Benefits (Kats, 2003)



The financial benefits of building green, as calculated and reported in the Capital E LCC assessment, are estimated to be approximately \$44/ft^2/year for Certified and Silver rated buildings, and \$63/ft^2 for Gold and Platinum LEED rated buildings (Kats, 2003). This estimated cost saving is about 10 times more than the 2% green premium (about $3.00 for Buildings in California) for the 21 buildings assessed (Kats, 2003).

Table 26: Summary of Findings Square Foot (Kats, 2003)

Benefit Categories	**20-Year Present Values**
Energy Usage	$5.79
Emissions	$1.18
Water	$0.51
Productivity and Health (Certified and Silver)	$36.89
Productivity and Health (Gold and Platinum)	$55.33
Less Green Upfront Premium	($4.00)
Total 20-Year NPV (Certified and Silver)	**$44.37**
Total 20-Year NPV (Gold and Platinum)	**$62.81**

3.1.4.8 Analysis Limitations

Building green has many cost savings that can be gained over the life of the building. The life cycle costing presented in the previous sub-sections has some of the following limitations:

- The Capital E report did not use any specific tools to generate the results. Rather, a broad literature review was performed using the small amount of data available on the 60 subject buildings.
- There were too many “substantial information gaps (Kats, 2003)” to render the assessment comprehensive (i.e. data on cost of water was either unavailable or incomplete for some of the buildings).
- Life Cycle emissions from building energy usage, beginning with energy extraction and ending to energy usage, is not reflected in the results presented in the report.

3.2 BARRIERS TO GREEN BUILDINGS

As shown in Section 2.3.1, green buildings are “going mainstream” (Yudelson, 2008). The industry has grown exponentially since its inception. Soon, conventional buildings will be “functionally outdated the day it is completed and very likely to underperform the market as time passes” (Yudelson, 2008). It is predicted that green buildings will one day become “business as usual” (Yudelson, 2008, pp. 53-54). Still, there are many market barriers to green development, actual or perceived. Despite the evidence to the contrary, many still perceive green buildings as too expensive regardless of the many benefits the latter may provide. The few market impediments to the success of sustainable development will be elaborated upon in this section.

3.2.1 Lack of information about Green Buildings

In 2007, the Environmental Protection Agency (EPA) held a series of workshops to uncover a list of the perceived and actual market barriers affecting green development. Fifty experts in the fields of commercial and residential development were brought in to identify those barriers. These experts included architects, attorneys, appraisers, bankers, brokers, developers, equity providers, and various owners (Choi, 2009).

One the main market barriers identified during the workshop was the lack of available information regarding the performance, costs and benefits of green features and technologies. The developers also cited that there is a lack of demand from consumers for green technologies and features. For instance, in the residential sector, it is common for consumers to value high quality finishes and spaces rather than sustainable features. Some owners stated that this is partly due to the fact that building owners lack the tools and incentives to record short and long-term information regarding their development’s energy savings, utility costs, environmental impact, and occupant health improvements. Similarly, developers and designers rarely possess the proper tools to present these features to prospective buyers and tenants. Without knowledge about the various benefits and costs, consumers are unaware of the values in sustainable development.

3.2.2 Transfer of Benefits and Financing Issues

Developers and owners of leased structures find that they have little to no motivation to build green because of the issue of “transfer of benefits.” A transfer of benefits happens in cases where the beneficiaries of the green long-term cost savings are different from the original decision-makers. This typically happens when the green building is sold or leased upon completion. In the cases of enterprises, government agencies and institutions, the sustainable developments remain the properties of the decision-makers; therefore, since the sustainable features directly benefit their employees or students, the decision-makers are indirectly also benefited.

When the development is sold upon completion, the benefits get transferred to the new owner. In these cases, the developers and owners in the workshop maintained that they have little to no motivation to design green because they do not benefit in the long term (Choi, 2009). It was seen as burdensome to go through the complicated and expensive process of designing a green building and get a LEED rating only to transfer those benefits over to a new owner (Choi, 2009). In leased situations, the owners also felt no motivation to invest in sustainable development since they typically transfer the operation cost responsibilities to the tenants.

3.2.3 Financing Issues with Green Premium

Since green buildings can cost more than conventional buildings, oftentimes owners and developers have to finance the green technologies along with the cost of the building. Aside from the added amount needing to be financed, when equity markets evaluate projects, they use standards applicable only to conventional buildings rather than green buildings. For instance, the standard criteria for time horizons are said to only pertain to conventional buildings. These standards have not been revised to account for green buildings because the current time periods are not long enough to capture all the benefits that a green development might accrue over the life of the building (Choi, 2009). Additionally, the industry and government criteria for evaluating project cost escalations financial feasibilities have not been revisited to ensure that, when applied to green buildings, the payback time is not lengthened (Choi, 2009).. It was also cited that it is difficult to get mortgages for non-conventional buildings as the market perception is that green development is risker from a return point of view (Choi, 2009).

3.2.4 Construction safety risks and issues

Another barrier cited was the lack of expertise during green building construction. Since the well tested and already in-place rules and techniques of construction are usually defaulted to, there are few construction companies willing to undertake green building construction because of the safety risks and financial liabilities associated with these buildings (Choi, 2009). Green projects were observed to have many construction worker safety risks. Through the study of 86 LEED rated projects, a 2009 report by Rajendran provided evidence that green projects have a higher number of recorded injuries on the job sites. These safety risks are due to the fact that green buildings feature innovative technologies and designs, many of which some contractors have no experience in installing or constructing (Fortunato, 2010). These innovative technologies also present new hazards for the workers. For instance, the installation of photovoltaic systems and atriums require workers to perform work in “unfamiliar work environments” (Fortunato, 2010). These panels may increase the “potential for human error” (Fortunato, 2010), like the possibility of workers sustaining injuries or dying from electric shock. Finding experienced contractors willing to undertake these types of projects is difficult (Choi, 2009).

Additionally, when contractors are not equipped to handle the construction of green buildings the development time may increase. With these potential schedule delays and other delays that might arise from the repeated occurrence of job site accidents, higher risks and costs may result. With the prevalent tight budgets and limited development time frames, developers tend to avoid bidding for green projects (Choi, 2009).

3.2.5 Building Codes

Another barrier to the implementation of green development is the difficulty that designers have with getting these sustainable designs approved by the building code officials. Building codes' main purpose is to provide standard guidelines to ensure the building occupant welfare, safety and health. Many of current codes are prescriptive and designed based on industry standards, thereby precluding any innovative green design principles and approaches.

The Development Center for Appropriate Technology (DCAT) conducted a survey on 198 code users (primarily designers, developers, and owners- all those who usually interact with the building code officials), and 56 code officials, to determine what reasons they cite for the preclusion of innovative design within the building codes (Garman, 2011). The result of the survey indicated that the building code regulators are not educated on the risks and consequences associated with current buildings and construction practices (Garman, 2011). Additionally, most municipalities and buildings permit departments lack the necessary resources to educate their officials on the benefits and features of green buildings (Garman, 2011). Consequently, knowing this short coming, 65% of the code users surveyed indicated that they leave out green features from building designs due to the anticipated design rejection from the building code officials (Garman, 2011).

3.3 OVERCOMING MARKET BARRIERS

There are many ways that these market barriers can be overcome. Various green industry proponents have researched ways that have been seen to be successful in breaking down the barriers to green development. Described below are some solutions and methods that have been reported as effective.

3.3.1 Integrate Green Features into the Building Design Process

An integrated design approach to green building requires that all stakeholders be involved in the early project development phases to address project goals and potential barriers (Choi, 2009). This “whole building” approach gives the team the ability to effectively analyze the project in its entirety so as to avoid overdesigning the building and its various components. Eliminating superfluous systems whose functions have already been addressed by other features in the building design and properly sizing and designing the green features can reduce upfront and life cycle costs. Additionally, with an integrated design, all the design priorities get aligned to the project budget and objectives from the conceptual phases. Project cost overruns, schedule delays and change orders can be prevented.

In addition to the early involvement of the project stakeholders, utilizing the Building Information Modeling (BIM) software to gather data about the building can help reduce time spent gathering resources during the design and construction processes, as well as help in creating the optimum design, thus saving time and expenses (Choi, 2009).

3.3.2 Document and Communicate Costs and Benefits of Green Buildings

Publishing data addressing the features, costs and values of green design and technologies can further the general population’s education on their expected performance. With that information, consumers will be better equipped to “gauge the value of their purchases”

(Choi, 2009). Educating consumers aside, the market representatives need the proper tools to evaluate green development projects and disseminate the information to potential clients.

Widespread knowledge about green building values is one of the main important steps for the green industry to move from being a small "niche" in the US construction market to the norm (Yudelson, 2008). Many institutions and organizations have led the way in gathering data and analyze information that aid in advocating green features. These institutions and organization need funding and support to continue their efforts. Many government agencies, private foundations and donors can provide the funding necessary to continue with the data analysis and dissemination, while the current green building owners and operators can publish and make available the performance of their green developments.

Using already established and accepted systems to display predicted energy and water usage as well as other building maintenance and operation costs can help consumer become more aware of the value of their purchases. For instance, displaying the predicted cost of utilities on an MLS listing can provide information to a potential client on how much they can expect to pay for utilities living in that property. The information on a "built-in distribution network" (Choi, 2009) like the MLS listings is already accepted as accurate; thus any additional information about a property's green features can aid in marketing the value of the green building.

Additionally, developing training programs for all the market representatives can assist the green industry in educating the key stakeholders on the values of green buildings. These stakeholders are usually influential in the funding, construction, sale and design of green development projects. Even though some of these professionals have become more experienced and educated on green designs, there is still an education gap. To bridge the latter, more educational incentives need to be created with training and certification programs.

Another way of educating the public about green development values is to include green building information in the discussions of climate changes, energy crises and environmental degradation. Since buildings are in part responsible for the current environmental and energy crises, the discussions about green development and these issues should be interconnected. Increased public knowledge of these features can increase the “market acceptance of green development” (Choi, 2009).

3.3.3 Regulatory Codes used as Non-financial Incentives

Even though the existing codes and standards in certain municipalities may discourage green development innovative designs, they can and have been seen to be effective in encouraging green development practices. In certain states where local jurisdictions have “greater administrative roles in determining issues over state regulations,” (Choi, 2009) municipalities have the authority to determine appropriate methods in interpreting codes and standards. These municipalities can, based on their needs, develop codes similar to those prescribed by the state so as to encourage innovation in design by setting minimum prescriptive and performance-based criteria. In many instances, those municipalities have principles and processes where they allow for leniency in the codes, thus creating situations in which these allowances can be “adjusted to encourage green practices” (Choi, 2009). Some of the tools used by that state and local governments as incentives to encourage green development are described below.

Bonuses: Floor Area Ratio (FAR), and height

Some jurisdictions have implemented programs where some of the requirements for permitting, such as minimum open and green spaces, floor ratio and height requirements are waived if the building is LEED rated. These programs are particularly attractive to urban developers (AIA, 2012). FAR and height bonuses allow developers the ability to increase their development density by reducing or increasing floor area ratios or building height in exchange for adding in a green feature or "fulfilling a green design standard" (Choi C. , 2009). In such a way, developers or owners have the ability to recover some of the expenses spent on the green design features with the extra rentable or saleable space gained from the FAR bonuses. Some communities that offer such bonuses are listed in the Table 27.

Table 27: Types of Non-economic Incentives for Green Buildings (AIA, 2012)

Location	**Name of Incentive**	**Description**	**Year Instituted**
Seattle, Washington	Ordinance 122054	All buildings achieving LEED silver and above can receive greater heights and floor area ratios. All buildings must submit proof of LEED rating within 90 day or face a $500 fine.	2003
Arlington, Virginia	Arlington Green Incentive Program	Commercial and private development achieving any LEED rating level can have an additional 0.15 or 0.35 FAR and additional height up to 3 stories. The higher the level of certification, the greater amount of density accorded.	2003

Expediency in the Permitting Process

Certain municipalities have developed programs in which any potential LEED rated building requesting permitting is allowed faster permitting by reducing the waiting period. With such a program, developers and owners now have the incentive of integrating green features into their building designs because they can now bypass the conventional permitting systems, and can have a guaranteed approval or denial within a certain time period. In Chicago, wait periods for permitting for conventional buildings be as long as 4 months (Spielman, 2011). Under the new Chicago Green Permit program, LEED rated buildings can receive a building permit in as little as 15 days (AIA, 2012).

Dedicated Staff in Building Department Knowledgeable About Green Development

Some building permit departments have "dedicated green tutors" or "go-to" personnel that are available to consult with developers or owners at the onset of the project. The tutors typically meet with the project teams to inform them about the available incentives, permitting process time period and any other pertinent information (Choi, 2009). Since the green tutor program staff usually meets with the project stakeholders at the beginning of the project planning, many challenges are addressed before the plans are complete. Also, involving the tutors during the project developmental phases has been shown to aid the designers in identifying and integrating different green elements into the building design. Examples of municipal technical assistance are provided in Table 28.

Table 28: Examples of Technical Assistance programs (AIA, 2012)

Location	**Name of Program**	**Description**	**Year Instituted**
St. Paul, Minnesota	Resolution 12407	The law requires that at least 5 LEED accredited professionals be employed at the planning, economic developments, licensing and inspections, environmental protection, parks and recreations, and public works departments	2009
Seattle, Washington	"Implement" Design Tool from the Depart. Of Planning and Development	Green Educational program where the department of Planning and Development provides learning tools and services to buildings and owners of green buildings.	2003

In some of the tutor program, designated tutors meet regularly to identify methods of integrating and updating current codes and standards to include innovative designs (Choi, 2009). This is instrumental in removing the barriers in the current codes by opening up “communication channels across different departments and aligning various programs” to ensure that no procedures hinder innovative practices (Choi, 2009).

3.3.4 Monetary Incentives

Another way of promoting green building is to link it to the local economic and community incentive programs. In such a way, planning departments can both achieve their environmental suitability and their community goals (Yudelson, 2008). Incentives designed at the local level to meet regional needs have been seen to be most effective. Those incentives are usually offered as monetary or non-monetary, and are adapted to what works best in the local market.

State and local governments can offer tax credits, reductions, exemptions and rebates, as well as grants and vouchers as monetary incentives (Choi, 2009). Tax incentives are the most commonly used forms of incentives in encouraging green building development because they are more flexible when implemented (AIA, 2012). These incentives allow the government to “partially share” or offset the cost of installing, constructing, or creating new green technologies (Choi, 2009). They can also offset the cost of the “learning curve” for those developers who are learning how to build green, or used to promote the sale of green developments (Choi, 2009). An example of tax incentive is the federal Energy Policy and Conservation Act of 2005. The energy policy established incentives for residential green developments featuring solar electric and water heating systems and other green technologies, the details of which are shown in Table 29. The Energy Independence and Security Act of 2007 with its provision, the Energy Efficiency and Conservation Block Grant (EECBG), granted $2 billion to the states (AIA, 2012). This law instituted a program why which local communities can receive block grants to encourage "environmentally beneficial practices" (AIA, 2012). These grants, like the King County Grant Program in Washington, are used to provide technical assistance to developers and building owners, and to help offset the hard costs of sustainable design.

Table 29: National Energy Policy Act of 2005: Commercial Green Buildings (Yudelson, 2008)

Affected Technology type	Tax Rebate - % of Expenditures
Photovoltaics	30% (Residential Limit is $2000 credit)
Solar Thermal Systems	30% (Residential Limit is $2000 credit)
Microturbines	10% (up to $200/kW credit)
Energy Conservation Investments for HVAC, Envelopes, lighting and water heating systems	$1.80/ft2 (Federal tax deduction if exceeding 50% savings vs. ASHRAE 90.1-2001 STD)
New homes exceeding 50% energy savings vs. model code	$2000 for site-built homes

Table 30: Types of Tax incentive Programs Reproduced from (AIA, 2012)

Location	Tax Type	Name of Incentive	Description	Year Instituted
Maryland	Income	Code Ann 10-722	Income tax credit to owners and developers of Green Buildings. 8% of building costs or $120 per square foot of the base building.	2010
Cincinnati, Ohio	Property	Cincinnati Tax Abatement	Homeowners that retrofit their homes according to LEED can receive property tax abatement. Taxes are paid on the land and value of the property in excess of the maximum specified abatement amount (this maximum value differs for each LEED rating level).	2007
New York	Income/Corporate Taxes	CLS Tax 19	Tax credit to green building owners and tenants that can be applied to their income or corporate taxes. Building must not exceed 65% of the permitted energy usage	2009
Oregon	Other	ORS 469.185	Tax rebate designed to offset the cost of sustainable development. It is a refund from the Oregon Department of Energy and is based on square footage.	2007
Ohio	Exemption	Ordinance	100% tax exemption to LEED Gold buildings, not exceeding $500,000 in 15 years for new buildings and 10 years for renovations. Platinum ratings have no maximum exemptions.	2009

3.3.4.1 Effect of Monetary Incentives on Green Development

Although many communities throughout the U.S. that use various forms of tax incentives to encourage local green development, there is limited data on their effects on the growth of green buildings. It is difficult to directly relate incentives to the growth of green development for many reasons. There are many different types of building owners, and each has different needs. Some of these owners may take advantage of both monetary and non-monetary incentives; some others may use one type of incentive and not the others that are available. The data is not yet available where the distinction between how well one type of incentives work versus the others. There is also the matter of lack of visibility and complexity for some of these tax incentives. Several developers that were interviewed have maintained that some of these available tax incentives are too complicated. Some owners find the process to apply to them is too lengthy (AIA, 2012). Other owners are not even aware that the tax credits are available. Although there has been no recent study conducted on the growth of LEED rated buildings as a direct result of tax incentives in the cities listed in Table 30, an increase in LEED registrations was observed in these cities since they implemented these incentives (USGBC , 2013). Tax incentives, on the whole, can be positive drivers of green development.

Even though data linking the growth of green development to the aforementioned incentives is presently unavailable, the author conducted a review of the green development activities about the time the incentives were implemented in the various states. The result showed a sharp rise in the number of green buildings built in 2003. Figure 11 reports the number of green building (LEED) registrations in the states with green building incentives. All the incentive programs mentioned in this section were implemented in their various states starting in 2003. Prior to the year 2003, as depicted in Figure 11, many of the states referenced below had little to no sustainable development. From 2003 and 2007, there was a slow rise in green activities for each of the states. Then from 2008 onward, the increase in green activities has been exponential for some, mainly Oregon and New York, and steady for the others. Many of the tax incentives and other non-monetary programs instituted by the states were implemented on or after the year 2007. As can be seen by this graph, the sharp rise in the graphs of all the states begin with the year 2007. The growth in the number of green buildings continued to increase at a rate of 15-44% per year over the period from 2007 to 2012.[9]

Based on the trend observed from 2003 to 2012, the author speculates that the incentives may have contributed to that upward trend. With more developers and building officials becoming aware of LEED buildings and their benefits, and given the many incentives now available for green buildings, more are being encouraged to build green. Because of the shorter time periods for permitting, the many grants and specialty loans available to fund green buildings, the many tax incentives, and non-monetary incentives, developers are finding more reasons to build green.

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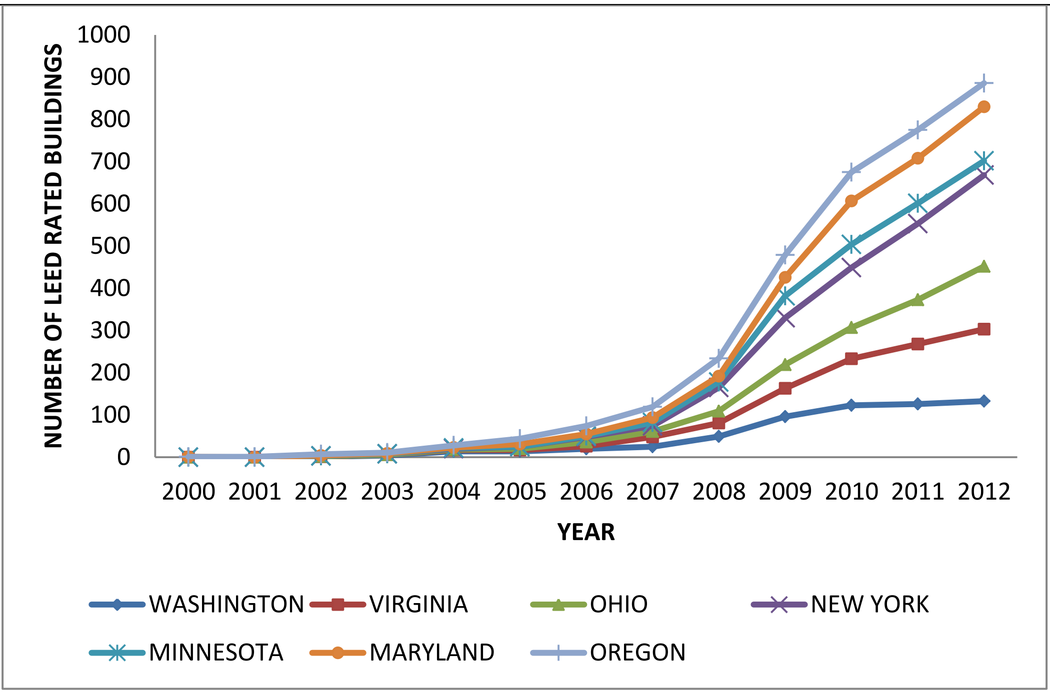
[9] The data used for this particular analysis was gleaned from the USGBC 2013 project directory. Projects that were not awarded a rating as of December 2012 were ignored. Only currently registered and pre-registered projects were counted in the numbers for Figure 11: Growth of LEED in WA, VA, MN, MD, NY, OH, and OR As of December 2012. Only the states of Washington, Virginia, Oregon, New York, Ohio, Maryland, and Minnesota were considered for this analysis.

Figure 11: Growth of LEED in WA, VA, MN, MD, NY, OH, and OR As of December 2012



CHAPTER 4: INTRODUCTION TO SEISMIC RESISTANT DESIGN

4.1 EVOLUTION OF US SEISMIC DESIGN PRACTICES AND BUILDING CODES

4.1.1 Introduction to Seismic Resistant Design

Earthquakes are one of the most destructive natural hazards. A large moment magnitude earthquake may last only a few seconds, but leave communities and economies "reeling in its wake" (Bozorgnia, 2004) for decades or longer. Due to many major earthquake occurrences in Italy, the United States and Japan, increased interest in earthquakes and their effects on the built environment and people has increased during the late 19th and early 20th centuries (Bozorgnia, 2004). A movement toward seismically resistant design began to emerge in the early 20th century, with an ultimate goal geared toward "wealth protection" (Elnashai, 2001). With widespread adoption of high performance seismic resistant building designs, the future outlook on the occurrences of earthquake events in industrialized countries is such that these buildings will not only seek to "assure life-safety" but to prevent large economic losses (Elnashai, 2001).

This section will aim to provide a chronological recount of the major earthquake events in the US, the building failures that occurred, and the ensuing building code changes. These changes were the results of the "reconnaissance observations," survey of damage to certain types of construction, during past earthquake events, and the code changes developed to address these failures (EERI, 2004). The historical narratives in this section aim to characterize the evolution of seismic design practices and building codes that govern current US seismic design practices today. The focus will be placed primarily on the evolution of California seismic design practices and building codes since most of the advancements in these areas have roots on earthquake events that occurred in the various regions of California beginning in 1906. Earthquake events that have occurred abroad will be omitted in the subsequent sections as it is outside the scope of this report.

4.1.2 1906 to 1933: Earthquake Events and Resulting Changes to Building Codes

The early versions of building codes were primarily concerned with reducing the risk of fire. The importance of developing building codes requiring earthquake resistant designs of structures did not begin with the 1906 San Francisco earthquake (Bozorgnia, 2004). The earthquake caused a considerable amount of damage in the San Francisco and Northern California regions and killed approximately 3000 people (the official count was 700, but 3000 were reported dead) (Ellworth, 1990). Even though the damage was extensive, engineers and city boosters attributed the loss to the subsequent fire (Bozorgnia, 2004). The lessons learned during the 1906 Earthquake did not spur the engineers and government officials into developing requirements for earthquake resistant construction (Bozorgnia, 2004). Instead, the engineers recommended the use of fire protection and fire-resistant materials in buildings (Bozorgnia, 2004).

The 1925 Santa Barbara earthquake, however, led to an increased interest in earthquakes and their consequences. Though the death toll was low, 12 to 14 dead, the losses from this earthquake were also extensive, $8 million in property damage (Stover & Coffman, 1993; Bozorgnia, 2004). The structural failures observed during the earthquake motivated building designers, architects, engineers, government officials, and building owners to improve the current building codes (Bozorgnia, 2004). In particular, the earthquake led to the creation of the first set of seismic code requirements. In 1927, the Pacific Coast Building Official Conferences, later known as the International Conference of Building Officials, published the 1927 edition of the Uniform Building Code (UBC). This early, non-comprehensive, seismic design provisions in mandated that buildings be designed to resist lateral forces, applied at each floor level, equal to a certain percentage of the building's total dead and live. The base shear, the equivalent lateral earthquake force, was the product of a constant coefficient and the building's total dead and live loads. These early seismic code requirements were established by Structural Engineers Association of California (SEAOC) volunteers. The provisions appeared in the 1927 UBC's appendix as non-mandatory (BSSC, 2010).

These building codes provisions began to formalize seismic design practices (Barclay, 2004) and their effectiveness was tested in subsequent events. As a result of their shortcomings, many revisions were made and other laws enacted following the 1933 Long Beach earthquake. The motions recorded during the 1933 Long Beach earthquake were "among the most significant" ones to have ever been recorded at that time (Bozorgnia, 2004). Because the earthquake struck in a more densely populated area than the Santa Barbara earthquake, the damage was more extensive (Barclay, 2004; Bozorgnia, 2004) and a number of commercial buildings and private residences suffered great structural damage, and even collapse. Aside from these buildings, more than seventy-five percent of schools in the southern Los Angeles region suffered intense damage (Barclay, 2004). The buildings that failed were seen to be of the types with elaborate architectural ornamentations, unreinforced masonry buildings built using inferior mortar, and those built 50 or more years before the earthquake (James & Fatemi, 1997). Others that were damaged had "irregular shapes," built of brick and not designed to resist any lateral loads (James & Fatemi, 1997). Engineered buildings or those designed with reinforced concrete saw little to no structural damage (James & Fatemi, 1997).

The Long Beach earthquake was seen a “major turning point” (Bozorgnia, 2004) in the history of earthquake engineering in the US because following this event that the first mandatory building code was introduced. Since the earthquake was seen as a visual representation of how unsafe most of the California school buildings were, two California laws were passed: the Field Act, which gave the State the authorization to review and approve all public school construction plans among other duties; and the Riley Act, which established earthquake resistant requirements for all structures other than school buildings, excluding agricultural buildings (Bozorgnia, 2004).

Later earthquakes provided a test of Field Act provisions. The stringent guidelines set forth by the Field Act created school buildings that were better able to resist seismic forces. These buildings fared better structurally than those using the traditional code provisions of the UBC (Barclay, 2004). In the Loma Prieta Earthquake of 1989, only five schools reported any significant structural damage (Barclay, 2004), and during the 1994 Northridge Earthquake, only 24 out of a total of 127 schools had structural damages (Barclay, 2004). The Field Act was proven as being effective in accomplishing its goals.

4.1.3 1933 to 1994: Earthquake Events and Resulting Building Codes

The 1971 San Fernando Earthquake resulted in many building code changes. The concrete frame elements were observed to perform poorly during this earthquake as they were not detailed for ductile response (EERI, 2004). As a result, this led to the 1973 code requirement mandating that all concrete frame elements that make up the lateral-force resisting systems be designed for ductile performance. Another code change required that all buildings located near active earthquake faults be designed to resist 40% larger seismic forces (EERI, 2004). As part of the reconnaissance observations after the damage of the 1971 earthquake, the effects of soils at the building site on the intensity of ground motion were incorporated into the 1973 code improvements in the form of a coefficient in the design base shear formula (EERI, 2004).

The Northridge Earthquake was seen as a full scale test for the 1973 and 1976 earthquake codes' effectiveness. Due to the establishment of importance factors that mandated more stringent design requirements for critical facilities with the purpose of ensuring that they remain operable for post-earthquake use, those constructed using the 1976 provisions performed better in the 1994 earthquake than they did in the 1971 San Fernando earthquake (NIST, 1994). During the 1971 earthquake, three hospital complexes, the Olive View Medical Center, the San Fernando Veterans Administration Hospital, and the Holy Cross hospital, had collapsed. In the 1994 Northridge earthquake, little to no damage was seen in hospitals built after 1971 (NIST, 1994). In addition, other buildings designed using the 1976 building code seismic design requirements sustained performed well structurally. The failures observed during the earthquake were in buildings built out of unreinforced masonry that were not rehabilitated and non-ductile (i.e. pre-1970s) concrete buildings (NIST, 1994).

The 1994 Northridge Earthquake resulted in several code changes, particularly those dealing with steel frame structures a system that was traditionally thought to be earthquake resistant (EERI, 2004). Additionally, vulnerabilities were observed in the tilt-up commercial and industrial constructions where the concrete or masonry walls were anchored to wood diaphragms (EERI, 2004). Lack of redundancies in the building structural systems were also observed to cause structural failures in some of the buildings. As a result of these deficiencies, provisions for redundancy and structural steel frames, in particular in more stringent connection requirements, were added to the codes (EERI, 2004).

4.1.4 1990 to Present: Building Code Improvements and Seismic Resistant Design Practices

As engineers and scientists learn from failures from earthquakes, organizations like SEAOC, would work to make improvements to the codes. Over the years, these seismic design requirements which originally figured in the appendices of the UBC moved into the body of the code and became mandatory. Noteworthy code changes took place on the West Coast after the four earthquakes discussed in preceding section. After the 1971 earthquake, SEAOC, through the Applied Technology Council (ATC), began developing recommendations to amend the current seismic code provisions, establishing the first modern seismic code (BSSC, 2010). Congress' parallel efforts to mitigate seismic risk led to the passage of the Earthquake Hazards Reduction Act in 1977 which established the National Earthquake Hazards Reduction Program (NEHRP).

Under the NEHRP, four agencies - The Federal Emergency Management Foundation (FEMA), The National Institute of Standards and Technology (NIST), The National Science Foundation (NSF), and the United State Geological Survey (USGS) - were authorized and provided with funding to develop seismic risk mitigation techniques. Some of these organizations' functions and responsibilities are described below:

- The USGS's primary focus is to identify the seismic hazard level for all regions of the US. Using a network of ground motion recording instruments, the USGS collects data on earthquake motions. The data is then used to make predictions on the intensity of ground motion that a specific site is likely to experience in future earthquake events. The hazard maps that are created with the likely ground motion intensity currently are used in the design maps that appear in the versions of the NEHRP *Recommended Seismic Provisions*.

- The NSF funds research programs and provides training for future engineers and scientists in the earthquake engineering field. One notable contribution of the NSF is the establishment of the recommendations for future seismic code requirements. The *Tentative Provisions for the Development of Seismic Regulations for Buildings*, first published in 1978, and later modified by the FEMA, amended the seismic code provisions that were in effect at the time. This document served as the basis for the initial version of the *Provisions*, and thus the seismic requirements that appear in the building codes today (BSSC, 2010).
- NIST is identified as the agency that coordinates the activities of the other agencies under the NEHRP. NIST also is responsible to designate a committee of experts to "assess scientific and engineering trends, program effectiveness, and program management" (BSSC, 2010).
- FEMA's role is to provide assistance to the public after an earthquake event. The agency helps to speed a recovery and to minimize the impact of the earthquake on the economy as a whole. In 1980, FEMA sponsored the development of the document used to generate the first edition of the *Provisions* that was published initially in 1985. The agency is responsible for updating the document. Revisions to the *Provisions* used to occur every three years during the early years. It is now updated every five years.

The first building code adoption of the 1991 edition of the *Provision* occurred in 1992 by Building Officials and Code Administrators International (BOCAI) and the Southern Building Code Congress International (SBCCI). Both of these organizations incorporated the seismic requirements into the National Building Code and the Standard Building Code respectively. Six years later in 1998, the American Society of Civil Engineers (ASCE) adopted the 1997 edition of the *Provisions* into the ASCE 7 standards. In 2000, the International Building Code (IBC) proceeded to also adopt the *Provisions* verbatim. Since then, the IBC and the ASCE continue to base their standards on the NEHRP *Provisions.*

4.1.5 NEHRP *Provisions*' Risk and Performance Concepts

The current seismic design practices, detailed in section **Error! Reference source not ound.**, provide professionals with the methods of designing structures earthquake resistant structures. Designing invulnerable structures for severe events that occur infrequently, with 100 or more years between occurrences, when a building's useful life is 50 or fewer years, is not a "wise use of society's resources" (BSSC, 2010). Instead of designing buildings such that there is no chance of collapse or damage during extreme earthquake events, the NEHRP seismic provisions are developed based on the concept of "acceptable risk" (BSSC, 2010). Using this approach, the NEHRP was able to develop minimum standards that aim to balance the cost of building a seismically resistant structure against the probability of unacceptable losses from future earthquakes. The NEHRP *Provisions* are developed based on the following minimum acceptable risks:

- A small chance (10%) that any building will partially or totally collapse as a result of intense ground motions. These intense earthquake events are considered rare in most building codes and are referred to as Maximum Considered Earthquake (MCE_R). The probability of occurrence of MCE_R ground motions vary by region. This collapse prevention approach is primarily to ensure life-safety and prevent losses that can occur from structural failure of buildings. This measure does not guarantee that no lives will be lost, but it is in place to prevent an excessive number of casualties in extreme earthquake events.

- A 6% chance that certain, highly important, structures will experience collapse as a result of MCE_R ground motions. This limit on the chance of collapse is intended for public assembly structures and other facilities deemed critically important to protect, such as schools and hospitals. Facilities containing or manufacturing toxic chemicals or materials that may be risky to the public are also limited to a 6% chance of collapse, since, should collapse occur in these facilities, structural failures may lead to the release of these toxic materials.
- A 3% chance that critical facilities like hospitals will experience total or partial collapse as a result of MCE ground shaking. Hospitals are needed as emergency response facilities after an earthquake and need to remain operable. Limiting damage to structural, electrical, mechanical and architectural systems in these critical facilities is essential.
- Minimizing the risk that damage to non-structural elements will generate debris that may become hazardous to building occupants and pedestrians.
- Limit economic loss, to an “extent practical”, resulting from structural and non-structural damage to buildings after “relatively frequent moderate earthquake events” (BSSC, 2010).

4.1.6 Effectiveness of NEHRP Code Provisions

Since no intense earthquake events have occurred since the establishment of the NEHRP Provisions, their effectiveness in mitigating seismic risk in the US has never been assessed. However, a joint venture research by the ATC and the Consortium of Universities for Research in Earthquake Engineering (CUREE) aimed to assess the effectiveness current US seismic design practices by examining the failures from the damages of the 2010 Maule earthquake in Chile. The study was conducted using Chile because the Chilean building codes governing seismic design practices are modeled for the most part after the US seismic requirements.

To be able to make these comparisons, the study identified some differences in design practices in Chile and the US. Earthquake resistant design of buildings in Chile is based on the NCh433 standards. The latter has provisions for seismic resistant design similar to those of the 1996 edition of the UBC (ATC & CUREE, 2012). In Chilean seismic resistant design practice, buildings are configured with short floor spans and a number of load bearing walls used as the seismic and gravity force resistant systems. This practice allowed for high level of redundancy in the structural system of Chilean buildings which resulted in a relaxation of the component ductility requirements. In contrast, US seismic resistant design practice is designing structures with longer floor spans and fewer load bearing walls. As a result, these walls are designed to be thicker which facilitates the inclusion of more confinement reinforcing and thereby increasing ductility. These differences in typical practice led to lower redundancy in US buildings.

Researchers found that Chilean buildings built using the recent seismic provisions were able to withstand damage without collapsing during the 2010 Maule Earthquake. Although there were concrete cracking and bar buckling in some of the recent buildings' structural elements because of the lack of confinement reinforcing and some the buildings experienced vertical displacement in their shear walls, they did not collapse. According to the 2010 EERI report, recently engineered buildings performed well structurally (ATC & CUREE, 2012). Based on a survey of the 50 multi-story buildings that sustained damage in the metropolitan near the earthquake epicenter conducted by the Engineer Association of Chile (EAC), approximately 2%

of these buildings experienced extreme failure and collapse; 12% were damaged and were rendered inoperable; and 86% were able to be occupied immediately after the earthquake (ATC & CUREE, 2012).

The greatest damage occurred in the cities with older buildings or due to the subsequent tsunami. The majority of older buildings had not been retrofitted to comply with the current building codes (Mosqueda, 2010). For instance, the city of Talca, seventy miles from the epicenter of the earthquake, reported that most of the damage was from the older (1960s-era) unreinforced masonry and concrete buildings collapsing (Mosqueda, 2010). In contrast, newly built reinforced concrete frames were left intact during the earthquake and the tsunami (Gee, 2010). Based on the performance of the engineered buildings built using recent versions of the Chilean code, engineers arrived at the conclusion that aside from ductility detailing and retrofitting older buildings, the codes achieved their purpose which was to ensure life-safe and minimize building failure (ATC & CUREE, 2012). Since these Chilean codes have their basis on the US codes, and since the latter require a much higher level of detailing, the author arrived at the conclusion that, should the current seismic design requirements undergo a full test scale, they will be effective in achieving their life-safety and minimal collapse objectives.

4.2 PERFORMANCE BASED EARTHQUAKE ENGINEERING

4.2.1 Limitations of Prescriptive Seismic Code

The NEHRP *Recommended Seismic Provisions* described in Section 4.1.5 establish prescriptive requirements, i.e. a minimum seismic design requirements and procedures, for design of structures to resist earthquakes (BSSC, 2010). The engineers that developed the codes intended that the provisions would ensure that buildings designed in accordance with the code would (1) not collapse in rare earthquake events; (2) ensure life-safety of building occupants during those rare seismic events; (3) sustain moderate, but repairable, damage when subjected to moderate ground motions; and (4) suffer minor damage in minor, but frequent, earthquakes. It can be concluded from these objectives that designing code-compliant buildings does not preclude damage from occurring in buildings during earthquakes (ATC, 2006). Although minimal to no loss of life has occurred from failures in buildings built according to current building codes, economic losses resulting from these damages have been “staggering” (Lew, 1997).

Following the 1989 Loma Prieta earthquake and the “unacceptable” (ATC, 2006) $20 billion economic loss incurred as a result of the 1994 Northridge earthquake, earthquake engineers began to realize that potential structural and non-structural damages in code-compliant buildings during earthquakes “may not be consistent with public notion of acceptable performance” (ATC, 2006). In a 2004 paper, a number of prominent engineers wrote that the prescriptive force-based requirements of the *Provisions* constituted a “complex compendium of convoluted and sometimes contradictory requirements” that did not provide a clear definition of performance and hazard (Whittaker, Hamburger, Comartin, Mahoney, Bachman, & Rojahn, 2004). Additionally, the engineers maintained that the forced-based procedures were not tied directly to the code-intended performance capabilities of the structure because actual evaluation of building performance is not part of the design process (Whittaker *et al.*, 2004). As a result, actual performances of code-compliant buildings are not only uncertain, but may in some cases, fall below the stated goals (ATC, 2006; BSSC, 2010). In some instances, the finished building design, in some cases, did may not attain the targeted performance level (Whittaker *et al.*, 2004).

4.2.2 Performance-Based Seismic Design History and Overview

Performance-Based Earthquake Engineering (PBEE) design procedures represent an alternative to the prescriptive requirements found in the NEHRP *Provisions* and building codes. PBEE design procedures were developed following the large economic losses of the 1989 and 1994 earthquakes, taking advantage of improved computational capabilities. PBEE's goals are to establish procedures for seismic resistant design of structures not just to ensure life-safety, but also to limit the extent of damages incurred during earthquakes (Lew, 1997; Whittaker *et al.*, 2004).

In the mid-1990's, FEMA funded ATC and the Building Seismic Safety Council (BSSC) to develop the initial guidelines that would be used in PBEE design of structures. The resulting guidelines, *NEHRP Guidelines and Commentary for Seismic Rehabilitation of Buildings (FEMA 273/274)*, established the concept of enabling designers and owners to design buildings structures to resist a specific earthquake event at a desired, preselected performance level (Whittaker *et al.*, 2004). The performance levels, per FEMA 273, are listed in Table 31. PBEE design procedures outlined in FEMA 273 were further developed by the documents *ATC-40 Methodology for Evaluation and Upgrade of Concrete Buildings* and *Vision-2000 Framework for Performance-based Seismic Design Project*. FEMA 273 was updated in FEMA 356 *Pre-standard for Seismic Rehabilitation of Buildings*. FEMA 356, now part of ASCE 41, together with the ATC-40, and Vision-2000 documents, define the current practice for PBEE design (Whittaker *et al.*, 2004).

Table 31: Building Performance Levels Per FEMA 273/274 (Whittaker, Hamburger, Comartin, Mahoney, Bachman, & Rojahn, 2004)

Performance Levels	**Damage Descriptions**	**Downtime**
Immediate Occupancy	Negligible structural damage; essential systems operational; minor overall damage	24 hours
Life Safety	Probable structural damage; no collapse; minimal falling hazards; adequate emergency egress	Possible Total Loss
Collapse Prevention	Severe structural damage; incipient collapse; probable falling hazards; possible restricted access	Probable Total Loss

The performance-based design process provides a methodology (described in Section 4.2.3) to assess the performance capability of a structure, building system or component (ATC, 2006). The performance based design paradigm allows engineers to design structures with a predictable level of performance (Lew, 1997). The concept is that PBEE can be used to evaluate the seismic performance of a particular design. If that design is unacceptable or poorly performing in comparison to other designs or an owner’s expectations, the structure can be redesigned. The PBEE design process can further be used:

- To develop and confirm higher levels of performance for critical facilities and other structures than the performance levels intended by the prescriptive provisions.
- To design high performance buildings that are configured with materials and systems which “fall outside of code-prescribed limits” and have lower potential losses than those built using the conventional prescriptive codes (ATC, 2006).

- To facilitate the development of a framework in order to determine what levels of safety and property protection, achieved at what cost, is acceptable to all the stakeholders.
- To predict future losses from earthquake events and estimate their costs.

By establishing a direct link between building design and performance, PBEE enables society to be more efficient and effective in investing its financial resources to avoid future losses from earthquakes. The methodology and technology used in the implementation of PBEE design can be applied to designing for protection against other disasters such as fire, blast, terrorist attack, flood and snow. Presently, the NEHRP seismic provisions allow engineers to use the PBEE design procedures as an alternative to prescriptive requirements, provided that the application has been approved by the local jurisdiction (BSSC, 2010).

4.2.3 PBEE Design and Assessment Methodology

The PBEE design process begins by selecting one or more performance objectives. Each objective represents the acceptable risk of sustaining certain levels of damages. These objectives establish a goal related to structural or nonstructural damage, the level of economic losses, and the level of building functionality (ATC, 2006).

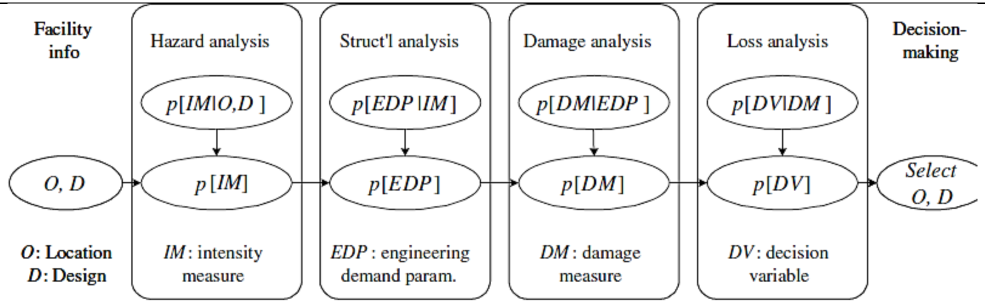
Several types of performance objectives can be defined:

- Intensity-Based: quantifying the level of casualties, damage repair, the costs associated with bringing the building back to its undamaged state, and replacement costs, and cost of the downtime, should the structure experience a specified intensity of ground motion.

- Scenario-Based: quantifying the level of casualties, damage repair and replacement costs, and cost of the downtime if a specific earthquake scenario or event occurs. The event is specified by its magnitude, fault, rupture location and other characteristics.
- Life Cycle-Based: quantifying the level of casualties, damage repair and replacement costs, and cost of the downtime over of a specified period of time. All possible earthquake and earthquake characteristics are considered, weighted by the probability of occurrence of each event within the predefined time period, or over the projected lifetime of the structure.

Once the performance objectives are selected, a designer then proceeds by selecting and developing a preliminary design. The designers specify an initial building configuration, occupancy, structural systems, and then decide on the types and location of the non-structural elements at all levels of the structure. Once the preliminary design is completed and performance objectives have been selected, the PBEE design process assesses the performance of the selected design to ensure that the initial objectives are being met (Figure 12) (ATC, 2006; Lew, 1997).

Figure 12: PBEE Methodology Illustration (Moehle & Deierlein, 2004)



The next step in the methodology process is to define a ground motion Intensity Measure (IM) (Moehle & Deierlein, 2004). IM characterizes, probabilistically, the ground motion hazard at the building site (Moehle & Deierlein, 2004). The effects of nearby faults with their magnitudes and probabilities of occurrence, distance to the faults, and site conditions, are evaluated (Porter, 2003). IMs can be scenario-based (occurrence of an earthquake of a specific magnitude on a specific fault or distance away from a fault), or time-based (all potential earthquake scenarios, on all nearby faults and their probability of occurrence within the time period) (BSSC, 2010). The IM parameters are evaluated for the structure while considering the structure's site location, and building period, and other building features to generate a hazard curve (Porter, 2003). The resulting hazard curve denotes the probability of exceedance of an IM (Porter, 2003). If the performance-assessment in PBEE will use non-linear dynamic time history analysis, part of the hazard analysis involves the selection of ground motion time histories that represent the IMs with 10%, 5% and 2% probabilities of being exceeded in fifty years for a given location (Porter, 2003).

The next step in the process is determining the Engineering Demand Parameters (EDP) by means of structural analysis of the building. A non-linear time-history structural model of the structure is created to assess structural responses (Porter, 2003; Moehle & Deierlein, 2004). These parameters, based on the IM, express structural response in the form of accelerations, deformations and other response quantities of interest (Porter, 2003). The EDPs are then input into a series of fragility functions, probabilistic models of different levels of physical damage that are expressed in the form of Damage Measures (DM) (Porter, 2003). The fragility functions denote the level of repair efforts necessary to return structure and its component to its original undamaged state, and express the probability of the different levels of structure's components as a function of internal forces, interstory drifts (Porter, 2003).

The final stage of the methodology involves the probabilistic assessment of the estimated performance, or Decision Variable (DV) parameters (Porter, 2003). These decision variables are used to assess the structure's performance (Porter, 2003). The damage assessed (i.e. economic losses resulting from repair costs, fatalities or downtime) are "estimates of the frequency with which the different levels of the DVs are exceeded" (Porter, 2003). These DV are then translated into quantities that can be used in risk management decision making (Porter, 2003; Moehle & Deierlein, 2004). These values can assess the life-cycle costs, in present value, of the selected performance level and objectives.

4.2.4 Limitations of PBEE Design Approaches

Designing with PBEE methodology requires that the process described in Section 4.2.3, which involves design, nonlinear modeling, dynamic analysis and assessment, be repeated for each new building designed, and sometimes several alternatives for each building design (ATC, 2006). The process is unique and the modeling and analyses are non-transferrable to buildings of other types, sizes or performance objectives (ATC, 2006). Additionally, because the methodology requires initial input variables like engineering demand parameters (EDP) during the structural analysis, by virtue, the building and its components would have to have already been designed (Bozorgnia, 2004). This process then becomes an iterative process by which the controlling parameters are identified, the building design adjusted, and the performance objectives are met. Since ways to explicitly design the buildings such that the decision variables are continuous has not yet been developed, this iterative design process is deemed onerous, because it will require that initial designs be based on "discreet limit states" (Bozorgnia, 2004). The challenge would then be to provide designers with minimum targeted EDPs before the performance assessment begins (Bozorgnia, 2004). Also, there is a limitation in the available modeling techniques that both represent structural response, and in fragility functions, to predict losses. The ATC-58 project is presently developing methods to parameterize the damage predicted in the structural response by directly tracking the individual structural components, “coupled with measures of global damage” (Hamburger, Rojahn, Moehle, & Bachman, 2004). Mathematical models are presently being developed as part of the ATC-58 to model fragility functions and estimate losses (Hamburger, Rojahn, Moehle, & Bachman, 2004).

Other limitations of PBEE methodology are the conflicts between the various performances objectives may require that designers select trade-offs. Since no single parameter controls performance objectives at all levels, there are some cases where achieving one objective may cause conflict with the input parameters. For instance, structural damage is dependent of element strength, which is in turn affected by element deformation capacities that denote the structure’s stiffness, but stiffness provides control to the forces generated in the structure. This example reflects the fact that performance objectives may led to conflicting demands on EDP of strength and stiffness. This will in turn lead to an iterative process during which designers are forced to select trade-offs between demands on strength and stiffness, though both are directly linked to the objectives of life-safety and collapse prevention.

CHAPTER 5: SEISMIC RESISTANT BUILDINGS: DESIGN CONCEPTS & MARKET

5.1 STATE OF PRACTICE FOR SEISMIC DESIGN OF NEW BUILDINGS

5.1.1 Seismic Design and Risk Categories

Today's U.S. prescriptive code provisions use the concept of Seismic Design Category (SDC) to categorize structures based on the level of seismic risk to which they are exposed (BSSC, 2010). SDCs range from A to F, with buildings in category F being exposed to minimal seismic risk, and buildings in category A to high seismic risk, as described in Appendix E. As the seismic risk increases, the code provisions impose more stringent requirements on strength and detailing for the structures.

Structures are also classified based on their risk categories. The seismic force that structures are designed to resist was once based on their occupancy level. This category would assign a risk level and factor to the structure. This risk factor is then used to amplify the force that the building is to be designed to resist. The new edition of ASCE 7-10 *Minimum Design Loads for Buildings and other Structures* has revised this requirement. The occupancy category levels have been changed to risk categories. This change reflects the acknowledged fact that, though the goal of the previously defined categories was to assign acceptable risk levels of failure to buildings, these acceptable risks depend on other factors, not just a building's occupancy (Hamburger, 2010). Under the new risk categories, structures that serve thousands of people, and have no system redundancies, are assigned to higher risk categories than structures that serve a lesser number of people or have redundant systems (Hamburger, 2010). Thus, the traditional equivalent lateral force design of structures is configured based on the structures' seismic design and risk classifications.

5.1.2 Factors Influencing Seismic-Resistant Design

The NEHRP Provisions require that structures are configured with characteristics that will ensure that they behave adequately in the event of an earthquake. Many factors affect a building's performance under seismic loading. These factors are the building configuration of stiffness and strength and building plan regularity; the structural system design (i.e. establish redundancy, element ductility, and provide a continuous load path); and the design of the non-structural elements (BSSC, 2010).

The design of the above factors embodies the current traditional seismic resistant design practice in the US. The Provisions require that buildings classified under SDC D, E, and F, be designed in accordance with the requirements for all the above-listed factors (BSSC, 2010). The buildings classified under the SDC A and B, are allowed to exclude some of the above characteristics in their designs if the structures are designed with a higher force capacity (BSSC, 2010).

5.1.2.1 Building Configuration: Stiffness and Strength

The *Provisions* require that buildings be designed with adequate strength and stiffness to resist induced seismic forces and other types of loads (BSSC, 2010). Structures are designed to resist a fraction of the induced seismic forces (SEAOC Seismology Committee, 2008). This ensures that the basic life safety performance goals are met and implies that inelastic behavior (i.e. cracking, buckling) of structural elements are expected (SEAOC Seismology Committee, 2008). The strength requirements, the earthquake design force level that the structure is designed to resist, are generally determined based on the building's assigned seismic design category. For instance, the required strength for buildings in SDC A is calculated as a total static lateral load (1% of structure's weight) and applied at each floor level in two directions. In SDC B and C, the buildings are designed to resist both vertical and horizontal seismic forces. The building's required strength may be determined using the equivalent lateral force (ELF) method, which produces estimates for the earthquake forces (SEAOC Seismology Committee, 2008). During the ELF, the base shear, V, is taken as the product of the seismic base shear coefficient and the building's seismic weight. The base shear coefficient is dependent on multiple factors, such as the building's fundamental period of vibration (the time it takes for the building to complete one full cycle of vibration), the response modification and risk category factors (BSSC, 2010). The base coefficient is used to reduce or amplify the base shear depending on the building's designated SDC (SEAOC Seismology Committee, 2008). The intent of these modifications is to simplify the design process to an elastic static analysis (SEAOC Seismology Committee, 2008). In SDC's E and F, the ELF method of computing required strength is prohibited. The base shear is determined by more complicated analyses such as the response spectrum or nonlinear time history methods (a complete description of these methods is outside the scope of this report, and therefore will not be detailed herein) (BSSC, 2010).

Similar to required strength, the Provisions have requirements on building stiffness. These requirements aim to ensure that deflections in building levels are within acceptable limits (SEAOC Seismology Committee, 2008). A deflection amplification factor is used to control interstory drifts and the structure's deformation capacity (SEAOC Seismology Committee, 2008). This amplification factor is used to estimate the deformations that could potentially occur under the given seismic design forces. The elastic deformations, or drifts, expected under these forces are limited to a certain percentage of the building's story height (SEAOC Seismology Committee, 2008). These percentages are determined based on the building type and assigned SDC. By placing a limit on the deformation capacity, a minimum required stiffness is established (SEAOC Seismology Committee, 2008).

5.1.2.2 Building Configuration: Horizontal and Vertical Irregularities

The NEHRP provisions prescribed requirements for buildings based on the assumption that the structures have “regular configurations” (BSSC, 2010). The codes have basis on characteristic responses of structures with uniform distributions of mass, stiffness and continuous structural systems. In instances where the buildings have irregular configurations, the assumptions embedded in the code provisions can “become invalid” because they significantly impact seismic performance (BSSC, 2010). To account for these irregularities in the horizontal and vertical building design, either the designers must undertake exact analysis to counter their effects on the structure’s force and deformation distribution, or portions of the building must be designed with higher level of strength to resist the induced forces. Horizontal irregularities include torsional, re-entrant corner, diaphragm discontinuity, out-of-plane offset, and non-parallel structural system plan irregularities. Other irregularities are over the height of the building, and are referred as vertical irregularities. These include story weak and soft stiffness, weight/mass, and in-plane irregularities.

5.1.2.3 Structural System

The *Provisions* outlines design criteria for the seismic force-resistant systems (SFRS) based on the material types – wood, steel, concrete, or masonry- and type of structural system – wall, frame, etc. - used. The structural systems are categorized by their level of detailing. These systems are used to resist the horizontal (lateral), seismic or wind induced forces, as well as transfer the vertically (gravity) applied loads (i.e. building dead and live loads) to the foundation elements and the supporting soil. The following are four categories of typically used structural systems in traditional seismic resistant design:

1. Bearing wall systems: In these systems, walls located throughout the building provide both lateral and primary vertical resistance to applied loads. They are considered to be part of both the lateral and gravity force resisting systems.
2. Building frame systems: In framed structural systems, building dead and content loads are carried by horizontal frame members, beams, and vertical load bearing members, columns (gravity force resisting systems). Braces and wall elements between these members are used to provide lateral resistance (Lateral force resisting systems).
3. Moment-resisting frame systems: In moment frames, steel or concrete, beams and columns support the weight of the structure through flexure – these frames can serve as part of both the lateral and gravity force resisting systems. The rigid connections at between these members provide stiffness and strength and prevent rotations at points of connection serving as the lateral resisting system.
4. Dual systems: Dual systems combine moment-resisting frames, concrete, masonry, with steel walls or braced frames. The moment-resisting frames resist the building's gravity load as well as resisting some applied lateral forces. The concrete, masonry or steel braced frames or walls provide the lateral resistance.

Each of the SFRSs traditionally used in seismic resistant design behave uniquely when subjected to seismic loading. Usage of any SFRS is contingent upon compliance to the specific design criteria prescribed in the code provisions and industry standards.

5.1.2.4 Continuous Load Paths

In seismic-resistant design, the structures are designed to resist all lateral and uplift forces induced by the ground motions. All structural and non-structural elements are tied together to provide a continuous path through which these forces are transferred from any point of application directly to the foundation then to the supporting soil (BSSC, 2010). There should be breaks in the chain of elements that connect to the foundation. Each link in the chain is designed with sufficient strength to adequately transfer the loads.

5.1.2.5 Redundancy

The prescriptive code provisions established criteria for structural system redundancy. In seismic resistant design, a number of structural elements take part in in resisting earthquake induced forces. The concept of redundancy is such that if one or more structural elements fail in the building, the remaining elements will continue to perform without collapsing because of the other paths provided to transfer the loads. If systems are less redundant, the *Provisions* require that the structure be designed for higher forces.

5.1.2.6 Ductility

Ductility, which is typically provided for in the detailing, refers to the structural systems' ability to deform and sustain certain levels of damage and continue to resist forces without causing collapse. Each construction and material type has unique measures that can be used to achieve ductility. For instance, with steel members, ductility is achieved by properly sizing the member so as to avoid buckling from occurring. In masonry and concrete structures, heavy steel reinforcing is provided to provide tensile strength and confinement. Design criteria required to achieve ductility using these materials are provided for in the various industry standards (i.e. ACI

318, AISC 341…). Systems with better ductility are allowed to be designed for lower seismic forces.

5.1.2.7 Non-Structural Elements

In addition to the structural system, there are non-structural elements (NSE) – architectural features, mechanical, electrical, and fire protection systems, system, and plumbing fixtures – that may become damaged during an earthquake. The *Provisions* design criteria for non-structural elements are to ensure that they are properly attached to the structure to prevent them from falling and causing injury to building occupants or block exits. The prescriptive design of these elements is ensuring that equipment used in critical facilities like hospitals remain undamaged and operable post-earthquake.

The requirements of compliance differ for each non-structural element type; not all NSE are required to comply with the Provisions seismic requirements. The types of NSE that are to be designed in accordance to the Provisions are required to be anchored or braced into the structure. The anchorage and bracing are designed with sufficient strength to resist the induced seismic loads. These NSE are anchored such that, during differential displacements, they pose no threat to the life-safety of building occupants. There other types of NSE that are exempt from having to be designed in accordance to the code are mechanical equipment mounted at floor levels in buildings from SDC D, E and F. NSE's in seismic design category A through C are also exempt.

5.2 STATE OF PRACTICE FOR SEISMIC RESISTANT DESIGN OF RETROFITS

5.2.1 Context for Seismic Rehabilitation

Older buildings are potentially at higher risk of damage in earthquakes since they may have been designed without a good understanding of the strength, stiffness and ductility required for structures to withstand seismic loads. In California, the practice of rehabilitating existing buildings began after the Long Beach earthquake with the Field Act of 1939. The Field Act mandated that all existing school buildings be brought up to code or abandoned by 1975. Following that mandate, in 1984, FEMA established a program to retrofit existing buildings as a way of mitigating seismic risk. This program developed resources to assist engineers and stakeholders with rehabilitating the older buildings, providing guidelines for existing building evaluations and retrofit cost estimations. This program evolved into comprehensive performance-based design criteria, first known as FEMA 273. FEMA 273 became part of FEMA 356, which later was integrated into the ASCE 41 existing building rehabilitations standards.

The seismic evaluation of buildings may be mandated by the municipal, regional or federal seismic risk reduction programs like the 1994 California Hospital Act. The act, which was first established in 1994 following the Northridge earthquake, mandates that all existing hospitals be evaluated and retrofitted by the year 2030 such that they are able to withstand earthquakes without collapsing (SSC, 2011). In instances where seismic evaluation is required, the buildings chosen are generally identified based on their type of structural system (i.e. Unreinforced Masonry – URM), by their age and location, or other factors defined by the risk reduction program.

Evaluation of existing buildings may also be required by the local building officials when certain alterations are being made to a building such as an occupancy change, or a change in structural systems. For instance, in 1976, the city of San Francisco required that, if building owners are making changes to the buildings' structural systems or occupancy levels, the building be rehabilitated to 75% of the seismic force requirements of the new building codes. Since the establishment of these requirements, seismic damage repair triggers have been mandating that buildings be rehabilitated should the building experience a loss of seismic capacity (i.e. 33% loss of seismic capacity as set by the 2012 IBC) (ATC & SEI, 2009). These evaluations typically have a specified minimum acceptable performance level set by the governing jurisdiction that the buildings must meet. Conversely, owners may voluntary chose to conduct seismic evaluations because they are concerned about potential economic and building functionality losses in the events of an earthquake.

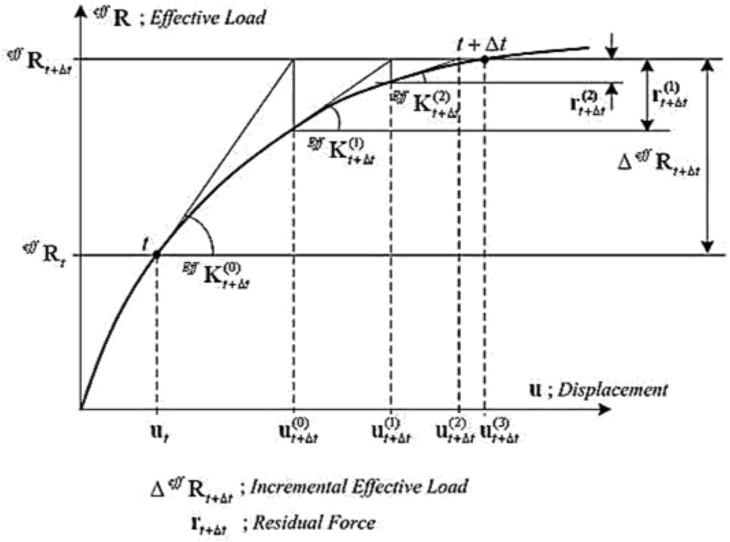
5.2.2 Existing Building Seismic Evaluation Techniques

There are many procedures that can be used to evaluate buildings. They range from the prescriptive provisions governing seismic rehabilitations to performance-based non-linear analysis of the building cyclic responses when subjected to seismic time histories. Some of these evaluation methods are:

- Compare existing building to seismic design requirements for new buildings: Before the establishment of the prescriptive codes and performance based guidelines, seismic deficiencies in existing buildings were determined by comparing them to new building design requirements. In certain cases, this comparison was difficult, if not impossible. For instance, when comparing structural systems or materials that were once permitted to be used in buildings and no longer are, comparing these existing buildings to the new requirements would often require that the materials or systems be removed. Complete removal of these systems would be impractical. To address the deficiencies, it would be common to introduce new seismic compliant systems, which may be costly and cause disruption to building activities.

- Prescriptive Provisions: among the other prescriptive codes available for the rehabilitation of existing buildings, the 2003 edition of the ASCE 31, Seismic Evaluation of Existing buildings is the most frequently used. This standard acknowledges that fact that older building may have used older structural systems that were once accepted in older codes. The standard establishes a three-tiered evaluation process for existing buildings. These buildings are evaluated based on the Life Safety and Immediate Occupancy performance levels. If the minimum life safety is met, the building is said to be adequate.
- Performance-Based evaluation (hazard, structural, damage and loss analyses): The structural and damage analyses take into consideration the expected non-linear response of the structure during ground shaking. These analyses can be achieved using earthquake time histories or pushover analyses – static non-linear analysis (as detailed in the ASCE 41-06 document) during which the structure is subjected to gradually increasing forces until failure occurs (Figure 13). The analysis results are compared against the performance objectives to ensure that they are met. The advanced loss analyses of PBEE is used to estimate direct economic losses resulting from repair costs, and other non-direct losses due to building loss of function and human fatalities. Using these forms of evaluation, the local governments or owners select a minimum acceptable performance level.

Figure 13: Pushover analysis (Islam, Jameel, & Jumaat, 2011)



5.2.3 Categories of Seismic Deficiencies

Some of the deficiency categories typically found in older buildings are summarized below. The deficiencies, once identified, dictate which techniques that may be used to address them. This list is not exhaustive, as there may be other deficiencies found in existing buildings that are not covered in the categories below.

5.2.3.1 Lack of “Global Strength”

“Global Strength” describes the lateral strength of the lateral-force resisting vertical elements at the “global yield point”. Global strength deficiency is common in older buildings because of lack of seismic resistant design (i.e. little or no lateral loads) or design in accordance with an older code with a lower strength requirement. Since the global strength affects the inelastic displacement demands, adding strength may reduce the non-linear deformations to acceptable values.

5.2.3.2 Global Stiffness

Global stiffness is the entire lateral force-resisting system stiffness. In buildings with walls that are narrow, interstory drifts are critical at the upper levels. Conversely, in frame buildings, critical drifts typically occur at the lower levels. Adding stiffness to the poorly designed structural elements can effectively reduce the critical drifts at the levels of concern.

5.2.3.3 Configuration

In this category, deficiencies are based on the building configuration irregularities. In older buildings, the horizontal and vertical irregularities of the type now addressed in the code may be present. In prescriptive evaluations, these irregularities are addressed using rules, similar to those governing new building irregularities. In performance-based evaluation, non-linear analysis of the building irregular configuration is used to identify force concentrations due to these irregularities and the elements that are inadequate designed to resist these forces.

5.2.3.4 Component Detailing

Component detailing refers to the detailing of structural elements to resist demands that exceed component capacity such that the component responds in the non-linear range. One example of component detailing deficiency is concrete elements designed without adequate confining reinforcement, which increases their risk of shear failure and decreases their ability to deform by bending. In older existing concrete structures, the predicted drifts from a seismic event are often greater than the deformation capacity of the reinforced columns. These deficiencies may be addressed at the component level instead of adding new structural elements, which can minimize cost.

5.2.3.5 Diaphragms

Diaphragms are the horizontal components of the load path that distributes load between different lines of the lateral force-resisting systems. Deficiencies affecting diaphragms are insufficient shear strength, element stiffness, or re-entrant corners. Other deficiencies in diaphragms such as lack of shear transfer to lateral systems, or missing shear collectors may lead to a break in the load path, and thus create another deficiency.

5.2.3.6 Deterioration and Degradation

Deteriorating materials in structural elements may adversely affect performance during earthquakes. Deterioration may be resulting from fire, poor workmanship, or damage incurred from previous earthquakes, and corrosion or other weather induced damage. Prior to outlining and carrying out an overall strengthening plan, the condition of deteriorated element should be evaluated and addressed.

5.2.4 Methods of Seismic Rehabilitation

Once all the deficiencies have been identified, the rehabilitation scope of work is determined by addressing these deficiencies directly. The common rehabilitation measures usually address the deficiencies in the vertical elements because of they are used to provide lateral and gravity loads resistance. The following are some techniques that may be used in addressing some of the deficiencies mentioned in the preceding sections.

- Element addition
- Existing element performance enhancement
- Connection improvements
- Reduction of seismic demand

5.2.4.1 Adding Elements

Adding elements like shear walls, braced or moment frames to existing buildings can address the deficiencies in global stiffness and strength; in diaphragms, by shortening the spans between the lateral force-resisting systems; and in the building configuration. The added elements may serve as collectors and fix any deficiencies in the load paths. When carrying out a rehabilitation scheme, some of the techniques used to address on deficiency may create a deficiency in another category. For instance, adding new elements to add global stiffness and strength may create a load path deficiency if the new loads generated by the addition are not adequately carried by the other members. In concrete buildings, for example, shear walls are commonly added in seismic rehabilitation, which can improve strength and address soft/weak story deficiencies.

5.2.4.2 Enhance Performance of Existing Elements

Instead of techniques that affect the structure as a whole, deficiencies may be addressed on a local level, by fixing the component instead of a system of components. This is done by working with one component and fixing its shear and moment strength, or increasing that element's deformation capacity. In addition to addressing deficiencies on a component level, designers can also establish a force-resisting system yielding sequence. Since yielding will occur in some elements, it is preferable to allow beams to yield before columns, braces before connections; and flexure before shear in columns or walls. By allowing the vertical elements to yield last, safe exit passage to building occupants is ensure in addition to collapse prevention.

5.2.4.3 Improve Connections between Components

This technique is commonly used to address load path deficiencies. Improving connections between load carrying elements can aid in mitigating load path deficiencies. There are other connections not directly in the load path that may be brittle and require strengthening to ensure that gravity loads are adequately supported during ground motions.

5.2.4.4 Reduce Demand

Seismic demand may be reduced by using seismic isolation devices (discussed in section 5.3.1 of this chapter). This is viewed as being costly when compared to alternatives techniques, but is commonly used in historic buildings or others with building occupants that cannot be disturbed. A more economically viable option to reducing demands is the addition of damping devices in the structure. These devices aid in reducing deformation demands by supplementing the structure with damping. Use of these passive control devices in new and retrofit construction is discussed in more detail in the subsequent sections.

5.3 PASSIVE CONTROL SYSTEMS

Over the years, engineers have worked to improve the seismic resistance of traditional systems by further refining the prescriptive provisions that govern them. Nevertheless, these systems are still being designed with the projected outcome that they will sustain damage during earthquakes (BSSC, 2010). After the 1971 earthquake, scientists and engineers began researching and developing passive control systems and technologies that are able to resist earthquake ground shaking without damage, thus protecting the superstructure (Naeim & Kelly, 1999). These seismic protective systems (SPS) are referred to as passive as their operation does not depend on any additional energy input; they are activated by the seismic ground motions (CEHNC, 2007). These passive control systems are designed to dissipate the input seismic energy through the deformation and yielding of specialized devices or connections. Damage to the superstructure is minimized because the deformation and yielding are concentrated at the level of isolation or energy dissipation. The NEHRP *Provisions* currently have established design criteria for two SPS – seismic base isolations and energy dissipating systems (BSSC, 2010).

Seismic isolation and energy dissipation systems are an alternative to traditional seismic design. These systems are used to enhance buildings in such ways that allows them to achieve higher levels of seismic performance. They can be used to mitigate damage during an earthquake event, and ensure post-earthquake building functionality. The higher performance goals of damage mitigation and post-earthquake functionality provide owners with more protection than the minimum life-safety standard required by the prescriptive provisions governing traditional seismic design (CEHNC, 2007).

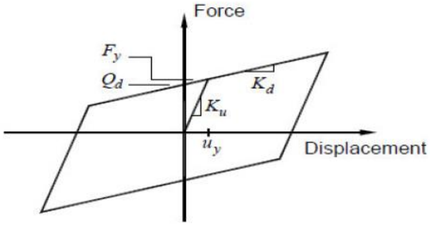
5.3.1 Seismic Isolation Systems

The first seismic base isolation application in the US was constructed for the Foothill Communities Law and Justice Center, in California in 1985. The facility was designed to rest on 98 laminated rubber bearings (Naeim & Kelly, 1999). The first code provisions for seismic isolation systems, the *Tentative Seismic Isolation Design Requirements*, were published in 1986 by the Structural Engineers Association of Northern California (SEANC) (Taylor & Aiken, 2012). These provisions became the first code governing seismic isolation systems. Building codes today reference the ASCE/SEI 7 for applications to new buildings and ASCE/SEI 41 for existing buildings (Taylor & Aiken, 2012).

The types of seismic isolation systems commonly used are elastomeric bearings and friction sliders. The objective of these systems is to decouple the building structure from the damaging components of the earthquake input motion, i.e., to prevent the superstructure of the building from absorbing the earthquake energy (CEHNC, 2007). Seismic isolation devices are considered “flexible mounting systems” since they are typically placed at the foundation level and support the structure (Sommer & Trummer, 1993).

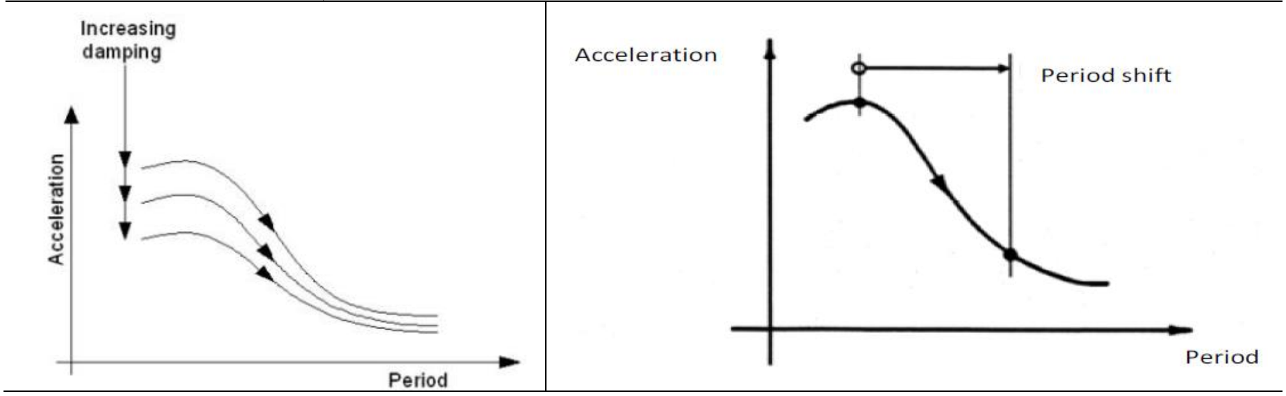
Base isolation devices are designed absorb seismic energy and to provide damping. These devices are hysteretic systems (Sommer & Trummer, 1993). The hysteretic characteristic of isolation devices refer to the gap seen during cyclic loading between the loading and unloading curves (Islam, Jameel, & Jumaat, 2011). The isolator’s response lags behind the imposed seismic ground accelerations (Sommer & Trummer, 1993). This hysteresis provides damping to the structure by means of hysteric dissipation of energy. (Islam, Jameel, & Jumaat, 2011) The damping allows for a way to dissipate energy from the building and restricts the displacements of the superstructure to acceptable limits (Sommer & Trummer, 1993). Figure 14 depicts and idealized hysteretic force-displacement loop where the area enclosed measures the amount of energy dissipated during one cycle of motion (Islam, Jameel, & Jumaat, 2011).

Figure 14: Idealized Hysteretic Force-Displacement Loop Of Base isolation systems (Islam, Jameel, & Jumaat, 2011)



The isolators effectively shift the building's peak responses away from those of the earthquake. The structure's natural frequency is decoupled from that of the earthquake, thus allowing the structure to vibrate at a lower vibratory frequency (Sommer & Trummer, 1993). With a decreased natural frequency, the period of vibration of the structure is increased (Figure 15). By lengthening the natural period, the floor accelerations and velocities, as well as the overturning moments and relative maximum base shear are significantly reduced (Sommer & Trummer, 1993). With displacement and yielding occurring at the level of the base isolators, the structure behaves likes a single degree of freedom (SDOF) rigid body (CEHNC, 2007).

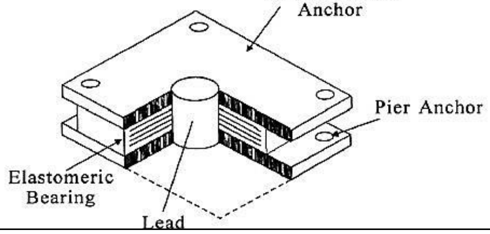
Figure 15: Isolator Decoupling peak responses of structure from those of Earthquakes (Islam, Jameel, & Jumaat, 2011)



5.3.1.1 Elastomeric Rubber Bearings: Lead and Shape Memory Alloy

The elastomeric isolator, also referenced as the Lead Rubber Bearing, LRB, is a laminated rubber block (Figure 16). During fabrication, a number of tightly fitted, horizontal rows of steel plates get bonded to individual sheets of rubber to create the block (Sommer & Trummer, 1993). This block has a cylindrical core made up of pure lead. The lead core acts as a vertical plug, binding all the horizontal rows of alternating steel plates and rubber together (Sommer & Trummer, 1993). It also acts as a central column that restricts the lateral movements of the plates, and prevents the rubber from bulging outward (Sommer & Trummer, 1993). The lead core has a high vertical stiffness, permitting it to carry large gravity loads.

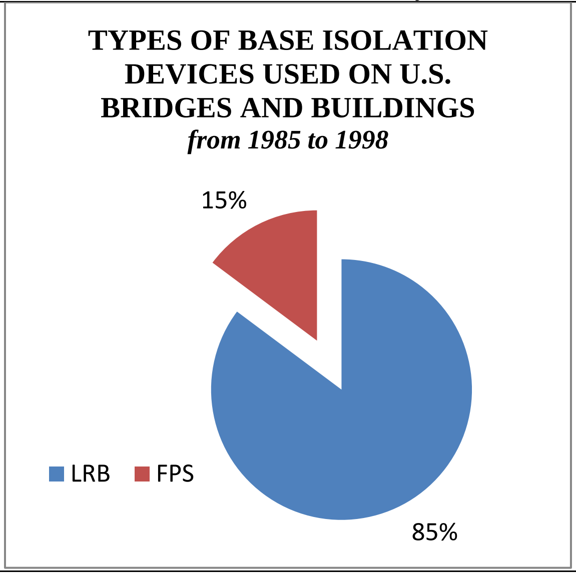
Figure 16: Lead Rubber Elastomeric Bearing
Reproduced from: http://hendrisingarimbun.com/2009/08/pengaruh-penggunaan-base-isolator-lead.html



Under small lateral displacements (e.g. wind-induced displacements), the lateral stiffness is effective in providing restraints. Under large displacement demands, the lead core yields in order to dampen the structure and provide the flexibility needed from the isolation system. The damping allows the bearing to absorb the earthquake’s energy and to restrict further lateral movements, and the horizontal elasticity of the rubber returns the structure to its original position (Islam, Jameel, & Jumaat, 2011). This elasticity originates from the restoring force generated by the rubber layers (Islam, Jameel, & Jumaat, 2011). Figure 17 compares the number of applications of the LRB to the Friction Pendulum systems (FPS) (detailed in following section).

From 1985 to 1998, of the different types of isolation devices applications in bridges and buildings, the LBR has been most frequently used.

Figure 17: Rate of Use of LRB in US Bridge and Building applications
Developed from EERC 1998 North America Base Isolated Structures Directory



5.3.1.2 Friction Pendulum Isolation Systems

The FPS, formerly defined as the friction pendulum isolation systems, is a sliding isolation system that supports the weight of structure by means of “sliding interfaces” (Mokha, Constantinou, Reinhorn, & Zayas, 1991) (Figure 18). The structure is isolated from the ground motions by the friction bearings. These bearing are comprised of a spherical slider resting on a chrome surface (Mokha et *al.*, 1991). The bearing material on the surface of the slider generates a frictional force- with minimum and maximum friction coefficient of 0.05 and 0.1 respectively (Mokha et *al.*, 1991) - when in contact with the chrome surface, while the concave spherical portion produces a restoring force (Matsagar & Jangid, 2008). Through use of a sliding mechanism the FPS is able to “reduce and spread the earthquake energy over a wider range of frequencies,” and thus is insensitive to the earthquake excitation frequency (Matsagar & Jangid, 2008). For instance, the range of frequencies observed during a laboratory experiment conducted on a six-story building resting on four 8-ft FPS devices subjected to the El Centro earthquake ground accelerations were between 1 to 4 hertz (Hz) (Mokha et *al.*, 1991).

Figure 18: Friction Pendulum

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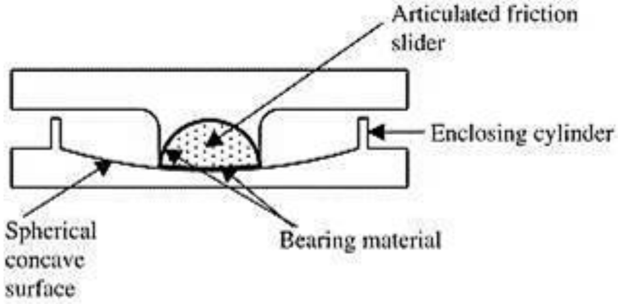


The use of the FPS over conventional rubber bearings is advantageous in that it helps to reduce the torsional effects produced by asymmetrical structures because the proportional frictional force of the sliding system at the base allows the FPS to align its center of mass and center of resistance (Matsagar & Jangid, 2008). This force is developed during the rising of the superstructure along the spherical surface during the ground motions (Matsagar & Jangid, 2008). The bidirectional lateral force produced by the FPS is equal to the frictional and the restoring force (Matsagar & Jangid, 2008).

Conversely, there are concerns of uplift forces which may compromise the integrity of the isolation devices (Fardis, 2010). Research on the providing uplift restraint in sliding isolator devices led to the development of the Uplift-Restraint FPS (UR-FPS) (Fardis, 2010). Contrary to the conventional FPS discussed in the preceding paragraphs, the UR-FPS (Figure 19) facilitates the transition from compression to tension and vice versa when subjected to bearing axial forces (Fardis, 2010). When the UR-FPS is subjected to overturning moments, the negative stiffness that results from tension forces developing in the isolator will be balanced by the compressive forces that generate as a result of the moment force; this will result in the same overall isolator stiffness and an increase in friction force (Fardis, 2010). Data on the current rate of application for the UR-FPS is not available to illustrate the device trend on the present earthquake resistant design market; however, from Figure 17 it can be concluded that the friction pendulum systems are not as widely used as the LRB isolators in the U.S.

Figure 19: UR-FPS Isolator (Fardis, 2010)

5.3.1.3 Seismic Isolation Non-Economic Technical Benefits

Base isolations have many technical benefits. There have been many tests conducted on base isolation and their overall effects on the structures that utilize them. Among the different benefits associated with base isolation, the most general and common are listed herein. Given that they are able to allow the structures to vibrate at a lower vibratory frequency, they effectively reduce the accelerations “felt” by the structure. Compared to a fixed based building that amplifies the forces at the roof level by a factor of 2.5 to 4, base isolation devices reduces these forces by a factor of 8 to 12 (recorded forces at the roof level of a 6-story base isolated building in Japan during the Kobe earthquake) (Mayes, Brown, & Pietra, 2012). Base isolation devices have also been shown to be effective in providing a 70%-80% reduction in seismic demand depending on the period of the structure (Goda, Lee, & Hong, 2010). These devices have the ability to reduce the design base shear by a factor of 3 to 7 depending on the soil characteristics, earthquake moment magnitude, building period and distance to a fault (Mayes et *al.*, 2012). With this reduction, the ductility demand is decreased, as well as the interstory drifts (reduced by a factor of 4 to 8) (Mayes et *al.*, 2012). As a result of this decrease in interstory drifts, damage to the structural and non-structural elements are also decreased (Mayes et *al.*, 2012).

5.3.2 Energy Dissipating Systems

Energy dissipating systems, also known as supplemental dampers, supply the superstructure with additional damping, thus allowing the structure to reduce its responses to the earthquake ground motions (CEHNC, 2007). The structure is able to dissipate the input seismic energy since deformation and yield occurs in the energy dissipation devices (CEHNC, 2007). Supplementary damping using these systems may be achieved by means of an added viscous damping through viscous fluid, viscoelastic, metallic, and friction dampers (Symans, et al., 2008). Only the commonly used energy dissipation devices are described in the subsequent sections. Their advantages and disadvantages are listed in Appendix F.

5.3.2.1 Viscous Fluid Dampers

Viscous Fluid dampers are made up of a hollow cylinder filled with silicone-based fluid (see Figure 20). As the piston head and the rod get stroked, the fluid is forced to flow through orifices located around and/or through the piston head. The result is a differential pressure across the piston head (relatively greater pressure on the upstream side than on the downstream side). This pressure is able to produce large forces to resist the movements of the damper. In addition to the pressure in the piston head, because of the high velocity at which the fluid flows, friction forces are developed between the piston head and the fluid particles. The friction force brings about energy dissipation in heat form. This temperature increase can cause potential heat-induced damage to the sealers in the dampers. In such instance, the temperature level can be reduced by using a damper with larger piston head. Alternatively, viscoelastic fluid dampers may be used instead of viscous fluid dampers. This type of damper, among the viscoelastic and the friction dampers, is the frequently used in U.S. buildings and bridge applications (Figure 21).

Figure 20: Viscous Fluid Dampers
Gleaned from: http://taylordevices.com

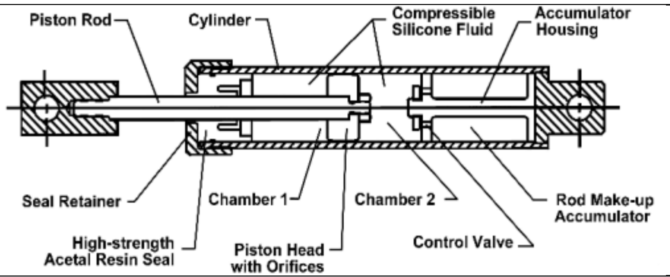
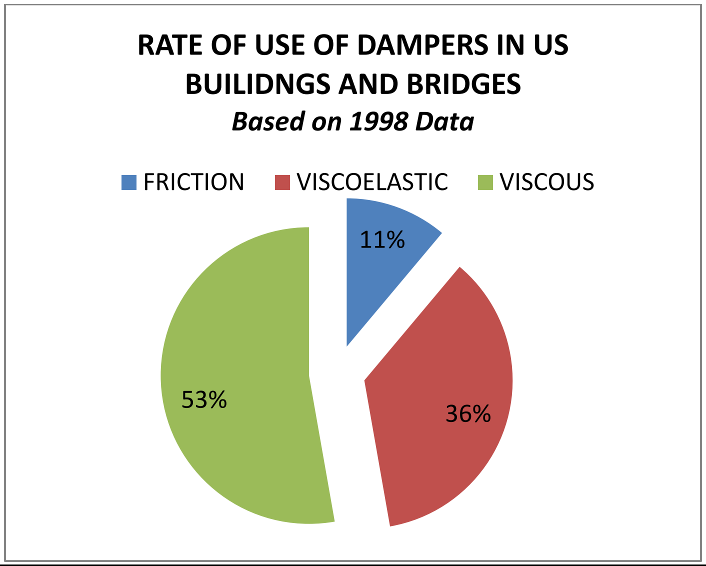


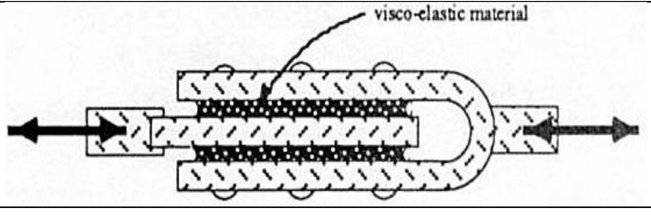
Figure 21: Rate of Use of Dampers in U.S. Bridges and buildings
Developed from EERC 1998 Data for US Damper Applications



5.3.2.2 Viscoelastic Solid Dampers

Viscoelastic fluid dampers are able to provide stiffness in addition to damping. These systems provide damping by means of “fluid orificing,” fluid flowing through orifices in the damper, and restoring forces by compressing an elastomer (Symans, et al., 2008). The viscoelastic solid dampers are comprised of elastomeric pads that are fused to steel plates (see Figure 22). These steel plates are attached to the structure via diagonal bracing or other methods. Differential movement of each end of the damper causes shearing of the viscoelastic material of the elastomeric pads, which diffuses heat. These dampers are velocity and displacement dependent –the restoring force is proportional to the displacements and the damping force is proportional to the velocity–, and is thus elastic and viscose in nature; thus, the dampers have the ability to dissipate and store energy (Symans, et al., 2008). These mechanical properties of loss and storage of energy depend on the properties of the viscoelastic material and the frequency of motion. For any given frequency content, the moduli of loss and storage values increase with the motion frequency. Therefore, at low vibratory frequencies, the dampers have low stiffness and energy dissipation capabilities, and at high frequencies, the dampers have lower energy dissipation and storage capacities. Based on 1998 data on U.S. damper applications, Figure 21 shows that viscoelastic dampers have been used less frequently than viscous dampers, but more frequently than friction dampers. Of the dampers used up to 1998, 35% were viscoelastic.

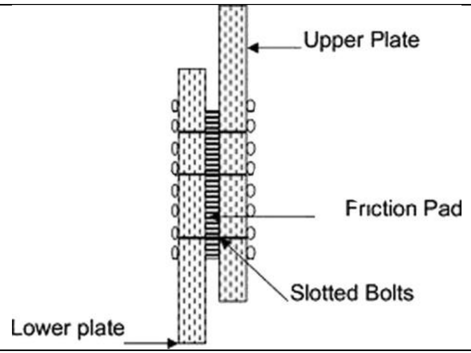
Figure 22: Viscoelastic Solid Dampers
Gleaned from: http://www.conservationtech.com



5.3.2.3 Friction Dampers

Friction dampers, like the slotted-bolted dampers (Figure 23), dissipate energy by means of sliding friction between two solid bodies. The slotted-bolted dampers consist of a series of steel plates, with a specified damping force, bolted together. The damper is typically bolted to the diagonal bracing of the structural elements. Under lateral loading, the structural frame elements move differentially, such that one is under tension and the other under compression. The damper is forced to deform into a parallelogram. The energy dissipated occurs at the bolted joints via sliding friction. Deformation of the framing element is restricted until the friction force in the damper has been "overcome" (Symans, et al., 2008). Therefore, the damper is used to add an initial stiffness to the structural element to which it is attached. For this damper to be effective, a restoring force mechanism is provided in the friction system to prevent permanent deformation of the structure (Symans, et al., 2008). The friction dampers are less frequently used in application compared to the dampers described in the preceding sections (Figure 21).

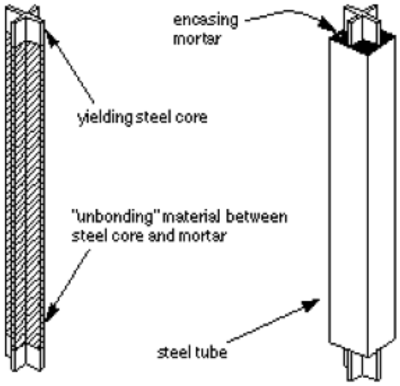
Figure 23: Slotted-Bolted Friction Damper
Gleaned from: http://www.sciencedirect.com/



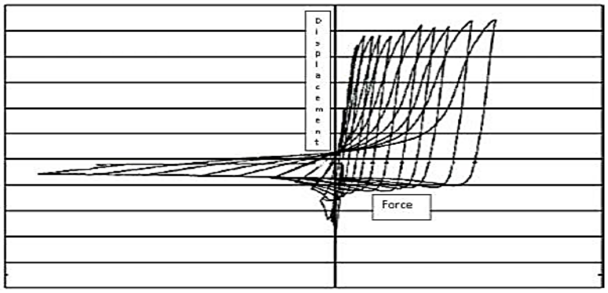
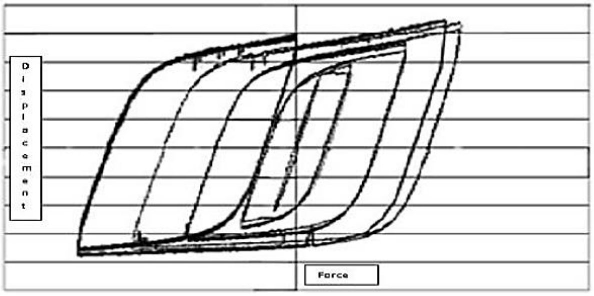
5.3.2.4 Metallic Dampers

The buckling restrained brace (BRB) is the most common type of metallic dampers. The BRB damper (Figure 24) is made up of steel brace (low-yield strength), which has a cross section defined by a steel tube surrounding a cruciform-shaped braces (Symans, et al., 2008). The structural framework of the BRB is developed such that the brace remains elastic in its responses to seismic loading, with all the yielding occurring in the braces.

Figure 24: BRB Dampers (Deulkar, Modhera, & Patil, 2010)



The braces are coated with a special material to prevent bonding to the concrete that fills the region around the brace and the tube. This coating allows the brace freedom to slide against the concrete-filled area inside the tube. This confinement provided by the concrete and tube provides flexural strength and stiffness to help prevent the brace from buckling when subjected to compressive loads. The tube and concrete encasements also help the braces with resisting lateral buckling (Deulkar, Modhera, & Patil, 2010). Therefore, with the prevention of buckling, the BRB is able to dissipate larger amounts of energy over each cycle of motion, as can be seen in the difference in areas under the hysteretic loops of the BRB compared to the conventional braces (Figure 25 & Figure 26) (Deulkar, Modhera, & Patil, 2010). The energy dissipated is achieved during the “tension-compression yield cycles” (Deulkar, Modhera, & Patil, 2010). The damper can thus be loaded in tension and compression, with the loads being entirely supported by the steel brace (damper behaviors are the same in compression and in tension) (Symans, et al., 2008).

Figure 25: Hysteretic loop for conventional braces (Deulkar, Modhera, & Patil, 2010)	**Figure 26: Hysteretic loop for BRB (Deulkar, Modhera, & Patil, 2010)**
	

The BRB was first introduced in the US in 1999, with the first application occurring in 2000 (Deulkar, Modhera, & Patil, 2010). Since 2000, the BRB has seen a more rapid growth compared to the other types of energy dissipating devices (discuss in more detail in later sections). Although no data yet exists comparing the rate of use of BRB to other dampers, with the total number of braces in use reported to be around 20,000 (López, 2008) in the US alone since 2000, it can be concluded that they are more frequently used than other dampers.

5.3.2.5 Energy Dissipation Devices Non-Economic Benefits

5.3.2.5.1 Buckcling-Restrained Braced Frames

The non-economic, technical, benefits of one of the most common types of energy dissipation, supplemental, dampers, the buckling-restrained braced frames (BRBF) are presented in this section. The benefits are illustrated as the level of damping that these devices have been proven, by means of large scale testing, to add to structures. Two studies are briefly outlined herein to illustrate the technical benefits of BRBFs. The first study aims to illustrate the BRBF’s level of supplemental critical damping capability, and the second, their capacity to reduce roof displacments.

The design of the Plant and Environmental Sciences Replacement Facility, a 3-story Eccentrically-Braced steel frame laboratory on the University of California Davis Campus, was analyzed during a recent study (Clark, Aiken, Ko, Kimura, & Kasai, 1999). Nonlinear static pushover analyses were conducted for the building designed using three different types of BRBFs, the concentrically (CF), eccentrically (EBF), and unbonded-braced frames (UBF), to analyze its behavior under seismic loading. The behaviors observed differed for all three types. The CF building was observed to have multiple member failures when subjected to the seimisc time histories, whereas the UBF members resisted the induced forces up to the performance point, the point at which the capacity of the frames intersected the demand, without failure (Clark et *al.*, 1999). On average, the braces were seen to add damping to the buildng in the range of 24% to 34% of the assumed 2% critical damping (Clark et *al.*, 1999).

The second second study assessed the the performance of conventional-braced frames (CBF) as compared to the BRBFs (Sabelli, 2001). For the analysis, engineering firms were contracted to design 3 sets of 3-story CBF and BRBF buildings, and 3 sets of 6-story CBF and BRBF buildings (Sabelli, 2001). A total of 6 CBF buildings were analyzed, three 3-story and three 6-story buildings. The same sets of buildings, configured with a variety of concentrically-brace frame configurations, were sujected to a variety of ground motion intensities, chosen to represent the types and magnitudes of earthquake that the building site might experience during a specific period of time.

When the 6-story BRBF builidng was subjected to the 1989 North Palm Springs earthquake time history (52g), the peak recorded roof displaceent, in inches, was 11.93 (Sabelli, 2001). The maximum interstory drift ratio observed at any floor level was 2.3%. Conversely, the roof displacements were seen to be magnified by a factor of 10 for the similar CBF 6-story building. When the same 6-story building was subjected to 1992 Landers ground motion, the average drift ratios were 1.6% for the BRBF and 1.8% for the CBF (Sabelli, 2001). The study showed that short- and long-period BRBF buildings have the same peak interstory drift ratios that remain below 2% (Sabelli, 2001). Conversely, the CBF buildings' peak interstory drifts reached close to 4%, with 14 out of 20 braces fracturing during the earthquake time-histories analyzed (Sabelli, 2001).

5.3.2.5.2 Viscous Dampers

Various models designed with viscous dampers were tested at the SUNYAB in 1995. Among the models were a one 3-story reinforced concrete frame and a bridge. The models were subjected to various earthquake time histories during 150 shake table tests (Taylor, 1996). The results indicated that the models' damping levels were in the range of 20% to 60% of the critical damping, assumed 5% for conventional buildings (Taylor, 1996). The dampers' responses were observed to be out of phase with the shear stresses in the structure, implying that the dampers are capable of reducing deflections and stresses. Other benefits of the viscous dampers compared to the friction and visco-elastic dampers is that the device is "self-contained," requiring no supplemental power source or equipment (Taylor, 1996). Their small and compact size make them easy to install (Taylor, 1996). They are also seen as versatile in terms of their application, given that they have been used in a great number of military applications since their first invention in 1897 (Taylor, 1996).

5.4 MARKET FOR BUILDINGS WITH HIGH SEISMIC PERFORMANCE

Compliance to the prescriptive provisions is mandatory, so all buildings in high seismic regions of the U.S., including California, Washington and Oregon are designed with such provisions and their applications to seismic resistant design of buildings will not the focus of this section. Sections 0 and **Error! Reference source not found.** detailed some potential benefits to sing PBEE design procedures and the SPS to achieve of higher than required seismic performance for structures. Although it is known that application of PBEE procedures and SPS in seismic resistant design will reduce economic losses and building damage after an earthquake, these methods are not widely used. The current applications of using PBEE and SPS to achieve higher seismic performing structures will be detailed in the subsequent sub-sections.

5.4.1 Adoption of PBEE for Design of New Buildings

Given that no known statistics regarding PBEE rate of use in seismic resistant design is currently available, personal communication with J. Hooper is used in this section to define its use in US current seismic design practices. Hooper is John is a Principal and Director of Earthquake Engineering at MKA. He is a national leader in seismic design is very involved with FEMA, ASCE, and EERI; he currently chairs EERI. According to Hooper, use PBEE is particularly common for design of tall buildings. This is because ASCE-7 requires that all buildings with heights greater than 240 feet to have a special moment frame designed as back-up, *i.e.* a dual system. These buildings designed without the back-up moment frame are becoming increasingly common due to the fact that the resulting building is “safer, quicker to construct, less expensive, and have a more flexible space layout” (Loesch, 2007). This practice is encouraged by the availability of the PEER Tall Building Seismic Design Guidelines, which provides recommendations for the seismic resistant design of tall buildings covered under the building code alternative (non-prescriptive) provisions. Therefore, the majority of the tall buildings built on the West Coast are built using PBEE design procedures (Hooper, Personal Communication; March, 2012). In addition, Hooper estimates that approximately 1 in 5 hospitals and other emergency centers use PBEE design procedures (Hooper, Personal Communication; March, 2012). The author believes that the underlying concept in using the PBEE methodology in these critical facilities is to provide higher performance. Since hospitals are needed for post-earthquake use, higher levels of performance are necessary to ensure minimal to no damage occurs to the structure and its content. Other structures that use PBEE design procedures are retrofit buildings since ASCE 41; the governing code for seismic rehabilitation of existing buildings is developed based on the founding principles based on PBEE (Hooper, Personal Communication; March, 2012).

5.4.2 Adoption of PBEE for Rehabilitation of Existing Buildings: US

With existing building rehabilitations, a regional analysis of current trend is necessary since the requirements for retrofitting may differ for different regions of the US. The focus is on examining the trend in the types of buildings, ownerships and materials of construction that have been retrofitted in two regions in California, Berkeley and San Francisco Bay. The data presented toward the end of this section will detail these characteristics. This section will further illustrate the public mind set underlying the trend in seismic rehabilitation in the Bay Area. An analysis conducted by Rabinovici (2012) will be used to illustrate the motivations behind these retrofits.

As stated in Section **Error! Reference source not found.**, the requirement for seismic valuation of existing buildings may originate from local jurisdictions, or municipal risk mitigation programs. In some case, these laws may require that structures that failed to meet certain established performance levels to be rehabilitated; in others case, the laws may make require the structures to be evaluated but not mandate rehabilitation. One instance of a mandated evaluation and a recommended rehabilitation law is the city of Berkeley's Soft-Story Ordinance. The ordinance, the result of the City of Berkeley's 2005 Municipal Code amendment, mandated the identification of any wood-framed multi-unit residential buildings with potential soft/weak story deficiencies. 321 multi-family residential tenant-occupied buildings, constructed between 1920 and 1950, were identified. The law mandated that buildings owners obtain engineering evaluations of their buildings, and display warning signs to indicate that the seismic risk posed by the building as a result of the soft/weak story deficiency. The law did not require that owners rehabilitate the identified buildings.

Rabinovici (2012) conducted a study, by means of surveys and interviews, of 43 of the 321 building owners that were affected, with the objective of illustrating the motivations behind their decisions to retrofit or not retrofit (Rabinovici, 2012). Those building owners were small business owners, and were not familiar with seismic risk mitigation strategies in their buildings; nearly all of the owners were not aware of the seismic risk their buildings posed (Rabinovici, 2012).

The result of the study indicated that about 20% of the 43 owners voluntarily retrofitted their buildings (Rabinovici, 2012). Some of these building owners saw rehabilitation as a protection of their investment, and as adding market value to their properties. The majority of these retrofitters were motivated to rehabilitate because they did not foresee selling the investment for at least 20 years (Rabinovici, 2012). In addition, Rabinovici (2012) found that they were compelled to take action as they realize the economic implications and consequences imposed by the law, including the stigma created by the building being identified as being deficient and the risk of this deficiency. These owners feared further impositions from the law. The non-retrofitters were owners that anticipated selling the buildings within the next years. Thus, these authors had no incentives to retrofit as any potential benefits would be transferred upon the sale property; they would not benefit from the rehabilitation. Although 80% of the owners did not retrofit, the majority came to the realization that their investments may be worth less because of the risks associated with the soft story deficiencies (Rabinovici, 2012). They acknowledged the fact that they may also be exposed to future financial burdens in the event of an earthquake. With seismic rehabilitation in some case seen as an investment, and others as providing no immediate benefits, as was the case with the non-retrofitters detailed previously, the author believes that, because of this barrier, the uptake on seismic rehabilitation is slower in the US.

With the motivations behind rehabilitation detailed in the Rabinovici study, certain trends have developed in the uptake of retrofit risk mitigation efforts. To illustrate the trend in rehabilitated projects in the Bay Area in California, 730 of 1443 projects were selected and studied. Information regarding these 1443 projects, located in the Bay Area of California, was gleaned from the Bay Area Retrofit database. This database includes information such as construction and ownership types, chosen rehabilitation schemes, and date of retrofit; project locations were not provided to keep client information confidential. A sample of projects from the database was chosen to illustrate the rehabilitation trends. The sample included a large enough number to properly illustrate the population; these projects were selected based on their order of appearance on the database. The author chose to select the first 730 projects of varying construction and ownership types, completion dates and rehabilitation schemes.

The trend on the project construction types observed from the review of the projects previously mentioned was that residential and non-government commercial projects from the private sector made up approximately 69% of the data sampling. Of the 69%, 59% of the 730 projects are residential properties (Figure 27). All of the 426 homes were originally wood-frame constructions (Figure 28). Government and other institutional properties such as churches and schools only comprise 27% of the 730 projects. From the Rabinovici study, it would be expected that a lower percentage of owners from the private sector would choose to retrofit for reason stated in the first few paragraphs of this section. A different trend was observed from the review of the projects listed under the Bay Area. More owners from the private than the government sectors are rehabilitating. The motivations underlying this trend was determined as part of the data sampling. The author estimated percentages to represent the owners who chose to retrofit as a result of certain incentives. These percentages are based on comments that owners posted with their buildings informing why they undertook the renovations. Not all buildings were noted with the motivations; therefore large assumptions were made in deriving the percentages. Some extrapolation across the whole data sampling was also done to make the statements presented below.[10]

The motivations behind the seismic rehabilitation of the 730 projects reviewed were due to offered monetary incentives, or building renovation code triggers. Out of 730 projects reviewed, the author estimates that approximately 30% of the owners, excluding those who retrofitted because of offered incentives, chose to voluntarily rehabilitate their buildings. Two monetary incentives were seen to effectively encourage owners to retrofit. The author estimates that approximately 5% of the 426 residential homeowners, assumed to be located in Berkeley,

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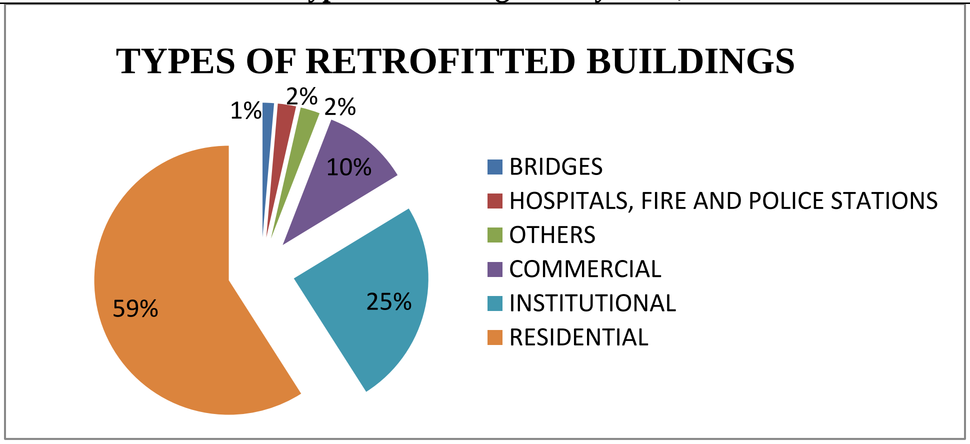
[10] These percentages may not be reliable as the data obtained was not comprehensive.

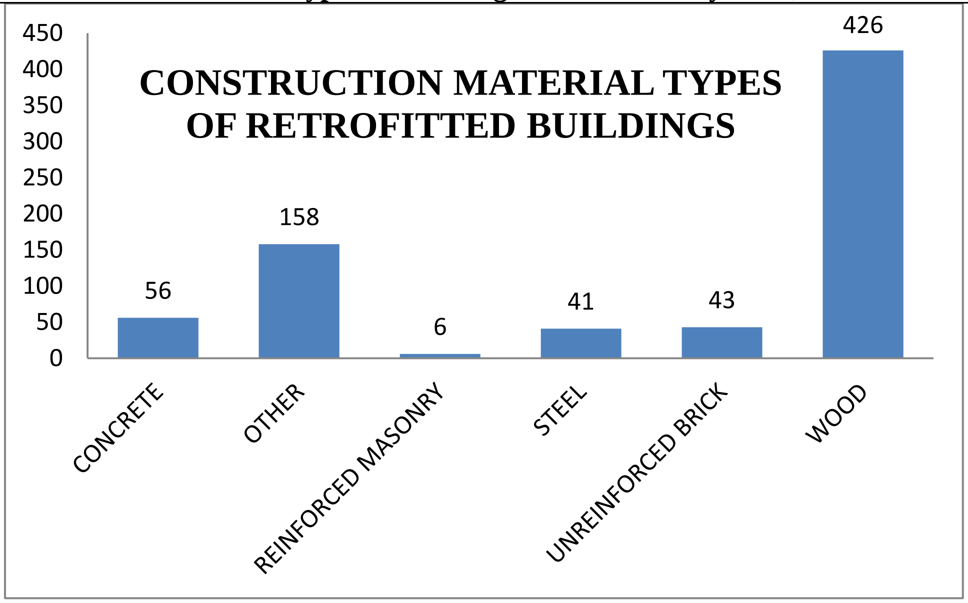
chose to rehabilitate their properties because of the Berkeley Incentive Program. This incentive is a rebate program that offers homeowners up to 1/3 of the City's transfer tax to be used as funding for qualified retrofit projects. Additionally, an estimated 20% of these homeowners, assumed to be located in Oakland, retrofitted because of the Oakland New Homeowner program. This program offers new homeowners who voluntarily retrofit 5% of their home purchasing price as rebate, or $5000, whichever is less. It is unclear from the data what the motivation behind the retrofit endeavors of the remaining percentage of residential homeowners. Furthermore, given that the percentage of the 426 homes that are located in both Berkeley and Oakland is unknown, the above-mentioned percentages of retrofit owners in each city cannot be used to identify the incentive's effectiveness.

Figure 27: Seismic Rehabilitation Types of Buildings in Bay Area, California



The author next examined the motivations behind the other types of rehabilitated buildings in the Bay Area (Figure 27). The motivation behind the rehabilitated institutional buildings (i.e. hospitals, police and fire stations, churches, and schools) was found to be largely due to mandated seismic upgrades. The hospitals, which comprise 2% of the 180 institutional buildings, were rehabilitated because the Senate Bill 1953 (SSC, 2011). Another 20% of the institutional buildings were rehabilitated because of FEMA's subsidized retrofit programs. This percentage was estimated based on the entry details that accompanied 20% of the institutional projects. The FEMA subsidized retrofit program is a seismic retrofit program that funds the replacements or upgrade of critical facilities. The retrofit of commercial or private corporations buildings were done primarily because of the seismic upgrade triggers in the building codes, with about 2% of the owners voluntarily upgrading the buildings out of seismic risk concern.

Figure 28: Seismic Rehabilitation Types of Buildings Material in Bay Area, California



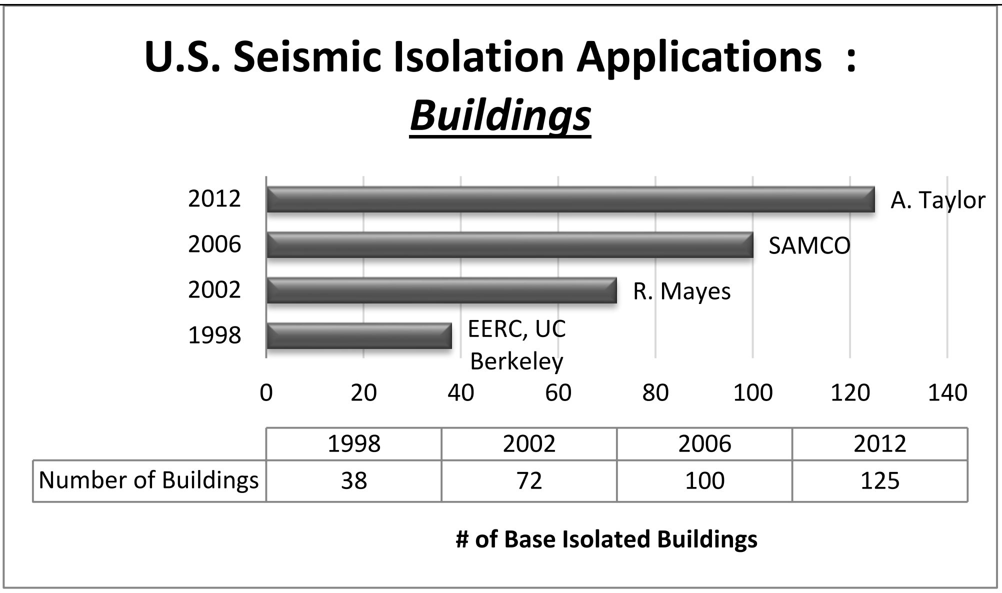
5.4.3 Adoption of Seismic Protective System in the US

5.4.3.1 Seismic Isolation Systems

Although the number of applications of base isolation has been growing exponentially in countries like Japan, the growth of building and bridge applications in the US has been slow, with most of the structures located in the west coast states due to their high level of seismicity (See Appendix G) (Martelli, 2006). From the first base isolation application in 1985 to 1990, only 5 bridges and 6 buildings were constructed using the LRB systems (EERC, 1998). The bridges were all rehabilitation projects. The buildings were mostly new construction projects with only 2 retrofits. By 1998, a total of 107 bridges and 37 buildings were either built or retrofitted using base isolators (EERC, 1998). Of the 107 bridges, 43 were rehabilitation projects, and 64 were new constructions; 61% of the 37 building applications by 1998 were new construction projects, and 39.5% of the 38 were retrofits.

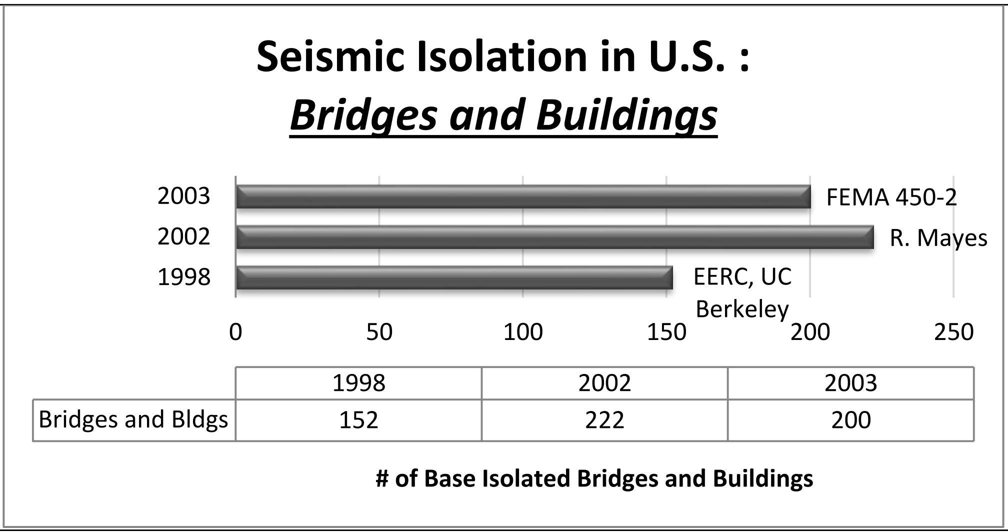
It is unclear from the literature review conducted on base isolation trends in the US what the current number of applications is. Figure 29 and Figure 30 show the reported numbers of buildings base isolated as of the dates shown. In Figure 30, R. Mayes and Hinman in 2002 reported that 222 structures have been built using base isolation devices, 72 buildings and 150 bridges (Mayes & Hinman, 2002). Contrary to Mayes and Hinman (2002), FEMA reported that, as of 2003, there were approximately 200 base insolated structures in the US (FEMA, 2003). This number included both bridges and buildings. There appears to be a lack of consensus on the correct number of isolated bridges and buildings presently located in the US. With the current number of base isolation applications reported in the US varying per source, it is assumed to be unknown; however, applications in buildings and bridges can be approximated to be fewer than 200 and greater than 100, with approximately five being built or retrofitted per year (Taylor & Aiken, 2012). Even though the reports are conflicting, the trend is apparent; the number of base isolation applications is increasing in the US, from 152 in 1998 to over 200 in 2012 (EERC, 1998; FEMA, 2003; Mayes & Hinman, 2002). Regardless of the exact number, it is much less than the reported 600 base isolated structures in Japan (Podany, 2006). This gap reflects the much slower implementation of base isolation in the US structures.

Figure 29: Seismic Isolation Applications in US Buildings, illustrating Varying in Numbers from Different Sources as of the dates shown



	1998	2002	2006	2012
Number of Buildings	38	72	100	125

Figure 30: **Seismic Isolation Applications in US Buildings, illustrating Varying in Numbers from Different Sources**



	1998	2002	2003
Bridges and Bldgs	152	222	200

Table 32 lists the types of buildings that Mayes and Hinman (2002) reported. Based on the numbers reported, the types of buildings that use base isolation are mostly high valued buildings such as data centers and museums, or critical facilities like hospitals, fire and police stations (Taylor & Aiken, 2012; BSSC, 2010; Mayes & Hinman, 2002). 97% of all the structures in Table 32 are buildings with sensitive equipment or content, or buildings that are highly valued like the historical and museum buildings. The need to protect the priceless collections typically contained in museums, the valued historic buildings, or sensitive equipment found in critical facilities or laboratories is reflected in the fact that these facilities make up the bulk of the base isolated buildings listed below. The type of ownership of these types of buildings was reported to be 55% (of the 222 structures) were government owned, and 45% were privately owned; 45% of 80 buildings were rehabilitated, and 55% were new constructions.

Table 32: Types of Seismic Isolation Applications in US Buildings (Mayes & Hinman, 2002)

# of Buildings	Building Type
12	Historic building retrofits
8	Hospitals
8	Emergency Operation Centers
7	Manufacturing Facilities
7	Computer Centers
6	University Buildings
6	Court Houses / Police Buildings
3	Laboratories
3	Library / Museums
2	Residences
10	Miscellaneous – Tanks/Labs /Airports /Church

5.4.3.2 Energy Dissipation Systems

Similar to base isolations, application of energy dissipation devices in the US has not seen the same growth as countries like Japan, with currently approximately 2000 seismically damped structures (Miyamoto & Hanson, 2004). By the end of 1998, there were only 64 structures reported to be using dampers as passive control devices in North America (EERC, 1998). Out of the 64 structures, 23 are located in Canada, 4 in Mexico, and 37 in the US. Of the 37 structures in the US, 25 are located in California. 36% of the 64 structures were new constructions, with the remaining number being rehabilitation projects (EERC, 1998).

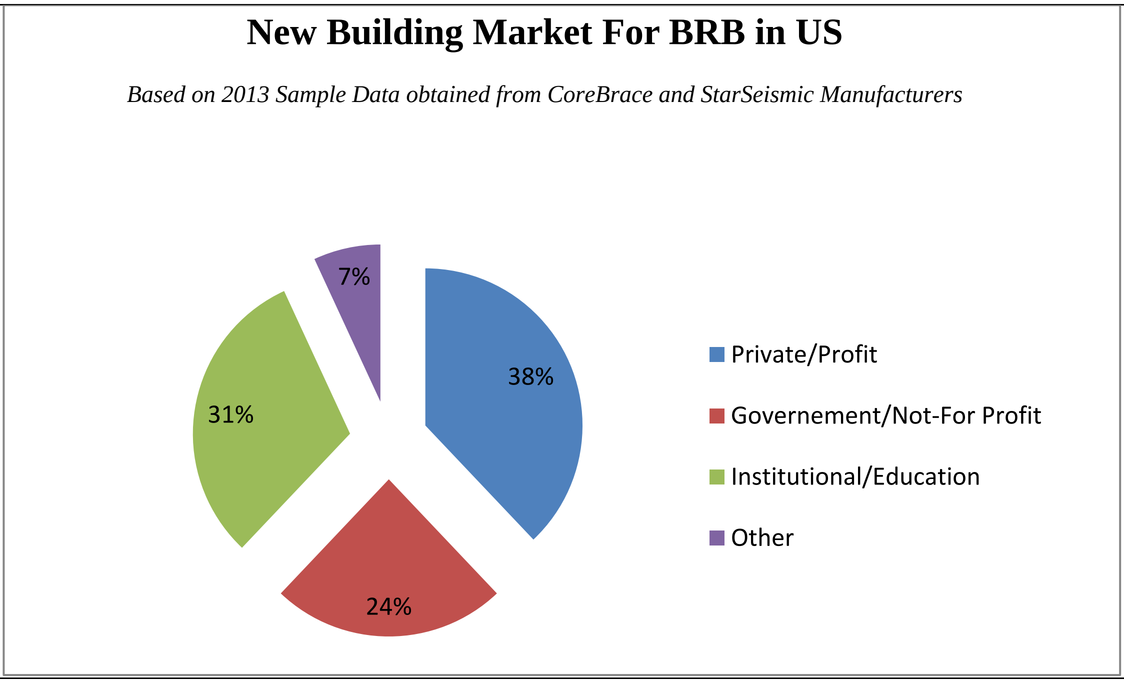
By the 1998, the types of dampers most frequently used were viscous fluid dampers, with 27 applications, and friction dampers, with 23. Symans et *al.* (2002) reported that the number of viscous damper applications had increased to a total of 84. It was unclear what the number of friction damper applications was in 2002, though the total device usage was approximated to be around 150 (Miyamoto & Hanson, 2004). The types of ownership were similar to those for the base isolated buildings, with 44% of the projects being government owned (see Table 33). To date, the current total number of energy dissipating device (excluding BRB) applications in the US is unknown; it is assumed to be greater than 100 and less than 200.

Table 33: US Applications of Energy Dissipation Devices in Buildings
Gleaned from EERC 1998 Data

# of Buildings	Building Type
3	Hospitals
7	Schools and University Buildings
26	Commercial Offices/Buildings
13	Miscellaneous
8	Bridges
7	Residential Housing

The Buckling-Restrained Braces (BRB) has seen a more rapid growth since its introduction in seismic resistant design in the US in 2000. By the middle of 2003, 30 structures were built using BRB, the majority of which was in rehabilitation of concrete structures in California and Utah (Sabelli & Aiken, 2004). A total of 150 BRB’s were reported to be in use in 2008 (López, 2008); that number increased to over 350 in 2011 (Robinson & Black, 2011). In August 2012, the current number of BRB applications was said to be over 500 (Robinson, 2012). The BRB grew from 30 in 2003 to over 500 a decade later. That is more growth than all the other types of dampers have seen in twice that period of time. Similar to the isolation damper systems, the buildings using BRB are located in the western states like California, Utah, Oregon and Washington. The types of ownership that most frequently use BRB differ from the other types of passive control devices. With BRB, more private and profit companies, like retail and commercial offices, are being designed using BRB. The types of structures are more varied, and is not limited to important and high valued structures, as was the case with base isolation and energy dissipating devices mentioned in the preceding sections. As seen in Figure 31: BRB Market, private corporations make up 38% of the buildings that use BRB, whereas the hospitals, police stations, and other valued buildings only account for 24% of the buildings.[11]

Figure 31: BRB Market



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[11] Percentages developed from 29 projects listed by manufacturers CoreBrace and StarSeismic. Only 29 new construction projects were able to be obtained from the manufacturers. The number does not include retrofit structures. Therefore, these percentages may not be accurate market representations for BRB applications as they only represent 5% of the reported number of BRB new applications in the US. They are used for illustration purposes only.

CHAPTER 6: COSTS, BENEFITS AND CHALLENGES TO HIGH PERFORMANCE SEISMIC RESISTANT DESIGN

Even after examining the economic strains that earthquakes have put on various regions of the world, like the $20 billion 1994 Northridge repair bill, and the predicted loss estimations for future earthquakes (see discussion of FEMA loss estimation in Appendix H), the majority of owners are still defaulting to the prescriptive codes for reasons detailed in section **Error! eference source not found.** of this chapter. The majority of these owners believe that the current conventional building codes already provide a guaranteed performance. In a series of interviews conducted by Taylor and Aiken (2012) with building developers on the issue of enhancing their buildings' seismic performance through the use of base isolation, the developers all stated that the code-mandated provisions made their developments "earthquake proof", leaving them with no incentives to increase their costs by upgrading their building using base isolation devices (Taylor & Aiken, 2012). According to Taylor and Aiken (2012), these developers, even after being presented with evidence that the conventional codes only provide a minimum performance, and that extensive damage can still occur, still did not choose base isolation as a preferable option.

In sections subsequent sections of this chapter, the author will seek to illustrate the economic and non-economic benefits of using high performance seismic design (HPSD) methods, the inclusion of PBEE, seismic rehabilitation, and passive control devices in seismic resistant design, as opposed to the minimum standards. These HPSD measures will be shown as being cost-effective because their life-cycle cost savings, due to their abilities to reduce earthquake losses, repay the initial costs of design and installations tenfold.

6.1 COSTS AND BENEFITS OF HIGH PERFORMANCE SEISMIC DESIGN

The upfront added costs associated with using passive energy devices, existing building rehabilitation and performance-based seismic design. The upfront premium reports for the retrofit and passively controlled structures mentioned herein are based on structures designed using performance based seismic design methodology. The ranges of number reported are assumed to include the cost of integrating the PBEE procedures.

6.1.1 Up-Front Costs of High Performance Seismic Design

6.1.1.1 PBEE Methodology ~~Up-front~~ Costs… (Savings)

Data regarding the upfront premiums associated with using the PBEE methodology is limited. The literature review on these premiums revealed that the only reported PBEE application costs are costs savings. Engineering firms are reporting cost savings, in lieu of upfront costs, resulting from using the methodology. This is in large part due to the fact that these firms often use the methodology to circumvent the prescriptive requirements of the codes. Using PBEE, engineers are able to reduce member sizes, eliminate code-mandated components, and simplify building designs. These design simplifications often lead to costs savings at the project configuration stage that offset the first costs of implementing PBEE methodology; the upfront costs are seldom reported as they are paid for by the costs savings. In instances where PBEE is used and substantial cost savings are achieved to offset the cost of the methodology, in lieu of an added cost, the methodology reduces the project costs.

The only study, to the author’s knowledge, that presents a range of upfront costs associated with the methodology, as used in seismic rehabilitation, is the National Research Council (NRC) report. The NRC, a subcommittee of the National Academic Press, compiled data on upfront costs associated with PBEE from engineering corporations with experience in implementing the methodology. It is unclear from the literature review how many engineering firms were studied or how many projects were used in their analysis. According to the NRC's report, the added costs of PBEE methodology were reported to fall in the range of 1 to 10 percent of total project costs (CEBISM, CSG, & NRC, 2006). The range reported is due to the difference in the selected performance objective levels, the engineering team experience level, and the project sophistication. These upfront premiums are considered negligible by other engineer professionals because of the cost savings that may be gained by using the methodology.

The cost savings reported from using PBEE vary per project. In the One Rincon Hill project, a 64-story residential development in the San Francisco Bay, the cost savings achieved from using PBEE to simplify the design reduced the project cost by \$5/ft^2 over the entire height of the project (Post, 2008). The project is engineered with a structural system that consists of a ductile concrete core of shear walls supplemented with BRB frames. The design simplification provided by using the PBEE methodology was to eliminate the need for a backup perimeter moment frame requirement of the conventional codes (Post, 2008).

Another study analyzed the costs savings associated with implementing PBEE in a commercial, 80-foot building, in Charleston, South Carolina. The engineers used PBEE methodology to determine optimum configurations for the building structural elements, originally designed using the capacity-based seismic design procedures mandated by the conventional provisions, and to redesign them. Based on the analysis results, it was determined that special detailing was only needed in members with expected large non-linear deformations, (Sease, 2013). These large deformations were expected to happen in structural members above the first floor. No special detailing was required for those elements at the first floor level. Therefore, the lower story was designed to resist the code-mandated capacity design loads; the higher stories were designed according to the PBEE calculated loads. This simplification saved the project approximately $23,400 per 2-bay frame (Sease, 2013); this cost saving translated to about 44% of the cost of the code-mandated capacity-based project (Sease, 2013).

6.1.1.2 Seismic Rehabilitation Upfront Costs

The upfront premiums reported for the seismic rehabilitation of existing buildings varied. Some sources are reporting these costs as a percentage of the building replacement value. These percentages depend on the type and value of the structure, the level of rehabilitation needed, the performance objectives, and how much architectural work is required as part of the rehabilitation scheme. The upfront premium for the seismic rehabilitation of buildings was reported to be approximately 20%, a percentage that could possibly increase to as high as 150%, of the building's replacement value (CEBISM, CSG, & NRC, 2006). In certain bridge applications, lower upfront premiums are being reported. In a bridge retrofit in Missouri, the upfront premiums for all the rehabilitation schemes ranged from 2% to 8% of the building replacement costs (detailed in following section) (Padgett, Dennemann, & Ghosh, 2010).

Other sources are reporting these upfront premiums as a cost per building square footage and the targeted performance levels (Table 34). These values were originally generated by FEMA's 1994 analysis on seismic rehabilitation costs. These values were recently converted to 2002 dollars (Zikas & Gehbauer, 2007). The analysis was conducted on 2000 seismic retrofit projects in the State of California (Zikas & Gehbauer, 2007). The factors used in the analysis were the buildings construction year, performance levels, their site's level of seismicity, the building types, and floor areas. The various rehabilitation schemes were not included in the analysis framework. As shown below, the upfront rehabilitation costs for a building with floor area greater than 1076 ft^2, and with a performance objective set at Immediate Occupancy, is less than \$50 per ft^2.

Table 34: Average Rehabilitation Costs per ft^2 based on Different Performance Levels (Zikas & Gehbauer, 2007)

	Life Safety		**Damage Control**		**Immediate Occupancy**	
Building Area	**< 1076 ft^2**	**> 1076 ft^2**	**< 1076 ft^2**	**> 1076 ft^2**	**< 1076 ft^2**	**> 1076 ft^2**
Average	\$ 25.8	\$ 18.8	\$ 25.8	\$ 14.2	\$ 48.8	\$ 19.4

6.1.1.3 Seismic Isolation Devices

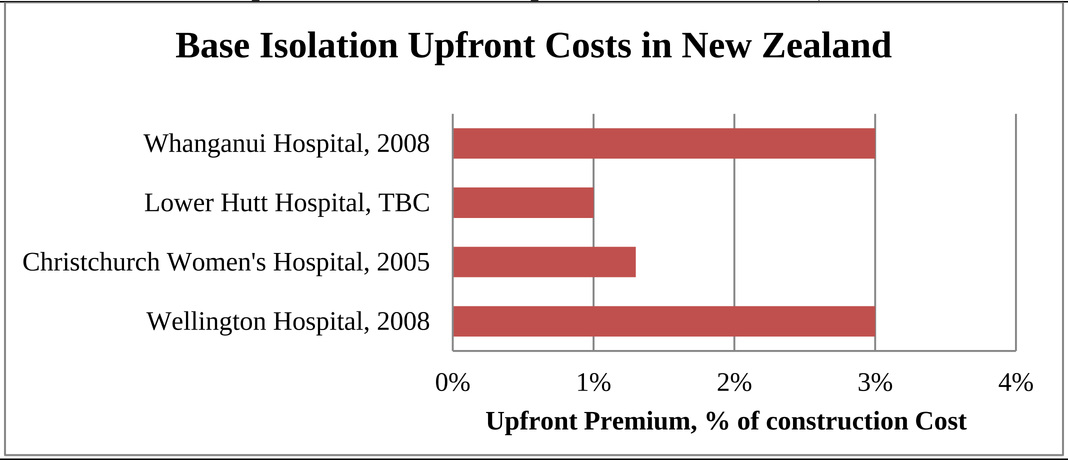
The upfront premiums that are reported for base isolation integration into buildings, similar to seismic rehabilitation, vary per source. The upfront premium ranges vary due to the different types of isolators that are available for use, the number of isolators needed, and the gross area needed to be isolated. Some projects may need below 50 isolators to achieve their owner's desired performance. Some others, like the four New Zealand hospitals detailed herein, need over 200 isolators. Furthermore, several different types of isolators are typically used in a single project. The literature review detailed in this section will aim to illustrate the different upfront costs reported for base isolation applications in the US, Japan and New Zealand, given that the latter two countries have the most base isolation devices currently in use.

The upfront premiums reported in each of the aforementioned countries vary from 1% to 15% of the buildings' structural or construction costs. One study conducted on a 10-story building in Japan reported the upfront premium for the base isolation application to be 5% higher than the construction cost of a conventional earthquake resistant building (Hitoshi & Matsutaro, 2005). Other studies of upfront premiums for seismic isolation maintained that base isolation upfront costs in the US ranged from 5% to 15% of the building's structural system costs, or 1% to 10% of the total construction costs in New Zealand (Charleson & Allaf, 2012; Taylor & Aiken, 2012). This New Zealand cost range was determined through an in-depth research, questionnaires, interviews, and analysis of existing building construction plans (Charleson & Allaf, 2012). Another analysis was conducted on four newly constructed hospitals in New Zealand. Figure 32 shows the range of costs reported from these newly or under-construction hospitals. The costs of the base isolation system itself never exceeded 5% of the buildings' total construction costs.

Further research was conducted to uncover the upfront costs of base isolation in bridge retrofit applications. The upfront premium for the bridge retrofit project in Missouri was reported to be approximately 5% of the bridge replacement value (Padgett et *al.*, 2010). Other studies on the upfront costs of seismic isolation in bridge applications reported percentages below 2% of the total bridge cost of construction (Mayes et *al.*, 2012).

As with PBEE, the base isolators may reduce cost elsewhere in the building. In the case of bridge applications, the isolators may reduce the some of the foundation costs, though it is unclear from the literature review what the reduction value is. The author believes that the cost of the isolators themselves do not tell us the whole story.

Figure 32: Base Isolation Upfront Costs for 4 Hospitals in New Zealand (Charleson & Allaf, 2012)



6.1.1.4 Energy Dissipation Devices ~~Up-front~~ Costs… (Savings)

The literature review on the upfront premiums of energy dissipation devices applications yielded similar results to the costs presented in the PBEE section (6.1.1.1). The studies reviewed did not present specific upfront costs associated with the integration of energy dissipation devices, only about the cost savings that can be achieved from designing with these systems (Soong & Spencer, 2002; Dasse, 2009; Taylor, 1996). Supplemental damping devices are said to be able to reduce the initial construction costs. One study reported that the cost of a building built with these systems was 1.5% less than the cost of a conventional seismic resistant building (Soong & Spencer, 2002). Another recent study on the buckling-restrained brace frames (BRBF) maintained that designing with these braces can reduce the construction cost by \$2.40/ft^2 (Dasse, 2009). [12] These studies implied that, if properly integrated into the structural system, these supplemental damping systems may reduce, not add to, the construction costs; therefore, instead of an added cost, they can provide cost savings (Soong & Spencer, 2002; Dasse, 2009; Taylor, 1996).

The limited date presented in the previous paragraph regarding supplemental damping device upfront costs reflects the fact that there are not many studies conducted on these upfront premiums. This is in part due to the difficulties associated with determining costs associated with supplemental damping systems. Typical construction costing tools usually report costs based on building square footage. Determining costs associated with dampers requires that the magnitude of earthquake force to be resisted, the quantity of dampers used on the project, and the displacement level sought, to be taken into account (Kargahi & Ekwueme, 2004). As the

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[12] These cost savings were calculated for two buildings, one 6- story and another 3-story.The cost comparison was done on the buildings designed first, with the conventional special moment-resisting frames, then with BRBF. Both buildings were seen to have a reduction in their construction costs by using the BRBF. The costs savings in the 6-story building was \$2.40 and \$1.10 for the 3-story building. The study implies that the BRBF reduces instead of increasing costs.

displacement (stroke) sought increases, so does the special design requirements for the damper (Kargahi & Ekwueme, 2004). As the design requirements increase, so does the cost for each damper. As a result, the costs of these devices will vary (Kargahi & Ekwueme, 2004; Pettinga, Oliver, & Kelly, 2013); therefore, making a statement about their costs as a percentage of total building construction costs would be challenging.

6.1.2 Benefits of High Performance Seismic Design

6.1.2.1 PBEE Methodology Life-cycle Benefits

The goal of this section is to quantify the life-cycle cost (LCC) benefits directly associated with PBEE. These may include the reductions in future damage repair costs, and economic loss resulting from fatalities that using the PBEE methodology provides. However, this process is challenging for many reasons. First, PBEE methodology results vary for each building and for each performance level. Additionally, the methodology typically results in structures designed with high performance design techniques and devices. As a result, an LCC analysis could not be performed for the PBEE methodology without accounting for the effects that these high performance techniques and devices have on future cost reductions; these devices, the design techniques, and PBEE are interlinked. One study – the only study found - presented herein, details the LCC costs reductions associated with the using PBEE to upgrade a building performance level from Life-Safety (LS) to Immediate Occupancy (IO). The structural system was enhanced to perform at the IO level without the use of passive control systems. The LCC associated with these systems are discussed in later section of this chapter.

The LCC analysis was conducted for a 6-story, 5-bay by 6-bay, steel moment frame building. The goal of the analysis was to compare the cost and benefit differences between the building designed to operate at the IBC’s conventional LS level, and the same building upgraded to the higher performance level of IO (Carmona, 2012). The PBEE methodology was used to analyze the difference in performance levels of both buildings, and to evaluate the risk and costs of damage to each building. The cost component accounts for the initial cost of construction and the damage repair costs for each building. The construction cost of the original LS building was estimated to be $33.4 million (Carmona, 2012). The upgraded IO building cost was about $33.9 million (Carmona, 2012). The difference in construction costs between the two buildings was the structural system upgrade from the LS level the IO level. This upgrade increased the initial construction costs by $500,000 (Carmona, 2012).

The LCC savings provided by this upgrade yielded an equivalent annual savings in repair costs of approximately $40,000 in 2009 dollars, which is about an 18% annual cost saving over the life of the building (Carmona, 2012). This annual net-present value was calculated based on a 50-year building lifespan and a discount rate of 7 (Carmona, 2012). This LCC savings, determined using the ACT 58 financial risk assessment guidelines and the Performance Assessment and Calculation Tool (PACT), represents the difference between the estimated annual losses calculated for the IO and LS buildings. Considering the reduction in damage, and the cost saving of the IO building compared to the LS building (number of fatalities, and downtime were not included in the loss evaluation calculations), PBEE methodology yielded a higher performing seismically resistant, and cost-effective building.

6.1.2.2 Seismic Rehabilitation Life-Cycle Benefits

Given that there are many different retrofit measures that can be applied to the several different types of building and building deficiencies, and the various levels of possible performance, detailing every possible technique is beyond the scope of this report. Furthermore, because the benefits associated with those different retrofit schemes and performance levels are typically accrued during the building’s lifespan, a life-cycle cost analysis is necessary to illustrate the value of these benefits.

Using the recent PBEE methodology and technologies (Liel and Deierlein, 2012), a recent study compared the performance of 8 pre-1970 RC non-ductile (low level of reinforcing detailing) buildings to that of ductile RC buildings, to illustrate the cost-benefits of seismic rehabilitation. The non-ductile and ductile buildings that were developed and analyzed ranged from 2 to 12 stories in height, and were located in southern California. The non-ductile buildings were designed and modeled using the 1967 code provisions, and the ductile buildings, the 2003 building codes. Using the PBEE methodology, both sets of building performance levels were assessed, without the rehabilitation measures, in terms of each building’s probability of collapse, economic loss and fatality levels. The analysis revealed that the ductile RC buildings had a lower probability of collapse, 0.05% to 0.15%, than the non-ductile buildings (0.65% to 0.85%). The expected annual losses (EAL), expressed as a percentage of the building’s replacement value, were higher, 1.6% to 5.2%, for the non-ductile RC buildings than for the ductile buildings (0.8% to 1.0%).

A rehabilitation cost-benefit assessment was conducted for the non-ductile concrete buildings to evaluate the benefits of the enhancements and their effects on reducing future damage and number of fatalities (Liel and Deierlein, 2012). The retrofit methods chosen were to (1) use fiber to wrap the columns to improve their ductility capacities; (2) use reinforce concrete jackets (CJ) around the columns to improve their ductility and strength; and (3) provide additional wall piers (WP) to the structural system to increase the system’s ductility and strength (Liel and Deierlein, 2012).

A life-cycle analysis was done to quantify the benefits accrued over the buildings' lifespans as a result of the performance enhancements of each of all of the rehabilitation measures. The former were seen as cost-effective if their cost to benefit ratio of less than 1. The benefits, calculated based on the risks posed by the non-ductile buildings, are the cost savings gained from the reduction in future losses resulting from building damage and the number of fatalities prevented (taken as a value of $2 million per life saved) (Liel and Deierlein, 2012). The total benefits are expressed as a percentage of building replacement. These benefits are based on a 50-year building lifespan assumption, and discounted annual rate of 3% (Liel and Deierlein, 2012). The cost of achieving these benefits was taken as the cost of the retrofit measures (Liel and Deierlein, 2012). To be cost effective, the cost of the retrofit measure should be taken as less than or equal to the value of the total benefits, so that the resulting ratio is less than or equal to 1 (Liel and Deierlein, 2012). Although the analysis did not provide specific upfront costs to these rehabilitation measures, the benefits provided by the latter ranged from 8% to 52% of the building replacement cost. Therefore, for any retrofit scheme, as long as the initial costs remain less than the 50-year provided life-cycle benefits, the option will be cost effective (Liel and Deierlein, 2012).

6.1.2.3 Seismic Isolation Devices Life-Cycle Benefits

6.1.2.3.1 LCC of Seismic Isolation in Rehabilitation Applications

A risk-based, life-cycle cost-benefit assessment is presented below to illustrate the higher performance of elastomeric bearings, and their influential effect in reducing the life-cycle cost of existing structures. The analysis was primarily done to select the most cost-effective option for a bridge retrofit project in Missouri. Four bridge models were designed and developed to analyze the effect of the different rehabilitation schemes on the bridge LCC reductions (Padgett et *al.*, 2010). The results of the assessment illustrated that, though the elastomeric bearings had a higher initial upfront cost, as described previously, it yielded a much higher reduction in future cost (*i.e.* benefits) (Padgett et *al.*, 2010).

The analysis used the PBEE methodology to generate probabilistic hazard fragility models for the four bridges in their as-built conditions and the retrofit measures selected (Padgett et *al.*, 2010). These measures (steel jackets for the columns, base isolation devices, restrainer steel cables, seat extenders, and shear keys), were evaluated based on their costs and their influence in reducing future damage losses. The inflation-adjusted discount rate of 3% was used to convert future costs into present values (PV) (Padgett et *al.*, 2010). The life-cycle analysis only accounted for the future repair or replacement costs of the bridge due to exposure to seismic events during its lifespan. The analysis did not take into account the initial construction cost of the bridge since the bridge has already been built (Padgett et *al.*, 2010). The benefits of each retrofit measure is taken as the difference between the expected present-value (PV) of the losses in the bridge's as-built condition, without rehabilitation, and the PV of the losses with rehabilitation (Padgett et *al.*, 2010).

Table 35 lists the result of the LCC analysis. The expected LCC at the as-built condition illustrates the level of losses that the bridge will incur during its lifetime if not rehabilitated. Then, the rehabilitation measures are shown, with each illustrating a decrease in these future losses (Padgett et *al.*, 2010). The measure with the lowest expected future loss is the elastomeric bearing. This elastomeric bearing retrofit option decreases the expected future losses by 28%, the largest LCC reduction among the other rehabilitation measures (Padgett et *al.*, 2010). The bearing also is shown to have the greater dollar amount of yielded benefits (Padgett et *al.*, 2010). Although the upfront premium paid for the elastomeric bearings was costly relative to the other options investigated, the bearings yielded a larger cost saving over the bridge’s lifespan (Padgett et *al.*, 2010).

Table 35: Retrofit Life-Cycle Benefits of Base Isolation Devices (Padgett et *al.*, 2010)

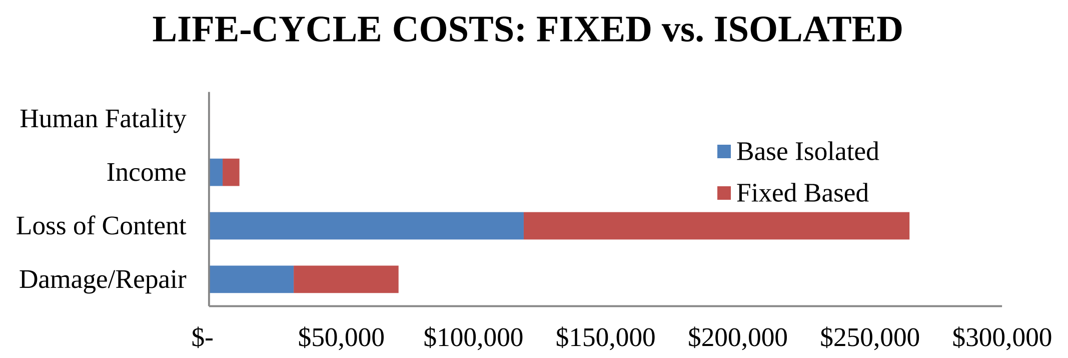
Retrofit Option	Initial Installation Costs	% of Replacement Cost	Expected LCC	LCC Reductions
As-built	$ 0	0%	$91,915	0%
Steel Jacket	$36,000	8%	$79,051	14%
Elastomeric Bearing	**$21,912**	**5%**	**$65,760**	**28%**
Restrainer Cable	$11,280	3%	$87,101	5%
Shear Key	$23,250	5%	$91,251	1%
Seat Extender	$9,000	2%	$76,601	17%

6.1.2.3.2 LCC of Seismic Isolation in New Construction Applications

A recent LCC analysis was conducted for a 3-story RC new building located in Athens, Greece, to analyze the costs and benefits associated with a fixed-based versus a base-isolated building (Chatzidaki, 2011). The analysis aimed to determine the optimum design for the building, either fixed-based, or base-isolated. To conduct the analysis, two 3-story symmetrical buildings were developed and designed: one base isolated, and the other fixed-based (Chatzidaki, 2011). The isolation devices used on the base isolated building were elastomeric rubber bearings. The study used the ASCE 41-06 PBEE methodology to compare the costs of repairing the two buildings’ structural and non-structural elements as a result of seismic damage, loss of building contents, loss of income due to building downtime, and fatalities (Chatzidaki, 2011). The benefits were considered to be the difference between the losses expected from the fixed based building and those of the base-isolated building, *i.e.* the avoided losses (Chatzidaki, 2011). The initial costs of the base isolation applications were included in the analysis, expressed as a percentage of the building's initial construction cost. The LCC values were discounted a rate of 5%, over an assumed 50-year building lifespan (Chatzidaki, 2011).[13]

As shown in Figure 33, the LCC damage repair, losses of contents, and income over a 50-year period of the base isolated building was approximately 20% less than those of the fixed based building. The human fatality life-cycle cost, though the cost was small for both buildings, and given that conventional buildings are already designed for the life-safety performance level, saw a 64% reduction in the base isolated building (Chatzidaki, 2011).

Figure 33: Base Isolated New Buildings vs. Fixed Based New Building Life-Cycle Costs *Adopted from* (Chatzidaki, 2011)



	Damage/Repair	Loss of Content	Income	Human Fatality
🟦 Base Isolated	$32,000	$119,040	$5,120	$64
🟥 Fixed Based	$39,680	$145,920	$6,400	$178

6.1.2.4 Energy Dissipation Devices: Life-Cycle Costs-Benefits

6.1.2.4.1 Energy Dissipation Devices Economic Benefits

Given the technical benefits provided by supplemental dampers, and the range of damping that they are able to add to the structure, the life-cycle costs and cost reductions presented below aim to illustrate the cost savings that can be achieved over a period of time with using these devices in new or retrofit schemes. The building case study was a 26-story steel

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[13] To the author's knowledge and the results of the literature review, LCC for seismic structures is typically conducted over a period of 50 years assuming a 50-year building lifespan. Since the analysis did not specify a building lifespan, the author assumes the latter to be 50 years.

moment-frame office building located in Palo Alto, California. The economic benefit of supplementary damping devices in the analysis was computed through a method of simulations (10,000) of life-cycle costs and benefits (King, Jain, & Hart, 2001). These benefits are expressed as avoided losses from earthquake hazards over the building's lifespan. The costs in the analysis included only the costs associated with damage repair of the building's structural and non-structural elements and content. The replacement cost of both the building and its content was estimated to be around 105 million 2001 US dollars (King et *al.*, 2001).

The effects of supplementing the structure with damping was investigated during the analysis over several different time periods, 5, 15, 30, 50, and 100 years(King et *al.*, 2001). For each time period, the supplementary damping ratios of 5%, 10%, 20%, and 30% were used (King et *al.*, 2001). These ratios are expressed as a percentage of the 2% critical damping ratio. Table 36 and Table 37 report the results of the assessment. Table 38 shows that, as the damping ratios increase, the expected losses decrease for each time period. This is due to the reduction in building damage provided by the added damping. Furthermore, as the damping increase, so do the expected life-cycle costs. For instance, assuming conventional damping ratio of 5%, increasing that ratio to 10% will provide a 43.4% reduction in losses in 50 years (King et *al.*, 2001). Similarly, adding 30% supplementary damping to the structure will decrease these losses by 82.7% over 50 years (King et *al.*, 2001).

Table 36: Total Expected LCC (Expected Loss) (millions of 2001 US dollars) (King et *al.*, 2001)

Time Frame	**Damping Ratio (% of critical)**			
	5%	**10%**	**20%**	**30%**
5	1.03	0.58	0.31	0.16
15	4.34	2.79	1.07	0.62
30	11.45	6.55	3.15	1.45
50	21.36	12.99	6.03	3.69
100	50.31	30.81	15.46	9.93

Table 37: Percentage reduction in total overall expected loss with respect to 5% damping (King, Jain, & Hart, 2001)

	Damping Ratio (% of critical)		
Time Frame	**10%**	**20%**	**30%**
5	43.4	69.8	84.7
15	35.6	75.2	85.7
30	42.6	72.5	87.3
50	39.2	71.8	82.7
100	38.8	69.3	80.3

6.2 BARRIERS TO HIGH PERFORMANCE SEISMIC DESIGN

6.2.1 Risk Perception

Defining an acceptable risk that can be applied to everyone is difficult because the perception of risk, acceptable or otherwise, differs from one person to the next. Typically, the public perception of risk will affect their behavior and decisions in policy-making and risk mitigation efforts. Past research on risk perception, mainly based on “cognitive psychology and behavior geography,” has focused on people’s reception of natural hazard knowledge and information, and how their perceptions of the received information ultimately shape the decisions made to “reject or accept, fight or prevent” these hazards (Yang, Gao, Liu, He, Fan, & Tang, 2010).

Numerous other studies have been performed to examine risk perceptions of citizens in high seismicity regions; the result of these studies suggest that, the primary reason that high performance seismic risk mitigation approaches are not undertaken is due to the public’s lack of awareness about the seismic risks posed by structures. Risa Palm and her team of researchers (1990) surveyed 3,500 homeowners in four counties in the state of California, two of which were impacted by the Loma Prieta earthquake in 1989, to investigate the public’s perception of risk. When these homeowners were asked if they perceived a 1-in-10 probability that a damaging earthquake will occur in the next 10 years, only 76% of the 1800 respondents responded affirmatively (Palm, 1998). Less than 25% of that 76% chose to rehabilitate their homes by bolting their homes to the foundations, and fewer than 10% had their exterior load bearing walls strengthened (Palm, 1998). The remaining 24% of the 1800 respondents surveyed did not perceive an intense seismic event occurring within that specified time period (Palm, 1998). Thus with no perceived risk, these homeowners chose to not adopt any risk mitigation measures, and in lieu of rehabilitation, 50% of these non-retrofitters chose to purchase earthquake insurance (Palm, 1998).

More recently conducted surveys on the public suggest that the public perception of risk has changed little since the Palm study. In a survey distributed to the students of a university in Japan confirmed that the level of public awareness of natural hazards and their socio-economic consequences is remains unchanged (Yang et *al.*, 2010). May (2001) surveyed an undisclosed number of people, and found that all are aware of seismic risks, but their level of indifference to those risks varies (May, 2001). As a result of the public's indifference or lack of knowledge, and the infrequent occurrences of catastrophic seismic events, the public rarely demands that government take action in reducing public risk (May, 2001). This, in addition to the initials costs of high performance seismic design, remain the fundamental impediment to the implementation of techniques and devices mentioned herein.

6.2.2 PBEE Methodology

The adoption of PBEE has confronted a variety of obstacles, technical and decision-related in nature. Technical barriers to more extensive use of PBEE relate to the uncertainty and inaccuracies involved in the methods of predicting earthquake effects on structures and the difficulties in translating these effects into states of physical damage, and then further relating these predictable physical damage states into loss metrics relevant to building stakeholders, such as fatalities, downtime, and repair costs (May, 2003).

There are also regulatory challenges associated with implementing PBEE. These involve the considerations that government officials must make when deciding on the seismic safety regulations (May, 2001). Seismic safety regulations include establishing minimum performance levels for structures, establishing levels of performance for public facilities, lifeline and critical facilities. The challenge is that determining performance objectives levels is considered a value judgment requiring “collective decision-making” (May, 2001). Part of this decision-making process also involves risk considerations, costs and benefits, and other technical details, while establishing and determining the performance objectives. The collective decision process invites public opinion, while the risk, costs and benefits, and technical guidance, involve technical experts. It has been a challenge to come to an appropriate consensus and common ground with of all these stakeholders involved in the decision process (May, 2003). A challenge of designing the PBEE methodology in a useful way such that the procedures provide “meaningful categories of choices, information about the costs of achieving different outcomes, and confidence by decision makers that the building will perform as stated” (May, 2003).

Another challenge is the ability of the regulatory systems to adapt to the PBEE methodology. More wide-scale implementation of PBEE would require adoption by building codes and standards as a valid method of analysis. With this implementation into the codes, there the challenge remains to devise appropriate methods to properly incorporate the advancements of the methodology into the code. Adapting to the advancing concepts and procedures of PBEE has been seen as challenging by the code implementation officials, and thus remain an obstacle to widespread implementation of the PBEE methodology (May, 2003).

6.2.3 Existing Building Rehabilitation

Though the benefits to seismic rehabilitation are obvious, there are still many challenges to more wide spread adoption. The literature review on the impediments to seismic rehabilitation suggests that the upfront cost of retrofit is the main barriers (ATC-71, 2009; DRM, 2013; Poland, 2008; Welliver, 2009). Owners and stakeholders view the costs of mitigating existing structures by bring them up to code is too costly (Poland, 2008). In addition, despite the enhancements in the structure, and the knowledge that seismic retrofitting can increase property’s market value, owners are still uncertain about being able to fully recover these upfront costs (ATC-71, 2009;

DRM, 2013; Egbelaki, Wilkinson, & Nahkies, 2012). In addition to the initial costs and cost recovery, other obstacles are the effect of the service disruptions will have on business revenue or employee productivity (Welliver, 2009; DRM, 2013).

There are also regulatory impediments to inhibiting the widespread adoption of seismic rehabilitation. When owners are rehabilitating their structures, other code requirements may be imposed on them. For instance, when retrofitting a building, building officials may require that disability and accessibility issues be addressed as well (ATC-71, 2009). Another impediment is the legal responsibilities that laws impose on non-retrofitters. The legal repercussions of not rehabilitation can lead to building owners being exposed to liability as a result to harm to occupants during an earthquake event should the building have been previously evaluated as seismically deficient (ATC-71, 2009).

6.2.4 Passive Control Devices

6.2.4.1 Economic Barriers

Similar to seismic rehabilitation and the PBEE methodology, passive control systems also face upfront costs and regulatory barriers to implementation. According to Taylor and Aiken (2012), the US building construction industry is driven by upfront premiums, rather than life-cycle costs and benefits considerations (Taylor & Aiken, 2012).[14] Given that the primary objectives of stakeholders in the building industry are to keep costs down, these added costs "dominate the decision-making process" (Mayes et *al.*, 2012; Taylor & Aiken, 2012). As a result, since these upfront premiums are viewed by some as "making no economic sense" because many perceive that the probability of an earthquake event occurring during the stakeholders' investment holding period is low, the public's unwillingness to accepts these costs has been

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[14] It was unclear from the literature review if this assumption is based on data or the authors' own experience.

shown has been shown to inhibit the PSDs widespread adoption (Mayes et *al.*, 2012). There is also the lack of data on these devices' costs and benefits to justify the upfront premiums (Mayes et *al.*, 2012). Furthermore, many believe that the conventional code provisions already guarantee a minimum performance, and that the added costs may cause their projects to be uncompetitive (Taylor & Aiken, 2012).

6.2.4.2 Regulatory Barriers

The code requirements for the design of passive control systems (PSD) also inhibit their applications in high performance seismic resistant design. In the recent years, there have been advancements made to simplify the procedures and requirements for PSD design. Nevertheless, these simplified code provisions have not been adopted in the US. The codes presently governing these systems place higher design requirements on the structure's higher expected performance. This typically requires extensive analysis and testing to be conducted as part of the design process of these systems. The performance-based codes regulating base isolated and other PSC structures are more complex than those for conventional structures (Buckle, 2000; Taylor & Aiken, 2012). As a result, the design of structures using these systems become challenging. The complex analyses, multiple peer reviews, and preliminary testing of PSDs used on projects often lead to added costs (design and construction fees) and schedule delays. As a result, many owners and designers are discouraged to design with these devices (Taylor & Aiken, 2012; Buckle, 2000).

6.3 INDUSTRY LEADERS AND AUTHOR'S RECOMMENDATIONS TO OVERCOME BARRIERS TO HIGH PERFORMANCE SEISMIC RESISTANT DESIGN

6.3.1 Overcoming Barriers to PBEE

Implementation of PBEE, and its transition from nebulous concept to practical application in high performance seismic design, can only occur if the barriers to its more widespread use are overcome. To date, PBEE has only been implemented in a small number of projects, mostly located in the West Coast States as previously noted (Hooper, 2013; Personal Communication). Below are some steps that are recommended to overcome these barriers.

The author recommends that PBEE advocates undertake research efforts to uncover data and information regarding the methodology's upfront costs, and immediate or future benefits, from experts in the field who have experience in implementing PBEE. The research would be used to address the values associated with PBEE. With these studies, instances where PBEE has less value, and is not appropriate should be identified; the reverse needs to be defined as well. Additionally, programs should be instituted, whereby the community can learn of the PBEE methodology, its value and benefits. Performance-based policies, and their purpose, should be communicated to the public by means of public awareness programs (Comerio, 2004).

6.3.2 Overcoming Barriers to Seismic Rehabilitation

The barriers to more widespread retrofit, noted in section **Error! Reference source not ound.**, can be overcome by a number of changes to how we communicate and make decisions about seismic risk. One important change that could be made is by increasing public awareness about the value of seismic rehabilitation by reinforcing information about the risks and consequences of earthquakes and the synergies between reducing seismic vulnerability and protecting cultural resources. For these buildings to remain accessible to the future generations and "inherit a sense of place," seismic rehabilitation is needed. Emphasizing the vulnerability of these buildings as a cultural resource may serve as an opportunity to bring together advocates of the mandatory code triggers and voluntary rehabilitation (ATC-71, 2009). Some other techniques that may be used to overcome rehabilitation barriers include attracting funding from federal sources, enhancing the regulatory approaches, and phasing the rehabilitation work into the business activities. These techniques are described below.

6.3.2.1 Incremental Phasing of Rehabilitation Work

It is recommended to integrate seismic rehabilitation incrementally into business daily operation to reduce rehabilitation costs and service interruptions. Integrating the rehabilitation activities into the daily cycle of business operation and maintenance schedule can potentially minimize the business service interruptions. For instance, during maintenance activities where scaffolding and other construction equipment are already laid out, and the work areas are already exposed, the work of rehabilitation can be less costly since no additional set-up would be required (DRM, 2013). Furthermore, it can reduce the costs associated with service interruptions because the use of the construction work area has already been accommodated into the business operation.

Additionally, the rehabilitation work can be phased out in increments over a period of time to reduce service interruptions and costs. By doing so, the retrofit work can be included into the business maintenance budget or the budget for capital improvements. Since FEMA's funded efforts in 1990 to research the concept of phasing retrofitting measures over a period of years, in 2002, the application of this approach to seismic rehabilitation was only seen in K-12 schools. Though, to the author's knowledge, there has not been data gathered on the effectiveness of this approach; however, the literature review of studies implied that incrementally phasing can be cost effective and reduce interruptions (Mahoney, 2011; VPISU, 2003; Hattis & Krimgold, 2009; DRM, 2013).

6.3.2.2 Adopt Active or Passive Implementation in Seismic Rehabilitation Programs

It is recommended to adopt either active or passive approaches in regulating seismic rehabilitation to ensure consistent implementation. Jurisdictions should review their approaches to seismic risk mitigation, and in high or medium seismicity regions, these municipalities should consider adopting an active approach to risk mitigation (Egbelakin, Wilkinson, Potangaroa, & Ingham, 2011). Conversely, in regions of low seismicity, jurisdictions should adopt a passive approach, which only mandates rehabilitation by the code triggers.

When using an active implementation approach in seismic rehabilitation, vulnerable buildings are rigorously identified and assessed, followed by a required retrofitting or demolishment of these buildings within a set time frame, preferably within one to ten years from the date of evaluation (Liel & Deierlein, 2012; Egbelakin et *al.*, 2011). With this approach, compliance is not optional. All owners are required to take action or face further implications from the law. The fear of consequences, as set forth by the law, would ensure compliance. As was seen in the Rabinovici survey, even in a passive implementation approach where only seismic evaluations were required, some owners still feared the repercussions from the law, should they not comply. An active implementation approach would ensure that all the identified deficient buildings get rehabilitated or replaced, thereby reducing seismic risk and lives lost. A successful example of an active seismic rehabilitation risk mitigation approach is the Mandatory Strengthening Programs in many jurisdictions in California (e.g. the Santa Monica mandatory ordinance). As of 2006, 87% of the 25,945 unreinforced masonry buildings have been either rehabilitated or replaced (CSSC, 2006). These mandatory programs displayed a high level of compliance, with 98% of all the URM now in some form of risk mitigation program throughout the state of California (CSSC, 2006). The mandatory approach proved more successful than the voluntary risk mitigation approaches in some jurisdictions, where only 13% to 31% of the identified deficient buildings have been retrofitted (CSSC, 2006). These voluntary programs proved ineffective and did not result in any over change of the jurisdictions' seismic risks (Liel & Deierlein, 2012).

To aid in implementing a mandatory risk mitigation approach in seismic rehabilitation of existing buildings incentives should be offered in the forms of loans, grants, and tax rebates and/or exemptions that can be used to offset the initial costs of retrofitting (Liel & Deierlein, 2012; Egbelakin et al., 2011According to Egbelakin et al (2011). For those jurisdictions with passive implementation programs, the incentives would be the driver of the voluntary rehabilitation efforts. The more incentives that are offered, the more owners would be motivated to rehabilitate. As was seen with the City of Oakland homeowners, an estimated 20% of the 426 residential homeowners chose to voluntarily retrofit their homes. With well-designed and effective incentives, more owners would be encouraged to rehabilitate their buildings. Additionally, effective incentives need to be developed and funded by the state or federal government for jurisdictions that lack funding (Comerio, 2004; Egbelakin et al., 2011). In addition to these incentives, the programs should be combined by public awareness and other community involvement or participation programs.

6.3.3 Overcoming Barriers to Implementation Passive Control Devices

Barrier to the widespread implementation of passive control devices can be overcome if the issue of initial cost premiums and complex regulatory design requirements can be addressed (see also section **Error! Reference source not found.**).[15] As described previously in Section REF _Ref353194286 \n \h * MERGEFORMAT 6.1.1, studies have shown that there is an upfront premium associated with the use of these devices. This upfront premium, similar to the green building approach, should be ignored because of the significant life-cycle cost reduction that using these devices provide. The building owners and stakeholders are unwilling to accept the premiums because of the lack of foreseen short-term economic benefits. One method to facilitate the acceptance of the high upfront premium of these devices is if incentives are presented to these owners. One such incentive is costs savings associated with seismic insurance premiums. There are cost savings that may be gained if insurers accept these devices, and acknowledge their benefits, by providing premium discounts. Insurers already have reductions in insurance premiums for the inclusion of fire protection devices; however, to date, insurers have been unwilling to provide similar premium discounts for base isolated structures (Taylor & Aiken, 2012). Should designing with these devices be able to bring down the costs of earthquake insurance, their use might be viewed as economical (Mayes et *al.*, 2012; Taylor & Aiken, 2012). The premiums could be accepted and viewed as an investment. On the issue of the code regulations, further research is recommended to be conducted, with the goal of uncovering techniques by which the design requirements for PSDs could be reduced and/or simplified. This could be achieved by means of streamlined peer reviews and testing processes.

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[15] To the author's knowledge, seismic isolation and passive energy dissipation devices have encountered the same barriers to implementation. These steps to overcome the barriers to seismic isolation are extrapolated to the passive energy dissipation devices as no data or studies could be found regarding these devices.

CHAPTER 7: LESSONS LEARNED FROM GREEN BUILDING INDUSTRY

The green building revolution has been instrumental at getting building owners and state legislatures to take steps toward reducing building energy consumptions and sustainable use of resources, reducing construction waste generated by the built environment, and promoting the use of local materials in construction. The green building movement is seen as a "significant force of change in the building design process" (ATC-71, 2009). The industry has been able to achieve success despite the many barriers that it has faced. A review of some of the solutions which have been used to overcome the barriers of high upfront costs, lack of information about benefits and cost of green buildings, and others mentioned in section 3.2 of this report will be performed in this chapter. These solutions, which have been shown as effective, will be used to formulate recommendations to overcome the barriers to all aspects of high performance seismic design (HPSD).

The identified barriers to HPSD are comparable to those that the green industry has faced, with the same challenges with the high initial first costs, and the public's lack of perception of the significance of risks and their consequences. In the instance of green design, these risks and consequences are associated with the built environment and its effect on the environment. In the case of seismic design, these risks and consequences are related to earthquake events and their consequences on local economy and life-safety. Given that these barriers have the same fundamental basis on upfront costs and challenges with risks and perception of risks, the goal of this comparison is to draw on the success of the green building industry, making recommendations about how the similar solutions could be used used to overcome some of the similar challenges that high performance seismic design currently faces.

Before discussing the lessons learned from the green building experience, it is important to note that such a comparison is could be considered a false equivalence to high performance seismic resistant design, in that compliance to seismic codes is not optional whereas applying green principles to conventional design is. In seismic design, building codes mandate compliance to their prescriptive seismic resistant provisions. In green building design, structures get awarded LEED rating levels based on how they've addressed certain green design concepts. These structures need not address all aspects of green building design principles to receive a rating. As a result of this checklist approach, designers often design for the points, rather than truly designing for sustainability. Even though critics view the LEED green building process as the designers' and contractors' efforts at gaining market exposure and advantages, and at having no true basis in sustainable building design, the industry has been successful. Some lessons that have proved effective for advancing the green movement are mentioned in the sections that follow. These solutions are then used to create recommendations that could be used in overcoming the similar challenges for HPSD.

The two main lessons learned from the green building industry are (1) the success of the establishments and activities of the U.S. Green Building Council in fostering partnerships, educating the building industry and public; and (2) the effectiveness of the LEED rating system at creating a standard for evaluating green buildings and market advantage, and at being used by lawmakers as a benchmark when developing policies for green buildings.

7.1 LESSON #1: ESTABLISH A LEAD NON-PROFIT ORGANIZATION TO PROMOTE CHANGE

Many of the changes that have been observed over the growth of the green industry have always been directly or indirectly related to either the USGBC and/or the LEED rating system. A brief overview of the USGBC as an organization, and its involvement in promoting change in favor of sustainability development, can give insight into the importance of a similar organization advocating for high performance seismic design in the earthquake engineering community.

7.1.1 Form Coalitions within Green Building Industry to Foster and Promote Change

The USGBC's coalitions in the building industry have allowed the organization to broaden its reach nationwide and internationally. These partnerships form a wide network of organizations and individuals that disseminate information regarding high performance green buildings, promote change, and gather resources and support for the industry. The USGBC presently consists of 13,000 member organizations, 77 regional chapters across the U.S., and 196,000 LEED accredited professionals (USGBC, 2013). The USGBC's membership encompasses colleges and universities; states, local and federal government agencies; and non-profit, government, and profit organizations from every sector of the building industry across the U.S. and abroad. These members share the USGBC's vision of transitioning from conventional to sustainable construction, and are all involved in moving the green industry forward.

The membership aspect in the organization of the USGBC facilitates the forming and retaining of coalitions. The member organizations, by becoming members, are partnering with the USGBC to help promote green buildings. Coalitions have also been formed by organizations sharing the same vision as the USGBC like the US Department of Energy and the Environmental

Protection Agency. The coalitions that are developed and sustained by the USGBC help to promote the green development agenda, with outcomes being monetary and non-monetary incentive programs and laws. Many state and local governments across the U.S. have developed laws and funded programs that favor sustainable development. Monetary and non-monetary incentive programs are now part of various states and local governments. Some of these programs may take the shape of mandates, like those requiring that certain government buildings be built to a certain LEED rating level. Others offer non-monetary incentives such as variances on building codes and bonuses for buildings using green features, and monetary incentives in the form of tax credits and or rebates (see section 3.3 for more details). For instance, in the state of New York, there have been over 50 programs that provide monetary incentives to green buildings as a way to promote and encourage the transition to environmental sustainability (NYCEDC, 2009). Over half of these programs are funded by the state of New York, with the majority of the tax incentives provided and funded by the New York State Internal Revenue Service (NYCEDC, 2009). There have also been many federal contributions to the green movement, some of which have been funded by the U.S. Department of Energy and the Environmental Protection Agency, two federal agencies that have partnered with and have always endorsed the USGBC and the green building movement. Two major federal government contributions, the Energy Independence and Security Act of 2007 and Energy Policy and Conservation Act of 2005, provided millions of dollars as grant money as well as tax incentives (detailed in section 3.3.4) to fund or offset the costs of sustainability.

Another outcome of the USGBC’s coalition building efforts has been the increased responsiveness of building departments to the unique needs of green development. For example, some building departments now require that LEED APs, viewed as individuals knowledgeable about green buildings, be part of the department to offer technical assistance, and assist in reviewing green building plans. Their expertise is used in the review process to ensure that, even though green building techniques and systems are included in the building design, they still comply with the code. Other building departments employ green tutors who are available to meet with project teams to provide guidance from the project conceptual phase. These tutors also aid in reviewing current building codes and provide recommendations to improve them so that they do not hinder green development.

In short, these coalitions have opened doors for green buildings in every sector in the green building industry. These opened doors have led to an increased interest and involvement in encouraging sustainable design. Coalition organizations and individuals are all becoming involved with developing solutions to overcome the barriers impeding green development. The USGBC's coalitions with these organizations and groups of individuals "whose collaborative reach extends beyond [its] efforts" (USGBC, 2013) have proven successful at fostering and promoting change.

7.1.2 Educate Industry Professionals and Public about Green Buildings

The USGBC helps to promote change in favor of green buildings by educating the public about sustainable development. The organization makes available webinars and courses on its webpage, as well as on the websites of all its affiliated regional and state chapters. The USGBC also provides tools and resources to policy makers to help them inspire change in favor of green buildings. These educational resources contain basic or technical information about green buildings and are formulated for technical or non-technical audiences. Therefore, they can be used by both the public and the professionals from all of the sectors in the building industry, which include designers, developers, owners, and contractors. To the author's knowledge, there is no data available regarding the rate of use of these educational resources; however, based on a review of some web seminars posted on YouTube, and considering the target audience for these videos, the average public views for the fifty selected courses was greater than 50,000.

Another method by which the public is educated is by the LEED Accredited Professionals on staff at the various building departments, organizations and corporations. The LEED Professional Credentials accreditation process requires that professionals seeking accreditation have a certain number of years of experience leading design teams through the LEED process, and the successful completion of an exam. The accreditation program helps to develop expertise in sustainable development because these LEED APs have knowledge in sustainable design, construction, operations and maintenance of buildings and communities. Those credentialed professionals who are part of the building department assist and educate the public, and are considered to be a source of reference for those with questions about green buildings.

7.1.3 Research and Disseminate Information about Green Buildings

One of the challenges that the green building has faced and continues to face is that building owners, the general public and lawmakers are not aware of their benefits and costs. Data about high performance green building costs and benefits is not easily accessible, and the information that is available is highly uncertain. To address this challenge, the USGBC, together with the Sustainable Building Task Force, the Capital E, and the Future Resource Associates, has contributed to the development of the Kats (2003) study, the first comprehensive cost-benefit analysis ever to have been conducted on green buildings. This study was funded by the Task Force members, Air Resources Board (ARB), California Integrated Waste Management Board CIWMB), Department of Finance (DOF), Department of General Services (DGS), Department of Transportation (Caltrans), Department of Water Resources (DWR), and Division of the State Architect (DSA), and carried out by the Capital E president, Greg Kats. Prior to the Kats (2003), study detailed in section 3.1.2, no comprehensive study had ever been performed where data from a large number of green buildings was gathered and analyzed to uncover upfront and life-cycle costs and benefits. Thanks to this study, a range of percentages that depict costs and benefits of green buildings as compared to conventional buildings have been published over the web by various proponents of green buildings. Because of that study, the information that was once unknown, is now, not only known, but readily available. The primary conclusions of the cost and benefit study were that green buildings on average reduced water usage by 50%, energy usage by 30% and pollutant emissions by 36%. The USGBC has greatly contributed to the green movement by contributing to this research about green buildings and disseminating the results of the study to the general public as a way of addressing the lack of information available about these buildings.

The USGBC has also implemented and developed many methods by which information about high performance green buildings is shared to the public. The organization has various campaigns dedicated to disseminate information about the benefits of green buildings to the public. Part of the organization's campaign to propagate information is the periodic publications of its success in overcoming present barriers to sustainable design in high profile newspaper like the Washington DC post. In addition to these publications, the USGBC reaches the public via the local and regional chapters, their members and volunteers. These chapters are used to carry out the USGBC's efforts at the regional levels through networking events and other programs. The USGBC is also well-connected online, not only through its webpage, but through many of the frequently used social media websites. These websites, in addition to the various USGBC chapters and LEED professionals, create a large network over which information about green buildings is propagated.[16]

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[16] To the author's knowledge, there is no known data about how much these websites and networks are used by the public and industry professionals

7.2 SEISMIC APPLICATION OF LESSON #1: ESTABLISH A LEAD NON-PROFIT ORGANIZATION TO PROMOTE CHANGE

7.2.1 Form Coalitions within Seismic Building Industry to Foster and Promote Change

Similar to the green building industry, an independent organization can take action to promote change in favor of high performance seismic design (HPSD) by forming partnerships with organizations and individuals within the earthquake community. This organization should draw from the success of the USGBC and incorporate these ideas into its own coalition plans. As was seen with the green industry, organizations and corporations either have a LEED AP professional on their staff, or are specialized in delivering LEED goods and services; they have integrated the USGBC and LEED into their organizations' culture. The coalition members have taken ownership of the green revolution. It is no longer the USGBC acting alone, but a group of individuals and organizations, with the same purpose, acting together to advance the green movement. With this outlook, greater involvement has been fostered, and with that involvement, greater change has resulted. Coalitions similar to those of the green building industry could be formed between the lead non-profit organization and organizations from the private, public, and government sectors. The member organizations or corporations could be technical design firms, contractors, manufacturers, and building and government agencies. This could help to facilitate the implementation of programs or policies in favor of HPSD. With strong government involvement and support, implementing PBEE in seismic resistant design could be achieved, and with PBEE implemented, the implementation of passive control systems like seismic isolation and passive energy dissipation system will follow.

The Earthquake Engineering Research Institute (EERI) presently employs a similar tactic as that which is mentioned in the preceding paragraph. The EERI is a non-profit organization, with members that include researchers, practicing professionals, educators, government officials, and building code regulators. The organization seeks to (1) advance the practice and science of earthquake engineering; (2) improve the “understanding of the impact of earthquakes on the physical, social, economic, political, and cultural environment”; and (3) advocate “comprehensive and realistic measures for reducing the harmful effects of earthquakes” (EERI, 2011). Different from the recommendations mentioned in the preceding paragraph, the EERI has targeted the engineering audience, with the exception of the government and building code officials. The organization’s reach is not broad enough, in that organizations from the private sector and the general non-engineering public are not included. Similar to the EERI members, the lead non-profit organization spearheading the movement from conventional to high performance seismic resistant design should have members and coalitions from every sector of the seismic building industry, both private and public.

7.2.1.1 Coalitions Used to Enhance Regulatory Process

In the green building industry, some building departments have LEED accredited professionals on staff to help with the green buildings requiring permitting. These individuals are knowledgeable about green buildings and their expertise is used to ensure that, even though green building techniques and systems are included in the building design, they still comply with the codes. The HPSD seismic community could adopt a similar approach, where credentialed individuals who are skilled at evaluating high performance PBEE and PSD designs could streamline the permitting and approval process for buildings incorporating these systems. These professionals could also provide technical assistance to owners and developers at the various stages of design and construction. Accredited HPSD professionals could act as inside advocates, mentors, and tutors, to educate, and meet to enhance seismic buildings codes such that they do not impede the inclusion of these systems and methodologies into seismic resistant design.

Some building departments, like the City of Chicago, similar to the green building case, have similar experienced personnel that are used to perform peer reviews on structural plans. They help to streamline the permitting and approval by reducing the time and effort it would require the department plan reviewers to perform and complete the plan review and approval process. These individuals are certified by the building department and hired by building owners. Under this program, these certified experts are retained by the department and are not hired consultants. Therefore, the program comes at no costs to the building department. This peer review process could be used in seismic regions to help in streamline the plan review process, assist and educate the public.

7.2.1.2 Coalitions Used to Foster Government Stewardship

Similar to the green building revolution, having the government lead in the implementation of HPSD can legitimize the system. At the onset of LEED, many of the buildings built using the "green" methods were government buildings. Additionally, some states presently require that government building be built to a certain LEED rating level. This has shown the government support for sustainable development. A similar approach should be used in HPSD, where governments, states, local and federal, are urged to take a greater part in taking the lead, and act as a steward for this system.

One method that could be used in fostering ownership and promoting change in favor of HPSD, and increase government involvement in HPSD, is to educate the public officials on seismic risk. Similar to the green building industry, and its annual conference, the Green Building Expo on sustainability, where all industry leaders including government officials have attended, it is recommended that elected officials attend some of the technical and non-technical conferences about seismic risk to upkeep their knowledge of these risks. With the integration of seismic training in the daily running of government, officials responsible for the passing and enforcement of policies can gain better understanding of seismic risk and its consequences on human lives and the economy. Considering the fact that the majority of earthquake repair bills are paid for by the government, by reinforcing understanding seismic risks and their importance through government official training, policies and funding for risk mitigation programs could emerge to reduce risks. Their increased involvement and knowledge could further support advocates efforts in implementing HPSD techniques and technologies into current seismic design.

7.2.2 Educate Industry Professionals and Public about High Performance Seismic Design

Similar to the efforts of the USGBC to educate the public and professionals about green building, a webpage should be established and be used as the reference point for all who seek information about HPSD. Resources such as instructional courses and webinars could be made available online through the USGBC and all its chapters nationally. These instructional resources should be technical and non-technical in nature based on the target audience.

Another method by which the public and professionals could be educated about HPSD is through conferences. There are already yearly conferences about seismic resistant design that bring together engineering professionals from around the world. These conferences are often technical in nature, and their proceedings are not made available to the general public. The only access to these journals is through databases which require paid subscriptions. As a result, many professionals in the industry do not have direct access to the information contained in these journals. It is unclear how the issue of access can be resolved given the monetary gains often associated with the publication of these journals; however, given that educating professionals and the public is needed to help further the move from conventional to high performance seismic resistant design, and that the information contained in these journals could be used to achieve this goal, a solution is needed where access is not restricted.

Similar to the green building industry, an accreditation program should be established where professionals are educated and can gain experience in HPSD. A similar credentialing system could be used in addition to the required state licenses used in structural engineering practice. As was seen with the green building industry, many of the LEED AP's are part of the building and planning departments. Others are part of the management team at various organizations and corporations. The credentialed individuals in the building departments can be used as tutors to provide guidance and educate owners and or designers seeking building permits. Those who are part of organizations and corporations can be used to educate the other professionals within these organizations. These accredited seismic professionals can be used as tutors to educate both the public and other industry professionals.

7.2.3 Research and Disseminate Information about High Performance Seismic Design

As previously noted, one applicable lesson is the establishment of a rating system. This rating system, detailed in the following section, would be administered by the lead non-profit seismic organization. Due to the lack of information about costs and benefits of each of the aspects of high performance seismic design, a directory similar to the one kept by the USGBC, which includes information such as project and ownership types, completion dates, and locations, should be organized and maintained by the lead non-profit organization foreseen to oversee the rating system. This information would be submitted along with the rating system's required submissions. Additionally, the author recommends that the methodology results be submitted as part of the required submissions of the rating system, since part of the PBEE methodology deals with loss estimation. These may include life-cycle costs, cost reductions due to a reduction in building vulnerability, as well as the costs or costs savings associated with the application of the methodology and the other high performance seismic techniques and technologies. With such a directory, the organization will be able to keep track of all the activities, cost and benefits of HPSD, and have a system from which case study analyses could be performed and be used to further promote the methods and systems used in HPSD. With records of current and past applications, the independent organization will be able to diffuse the innovation of PBEE, and PSDs. In addition to requiring that costs information be submitted, it would be beneficial for owners to have a consistent method of evaluating future benefits that HPSD provides. A systematic and consistent method for evaluating and tracking benefits could also be used when making the arguments that HPSD is more seismically sustainable than the prescriptive seismic resistant design provided for by the present codes.

The research and case studies performed on high performance seismic resistant buildings should be made available to the public. Similar to the USGBC's efforts, the research was published over the web in a manner that all audiences are able to access and comprehend the information presented; access is not restricted. The information is not only searchable using known search engines, but it is also displayed on the USGBC's and all its affiliated chapters' webpages. A similar method should be used in the seismic community, where the research results about benefits and costs of high performance seismic design is displayed on the lead-organization's webpage. Additionally, given that approximately 91% of adults actively use social media websites, the use of these available channels to display information about benefits and costs of HPSD could be effective (Experian, 2011). The large network created by the linked members on these websites could provide a way by which this information could be propagated to the public.

7.3 LESSON #2: ESTABLISH A RATING SYSTEM

The LEED rating system has also contributed to the green building industry’s success. This rating system, established and overseen by the USGBC, is used to help define and evaluate green buildings. It is an established standard or metric by which the greenness of high performance green buildings is measured. It is also a statement of environmental responsibility for those owners who choose to upgrade their buildings to that level. As such, when this rating system is associated with a building, the latter’s higher performance and higher quality is accepted by the public, as the rating system is widely known. With a LEED certification, the building’s rating is displayed as a public statement of the building’s performance. With this acceptance comes the prestige that gets associated with these LEED rated buildings. Having a rating gives green buildings a market advantage over conventional buildings (Yudelson, 2008). In addition to being used when marketing green buildings (other benefits are listed in section 3.1.4), the LEED rating system has been and is being used by governments, state, local and federal when designing and formulating incentives for sustainable buildings, many of which benefit sustainable development. Many of the incentives listed in chapter 3 are based on the condition of a building being able to attain a certain level of LEED certification. Considering the aforementioned benefits and uses of the LEED rating system, and those mentioned in section 3.1.4, some key lessons learned are mentioned below. These may be used to enhance the seismic rating systems that are currently being developed.

There are several lessons that the seismic community can learn from a review of the LEED rating system. One lesson is that the rating system can be used in a variety of settings. The LEED rating system can be used to evaluate buildings of all types, occupancy levels, and on new and existing buildings. It is divided into categories, New Construction, Existing Buildings and

Cores and Shell (refer to section 2.2.3 for details on these categories). Buildings that fall under each of these categories get rated using the metrics formulated specifically for these buildings types. Therefore, all buildings can be considered within in the LEED rating system.

A second lesson that can be learned from LEED is that the rating system is self-assessed. The design teams self-assign points to the building. Then, the consultants, hired on by the green building’s third-party credentialing body, the Green Building Certification Institute (GBCI), awards the assessed points based on merit. The points are awarded based on how the buildings successfully address predefined criteria in several different prerequisite and optional categories (a rating will not be given if prerequisites are not addressed). The consultants awarding the points are professionals and firms with experience in product certification. They provide unbiased reviews, thereby allowing consistency and quality to remain in certification process.

A third lesson that can be learned from LEED is its submission process. Submissions for certification happen throughout the design and construction phases by project team members and contractors. A LEED Accredited Professional manages the submissions and leads the project team through the certification process. Before the points are awarded, the hired consultants conduct technical reviews on the submissions, and once the points are accepted and approved, a rating is produced. The latter can only be achieved once building is constructed and furnished.

7.4 SEISMIC APPLICATION OF LESSON #2: ESTABLISH A RATING SYSTEM

Similar to the LEED rating system, a rating system can benefit the earthquake community in that it can be used to establish a standard and a consistent method to evaluate and measure the expected seismic performance of new and existing buildings (May, 2007). Currently, we have an implicit rating system that describes buildings either as compliant with modern building codes or not. This rating system can be used in a variety of applications and settings, and be performed with ease (May, 2007).

7.4.1 Seismic Resistant Rating System

7.4.1.1 Goals of Rating System

The Structural Engineers Associate of Northern California (SEAONC) is presently developing a rating system for seismic performance of existing buildings (Mayes, et al., 2011). SEAONC's Existing Buildings Committee (EBC), at the behest of the board of SEAONC, was called to develop an Earthquake Performance Rating System (EPRS). The rating system's objectives are that it will fill in the current gaps in public knowledge, and ensure that costs associated with implementation and that regulations are minimal.

The SEAONC EPRS is not considered a tool that could be used to evaluate the seismic performance of buildings (Mayes, et al., 2011). It is rather a translation of the results obtained from an existing evaluation standard into practical terms. The goal of the rating system is to establish rules by which the methodologies presently available for seismic evaluation of buildings can be easily translated into the predefined rating dimension categories.

In early 2011, the subcommittee of the EBC, the building rating committee (BRC), formed specifically to research and develop the rating system, met with building owners, policy officials, and building investors, to identify what they envisioned the important characteristics of a high performance seismic resistant design the rating system to be. The important characteristics, defined during this workshop, are as follows (Mayes, et al., 2011):

- *Rating Metrics:* The workshop participants concluded that the rating system needed to include the safety, repair costs, downtime (defined as the time needed to regain business functionality), and performance dimensions, all of which should be combined into a single rating. Thus, expected seismic performance can be assessed based on the priorities in each of the dimensions. This would provide for a weighting system that can be used to rate existing buildings over various aspects of performance.
- *Acceptable Minimum Safety and Hazard Levels:* The current method used by codes to measure seismic hazard for new buildings is to be used to determine the minimum required safety levels to be used in the rating system. Shorter return periods of seismic events were suggested for use in the repair costs and downtime dimensions.
- *Rating Symbols:* In lieu of a point-scale like LEED, the participants preferred a symbolic rating system that is simple and can effectively communicate the details of each dimensions. The simple rating symbols would avoid "the misperception of undue precision" (Mayes, et al., 2011).
- *Qualifications of Rating Persons and Overseeing Organization:* the participants suggested that certified Professional Engineers rate commercial buildings. A certified "credentialed" individual may oversee the rating of residential buildings. They also suggested that a non-profit, independent, organization be established and authorized, similar to USGBC, to oversee and administer the rating system, as well as establishing regular peer reviews of the process to ensure that the system retains its credibility.

- *Rating Cost:* The cost of the rating, as the participants agreed, would affect the rate of adoption. The cost was suggested to remain within a reasonable level, though the ratings produced by a PE would cost significantly more than one produced by a credentialing individual.

7.4.1.2 Rating Evaluation and Scale

The EPRS is not the introduction of a new evaluation method, but instead relies on the existing methodologies that evaluate building performance (Mayes, et al., 2011). The ratings received are a product of the outputs of evaluation criteria like those in ASCE 31-03 standards. Tables Table **38,**Table **39**, and Table **40** list the performance levels from the structural, geotechnical, and non-structural evaluations from ASCE 31-03 (Mayes, et al., 2011). The EPRS indicates the limits of the evaluation criteria, rather than attempting to control the evaluation quality. The process that the rating system uses to produce ratings from any evaluation standard is being developed such that it is well defined and transparent.

The EPRS proposes to use a symbolic 1 to 5 star rating scale to rate building performance in the three dimensions, safety, cost of repair, and business downtime (Mayes, et al., 2011). The EPRS, established to communicate seismic risk, and to convey the building performance level, is defined so that it can be used and understood by a non-engineering audience (Mayes, et al., 2011). The EPRS contains enough technical information such that it could be used to compare buildings in seismic risk mitigation programs. Currently, only existing buildings are covered under the EPRS. The SEAONC intends to include all types of buildings and building occupancies under the future versions of the EPRS.

Table 38: Safety Dimension of the EPRS (Mayes, et al., 2011)

Rating	Safety
* * * * *	Building performance would not lead to conditions commonly associated with earthquake-related *entrapment.*
* * * *	Building performance would not lead to conditions commonly associated with earthquake-related *injuries*.
* * *	Building performance would not lead to conditions commonly associated with earthquake-related *death.*
* *	Building performance in select locations within or adjacent to the building leads to conditions known to be associated with earthquake-related *death.*
*	Performance of the building as a whole leads to conditions known to be associated with earthquake-related *death.*

Table 39: Repair Cost Dimension of the EPRS (Mayes, et al., 2011)

Rating	Repair Cost
* * * * *	Building performance would lead to conditions requiring earthquake-related repairs commonly costing less than 5% of building replacement value.
* * * *	Building performance would lead to conditions requiring earthquake-related repairs commonly costing less than 10% of building replacement value.
* * *	Building performance would lead to conditions requiring earthquake-related repairs commonly costing less than 20% of building replacement value.
* *	Building performance would lead to conditions requiring earthquake-related repairs commonly costing less than 50% of building replacement value**.**
*	Building performance would lead to conditions requiring earthquake-related repairs costing more than 50% of building replacement value.

Table 40: Repair Cost Dimension of the EPRS (Mayes, et al., 2011)

Rating	Downtime (Time to regain function)
* * * * *	Building performance would support the building's basic intended functions within *hours* following the earthquake.
* * * *	Building performance would support the building's basic intended functions within *days* following the earthquake.
* * *	Building performance would support the building's basic intended functions within *weeks* following the earthquake.
* *	Building performance would support the building's basic intended functions within *months* following the earthquake.
*	Building performance would support the building's basic intended functions within *years* following the earthquake.

7.4.1.3 Establish a Non-Profit Organization like the USGBC

To retain a certain level of technical credibility in the EPRS, SEAONC envisions that a non-profit, independent organization will oversee and administer the rating system. The role of this organization will be to accredit engineers to produce the ratings. A peer review for the ratings produced by engineers would be required to ensure consistency in the applications of the rating system. SEAONC does not want to participate in the rating process. Rather, SEAONC will evaluate the rating system to ensure that they comply with the original EPRS.

The future of the EPRS, under the administration of the independent organization, may set forth requirements for accreditation of these rating engineers, as well as establish minimum standards for peer review. The independent organization that adopts SEAONC's EPRS will function similarly to the GBCI of the USGBC.

7.4.1.4 Other Disaster-Related Rating Systems

There are several other rating systems that have been used over time to rate natural disasters and/or building performance during these disasters. Two of these rating systems, the Earthquake Disaster Risk Index (EDRI), and the US Resiliency Council's CoRE earthquake rating system are described herein. The purpose of expounding on other currently in use disaster rating systems and LEED is to compare them to the EPRS, and to uncover some areas that the EPRS can be improved.

The EDRI is an index used to measure the overall relative earthquake disaster risks in cities worldwide. The factors that contribute to this overall earthquake risk are the cities' earthquak occurrence frequencies, structural vulnerabilities, and quality of emergency response and recovery planning (Davidson & Shah, 1997). In using this rating system, a city's relative risk in one factor can be compared to another, and be used to inform decisions regarding risk mitigation measures (Davidson & Shah, 1997). The indeces used to represent the risk level of each city are mathematically computed from measurable indicators (e.g. population), and data acquired from cities across the world (Davidson & Shah, 1997). The EDRI is continuouly improved and updated by The GeoHazards International organization (Cardona, Davidson, and Villacis 1999). This type of disaster rating system is similar to the EPRS in that the indeces are used to make a statement on relative seismic risk. In the case of the EDRI, the statement made is regarding regional seismic risk, and is used by local governments and municipalities and other industry proffessionals to assist in risk mitigation decision-making and allocation of recovery resources and efforts.

Another rating system is in the development stage for use on residential buildings of varying construction material types and sizes. This rating system, overseen by the recently established U.S. Resiliency Council (USRC), an organization foreseen to function like the USGBC, is based on the SEAONC EPRS (Berg & Reis, 2013). The goal of this rating system is to rate a building’s resiliency to natural and man-made hazards. This rating system initially will rate the resilience of structures in seismic hazards. Then the USRC plans to extend the rating system to include other natural hazards such as hurricanes and floods (Berg & Reis, 2013). The symbolic star ratings will be issued in the form of a certificate, the Certificate of Resilient Engineering (CoRE) (Berg & Reis, 2013), and similar to the EPRS, CoRE ratings will be produced by credentialed and/or licensed professional engineers. The USRC will perform periodic peer reviews to ensure that the rating system maintains its level of technicality (Berg & Reis, 2013). Each rating level will aim to qualitatively quantify the building’s performance level based on aspects of life-safety, damage repair costs, and business downtime. Though this rating system is based on the EPRS, different from the EPRS, it can be applied to new and existing residential buildings. It is being developed such that it can be applied to diverse applications, much like the LEED rating system.

7.4.1.5 Differences between Seismic Rating Systems and LEED

There are a few similarities between the LEED rating system and the EPRS. The green buildings rated using LEED are buildings that are designed to have minimal impact on the environment. This is achieved by their building designs, and the buildings' efficient use of resources. This can be expressed as the building's sustainable performance once built. Similar to LEED's measures on the sustainable performance of buildings, the EPRS and CoRE systems measure the level of expected performance of the building when subjected to seismic loading. Also similar to LEED, both the seismic rating systems intend to authorize a non-profit organization to oversee the administration of the rating system, with the USRC already administering the CoRE rating system. Another similarity to LEED is that the points in the seismic systems are awarded in categories, or dimensions, that reflect and reinforce the organizations' mission to enhance the seismic performance of buildings by mitigating damage.

Different from LEED is the rating scale used in the seismic rating systems. In the LEED system, the rating scale used allows buildings to acquire points based on a checklist approach, where the building could be designed specifically to receive points in certain categories. As a result, designers tend to design for the points rather than for sustainability. In the earthquake seismic rating systems the building is evaluated, and its performance is determined analytically. The rating scale received is based on the analytical evaluation results. Thus, designers optimize the building performance level to receive an overall higher rating, rather than selecting specific dimensions in which to receive a rating. The rating systems could then be used to encourage high performance seismic design.

Another difference between the LEED and the seismic rating systems is that the seismic systems are, for now, designed to rate specific buildings, rather than buildings of all types and occupancies. The LEED system has categories that rate new, existing, and renovation commercial, residential, government, and institutional projects. The system has every type of construction covered under one rating system with multiple sub categories. Although the EPRS and the CoRE are still in their infancy stages, both systems still are not applicable to all those aforementioned building and ownership types.

The author recommends that the seismic rating system developed be established to rate buildings of all types, new, existing and renovations. Additionally, this rating system should rate all building use, and occupancy levels. It is also recommended that the rating system has a separate evaluation system for critical facilities. It has been seen throughout the literature review that special emphasis is placed on these facilities due to their post-earthquake's needed use. Many laws, like the Hospital Act of 1953, have been established to regulate the design and performance levels of these facilities. Therefore, the development of a subcategory within the rating system to rate these facilities should be considered. Additionally, similar to LEED, the rating scales should be self-assessed and be submitted during the design phase; however, different from LEED, none of the submissions for the seismic rating system should be any of the contractor's responsibility.

7.4.1.6 Benefits of a Seismic Performance Rating System

Experience with existing rating systems such as the one that is part of California's URM law has shown that these systems can be used to dictate risk mitigation measures. California's URM law requires that the vulnerable URMs be identified in jurisdictions in specific risk regions, and a risk mitigation plan be developed (CSSC, 2006). Part of the URM identification involves measuring the risk that the structure poses to the life-safety of the public and building occupants. Based on the year, occupancy level and use, and number of stories, these URM are rated qualitatively using a scale of “most,” “more,” and “intermediate” to identify the level of danger that the building poses (ATC, 2009; CSSC, 2006; COES, 1994). This qualitative rating, determined after the city inspectors have identified the vulnerable buildings, is used to inform municipalities on which risk mitigation measure to adopt. In the case of Long Beach in 1989, the buildings in the “most dangerous” categories were required to be rehabilitated by a certain date (COES, 1994). Most of the URM buildings in that category were either rehabilitated or demolished; those remaining after the deadline were razed by the city (COES, 1994). The buildings in the “intermediate dangerous” category were not required to be retrofitted. FEMA-774 reports that 560 of the URMs in that category remain un-retrofitted (ATC, 2009). The author speculates that this may be due to the voluntary risk mitigation approach that Long Beach adopted for URM buildings in that category.

Having a rating scale applied to a building may increase the building’s property value. In the case of the rated URM’s, those that remained un-retrofitted, as was expressed by the owners in the Rabinovici (2012) study, could see a decrease in property value and a potential loss of income as tenants may find the building unsafe and choose to rent elsewhere. This implies that adverse ratings, though indirectly, may affect the market value of properties and building revenue. This was seen in the green industry. The buildings with a LEED rating had higher market values than buildings without the rating. Extrapolating to the seismic rating system, buildings with higher rating scales, implying a higher predicted expected performance, could have higher market values than others with lower or no ratings.

Additionally, the rating system could be used to enhance or change the earthquake insurance policies. Since the rating system will have the expected performance levels embedded into the ratings produced, the insurance companies could use these systems to measure their overall risk of earthquake losses. Given that insurance companies devise their premiums based on the costs of building damage repair. These companies can use the rating system to help design their policies premiums. It could help these companies to properly plan their portfolio diversification and establish earthquake premiums. This could result in lower premiums for HPSD buildings with higher ratings.

7.4.2 Using Seismic Rating System to Help Establish Incentives

Drawing from the lessons learned from the green building industry, the HPSD incentives could be designed like those offered for LEED rated buildings. In the green industry, building departments in many states provide bonuses to building owners with certain LEED rating. The rating system is used in all cases of monetary and non-monetary incentives, programs, and laws to establish minimum guidelines for compliance, approval and/or qualification. In some instances, because the rating is not received until after construction is complete, building owners are penalized if the end rating is not what the building originally was qualified under. The rating system is also used as a benchmark by policy makers when formulating the level of incentives that a building can or will receive. Buildings with the highest rating can qualify for higher rebates, credits or exemption, as was seen in the cases of tax incentives (see section 3.3 for more details).

The incentives offered for green buildings were seen to be non-monetary, which are incentives with no program costs to the municipalities, or monetary, like tax incentives, which have program costs. The non-monetary incentives are of the form of floor and height area bonus ratios, where a building owner can increase either height or floor area if the building has a certain rating. Other non-monetary incentives are expedited permitting processes, where the wait-time is reduced from months to days. In addition to non-monetary incentives, monetary incentives are also offered. These incentives are typically funded by the municipalities, states, and local governments. These incentives could be tax incentives in the form of rebates, exemptions and credits. These types of incentives, non-monetary and monetary, were seen as effective (section 3.3.4.1) as shown by the rise in green ratings since their introductions in the various states.

Similar incentives could be offered to encourage HPSD. The author envisions that bonuses like zoning exemptions, density and intensity, development standards reductions, and other code provision relaxations and waivers for the inclusion of PSDs in building design, could be offered as non-monetary incentives. Monetary incentives in the forms of rebates based on a percentage of the property value (e.g. City of Oakland), property tax exemptions, grants and long term or differed loans to fund the upfront premiums, and permit fee waivers, could all be offered as incentives to encourage HPSD. These incentives could be offered for buildings achieving a certain rating scale and/or including HPSD techniques or systems, and to encourage voluntary rehabilitation measures in regions of low seismicity. Combined with the implementation of PBEE into seismic design, and an active implementation approach for seismic rehabilitation in regions of high seismicity, these incentives could be effective in offsetting the costs associated with these high performance seismic design techniques and systems.

7.4.2.1 Effectiveness of Current High Performance Seismic Design Incentives

There have been, and still are, numerous seismic incentives in place to encourage risk mitigation through high performance seismic resistant design. Some of these incentives, monetary and non-monetary, are designed to encourage voluntary seismic rehabilitation. The non-monetary incentives typically require no additional costs for municipalities to offer them to the public. For instance, the Palo Alto zoning requirement exemptions requires no additional program costs. Conversely, monetary incentives have implementation costs, which typically require municipalities to obtain funding by means of bond issue and other techniques. Many of these incentives have been ineffective in encouraging voluntary rehabilitation (CSSC, 2006). These incentives' effect on reducing the overall seismic risk is minimal (CSSC, 2006; COES, 1994). As was shown in the California Seismic Safety Commission report in 2006, only 13% of the total URMs had been retrofitted voluntarily (CSSC, 2006). The development of effective incentives could be used to offset the implementation costs of all the aspects of high performance seismic design.

In order for incentives to be effective, much needs to be done in ways of preparation. State, local, and municipal governments should meet to discuss and prepare their plan of action on how the funds for their incentive programs would be acquired and what types of incentives they will be used for. Federal and private sources should be targeted. The resulting incentives should be clearly defined, advertised, and have a transparent application process where specific criteria to obtain funding are outlined.

CONCLUSIONS AND FINAL THOUGHTS

One of the purposes of this research document was to illustrate the many successes of the green building industry. At its inception in 2000, there were only 50 known sustainable buildings built and rated. 13 years later, there are over 16,000 rated green buildings worldwide, with over 14,000 located in the US. The green building industry has grown exponentially in the short 13 years since the development of the LEED program. Although this industry saw a slow rise in its number of registered project from 2000 to 2003, since the development of various incentives programs in many states in the US, their number of project saw a yearly increase of 15% to 44% across the US. Despite the many barriers to high performance green buildings, the main being their upfront premiums, these incentives, along with the USGBC’s aggressive advocacy and coalition programs to disseminate information about LEED to the public, the industry has and continues to thrive.

Another goal of this thesis was to compare and recommend solutions that could be used to diffuse the innovations of high performance seismic resistant design (HPSD) to the public using the green industry as a model. One of the main lessons learned from the green industry is its advocacy and coalition efforts. The green building industry has strong ties to many states, local and federal governments, one of latter being the US Department of Energy. The industry has partnered with high ranking organizations in both the private and public sectors. With these ties, policy implementations in favor of green buildings receive strong backing by these government officials. The earthquake community needs similar partnerships. With strong government backing, as is seen with the green industry, implementing the PBEE methodology into current seismic resistant design could be achieved. With PBEE implemented, so would all the accompanying high performance techniques and technologies. This step is the most crucial.

Once complete, then municipalities could develop incentives, very similar to those offered for high performance green buildings, to help offset some of the costs to implementing these methodologies and technologies into seismic resistant design. Because the existing seismic incentives alone have not been effective in encouraging the HPSD, HPSD implementation must be mandated in order for, should an intense earthquake occur, the economic losses to be reduced. Government endorsement would help to accomplish that.

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LIST OF APPENDICES

Appendix A: Total number of US, Canada, and Internal LEED Rated Projects (All versions, all systems) as of February 2013

Based on 2013 USGBC Data

US States:	Abbreviation:	# of LEED Projects	% of Total
Alabama	AL	81	0.5%
Alaska	AK	39	0.2%
Arizona	AZ	287	1.8%
Arkansas	AR	87	0.5%
California	**CA**	**2245**	**13.9%**
Colorado	CO	486	3.0%
Connecticut	CT	145	0.9%
Delaware	DE	28	0.2%
Florida	FL	722	4.5%
Georgia	GA	456	2.8%
Hawaii	HI	83	0.5%
Idaho	ID	60	0.4%
Illinois	IL	723	4.5%
Indiana	IN	148	0.9%
Iowa	IA	151	0.9%
Kansas	KS	89	0.6%
Kentucky	KY	76	0.5%
Louisiana	LA	49	0.3%
Maine	ME	80	0.5%
Maryland	MD	430	2.7%
Massachusetts	MA	490	3.0%
Michigan	MI	383	2.4%
Minnesota	MN	221	1.4%
Mississippi	MS	50	0.3%
Missouri	MO	204	1.3%
Montana	MT	47	0.3%
Nebraska	NE	54	0.3%
Nevada	NV	111	0.7%
New Hampshire	NH	66	0.4%
New Jersey	NJ	254	1.6%
New Mexico	NM	158	1.0%
New York	NY	773	4.8%
North Carolina	NC	433	2.7%
North Dakota	ND	27	0.2%
Ohio	OH	457	2.8%
Oklahoma	OK	56	0.3%
Oregon	OR	362	2.2%

Pennsylvania	PA	600	3.7%
Rhode Island	RI	48	0.3%
South Carolina	SC	173	1.1%
South Dakota	SD	33	0.2%
Tennessee	TN	192	1.2%
Texas	TX	932	5.8%
Utah	UT	123	0.8%
Vermont	VT	61	0.4%
Virginia	VA	569	3.5%
Washington	WA	624	3.9%
West Virginia	WV	20	0.1%
Wisconsin	WI	244	1.5%
Wyoming	WY	34	0.2%
District of Columbia	DC	371	2.3%
Puerto Rico	PR	18	0.1%
Virgin Islands	VI	2	0.0%
Armed Forces Africa	AE	0	0.0%
Guam	GU	5	0.0%
Total US LEED Projects		**14660**	**90.8%**
Total Canada LEED Projects		**130**	**0.8%**
Total International LEED Projects		**1354**	**8.4%**
TOTAL PROJECTS		**16144**	

Appendix B: Total number of US, and Canada LEED Rated Projects by Types (All versions, all systems) as of February 2013

Based on 2013 USGBC Data

Project Types	**# of LEED Projects**	**% of Total**
Assembly	165	1.0%
Commercial Offices	5473	33.9%
Health Care	438	2.7%
Higher Education	961	6.0%
Hotel/Resort	102	0.6%
Industrial	584	3.6%
K-12 Education	629	3.9%
Laboratories	408	2.5%
Libraries	201	1.2%
Military Bases	226	1.4%
Multi & Single Unit Residential	495	3.1%
Mixed-Use	97	0.6%
Other	4255	26.4%
Public Order/Safety	413	2.6%
Recreation	331	2.1%
Restaurants	299	1.9%
Retail	955	5.9%
Stadium/Arena	46	0.3%
Transportation	66	0.4%
Total Projects	**16144**	**100.0%**

Appendix C: List of 33 Project used in Kats Green Building Premium Analysis (Kats, 2003)

Project	**Location**	**Type**	**Date Completed**	**Up-front Premiums**	**Green Standard**
Energy Resource Center	Downey, CA	Office	1995	0.00%	Level 1-
KSBA Architects	Pittsburgh, PA	Office	1998	0.00%	Level 1-
Brengel Tech Center	Milwaukee, WI	Office	2000	0.00%	Level 1-
Stewart's Building	Baltimore, MD	Office	2003	0.50%	Level 1-
Pier One	San Francisco,	Office	2001	0.70%	Level 1-
PA EPA S. Central	Harrisburg, PA	Office	1998	1.00%	Level 1-
Continental Towers	Chicago, IL	Office	1998	1.50%	Level 1-
Cal EPA Headquarters	Sacramento,	Office	2000	1.60%	Level 1-
EPA Regional	Kansas City,	Office	1999	0.00%	Level 2-
Ash Creek Intermed.	Independence,	School	2002	0.00%	Level 2-
PNC Firstside Center	Pittsburgh, PA	Office	2000	0.25%	Level 2-
Clackamas High School	Clackamas, OR	School	2002	0.30%	Level 2-
Southern Alleghenies	Loretto, PA	Office	2003	0.50%	Level 2-
DPR-ABD Office	Sacramento,	Office	2003	0.85%	Level 2-
Luhrs Univ. Elementary	Shippensburg,	School	2000	1.20%	Level 2-
Clearview Elementary	Hanover, PA	School	2002	1.30%	Level 2-
West Whiteland	Exton, PA	Office	2004	1.50%	Level 2-
Twin Valley Elementary	Elverson, PA	School	2004	1.50%	Level 2-
Licking County	Newark, OH	School	2003	1.80%	Level 2-
3 Portland Public	Portland, OR	Office	since 1994	2.20%	Level 2-
Nidus Center of Science	Creve Coeur,	Office	1999	3.50%	Level 2-
Municipal Courts	Seattle, WA	Office	2002	4.00%	Level 2-
St. Stephens Cathedral	Harrisburg, PA	School	2003	7.10%	Level 2-
4 Times Square	New York City	Office	1999	7.50%	Level 2-
PA DEP Southeast	Norristown, PA	Office	2003	0.10%	Level 3-
The Dalles Middle	The Dalles, OR	School	2002	0.50%	Level 3-
Dev. Resource Center	Chattanooga,	Office	2001	1.00%	Level 3-
PA DEP Cambria	Ebensburg, PA	Office	2000	1.20%	Level 3-
PA DEP California	California, PA	Office	2003	1.70%	Level 3-
East End Complex-Blk	Sacramento,	Office	2003	6.41%	Level 3-
Botanical Garden Admin	Queens, NY	Office	2003	6.50%	Level 4-

Appendix D: Seismic Occupancy Category ASCE 7-05

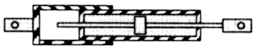
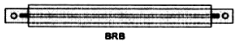
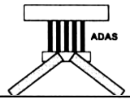
Occupancy Category	Nature of Occupancy
I	Building and other structures that represent a low hazard to human life in the event of failure, including agricultural, temporary, and minor storage facilities.
II	All other structures that aren't in categories I, III, or IV.
III	Building and other structures that represent a substantial hazard to human life in the event of failure including: • Covered structures the primary occupancy of which is public assembly with an occupant load of 300. • Buildings and other structures with elementary-school, secondary-school, or day-care facilities with an occupant load greater than 250. • Buildings and other structures with elementary-school, secondary-school, or day-care facilities with an occupant load greater than 500 for colleges or adult-education facilities. • Health-Care facilities with an occupant load of 50 or more resident patients without surgery or emergency-treatment facilities. • Jails and detention facilities. • Any structure with an occupant load greater than 5,000. • Power-generating stations, water-treatment facilities for portable water, waste-water-treatment facilities, and other public-utility facilities not included in Occupancy Category IV. • Buildings and other structures not included in Occupancy Category IV containing sufficient quantities of toxic or explosive substances that would be dangerous to the public if released.
IV	Buildings and other structures designated as essential facilities, including: • Hospitals and other health-care facilities with surgery or emergency-treatment facilities. • Fire, rescue, and police stations and emergency-vehicle garages. • Designated earthquake, hurricane, or other emergency shelters. • Designated emergency-preparedness, communication, and operation centers and other facilities required for emergency response • Power-generating stations and other public-utility facilities required as emergency-backup facilities for Occupancy Category IV structures. • Structures containing highly toxic materials as defined in Section 307 of the 2006 International Building Code. • Aviation control towers, air-traffic control centers, and emergency-aircraft hangers. • Buildings and other structures with critical national-defense functions. • Water-treatment facilities required to maintain water pressure for fire suppression.

Appendix E: Seismic Design Category ASCE 7-05 (BSSC, 2010)

SDC	Building Type and Expected Modified Mercalli Intensity (MMI)	Seismic Criteria
A	Buildings located in regions having a very small probability of experiencing damaging earthquake effects	No specific seismic design requirements but structures are required to have complete lateral-force-resisting systems and to meet basic structural integrity criteria.
B	Structures of ordinary occupancy that could experience moderate (MMI VI) intensity shaking	Structures must be designed to resist seismic forces.
C	Structures of ordinary occupancy that could experience strong (MMI VII) and important structures that could experience moderate (MMI VI) shaking	Structures must be designed to resist seismic forces. Critical nonstructural components must be provided with seismic restraint.
D	Structures of ordinary occupancy that could experience very strong shaking (MMI VIII) and important structures that could experience MMI VII shaking	Structures must be designed to resist seismic forces. Only structural systems capable of providing good performance are permitted. Nonstructural components that could cause injury must be provided with seismic restraint. Nonstructural systems required for life safety protection must be demonstrated to be capable of post-earthquake functionality. Special construction quality assurance measures are required.
E	Structures of ordinary occupancy located within a few kilometers of major active faults capable of producing MMI IX or more intense shaking	Structures must be designed to resist seismic forces. Only structural systems that are capable of providing superior performance permitted. Many types of irregularities are prohibited. Nonstructural components that could cause injury must be provided with seismic restraint. Nonstructural systems required for life safety protection must be demonstrated to be capable of post-earthquake functionality. Special construction quality assurance measures are required.

F	Critically important structures located within a few kilometers of major active faults capable of producing MMI IX or more intense shaking	Structures must be designed to resist seismic forces. Only structural systems capable of providing superior performance permitted are permitted. Many types of irregularities are prohibited. Nonstructural components that could cause injury must be provided with seismic restraint. Nonstructural systems required for facility function must be demonstrated to be capable of post-earthquake functionality. Special construction quality assurance measures are required.

Appendix F: Type of Energy Dissipation Dampers: Advantages and Disadvantages (Symans, et al., 2008)

	Viscous Fluid Damper	**Viscoelastic Solid Damper**	**Metallic Damper**	**Friction Damper**
Basic Construction			 	
Advantages	- Activated at low displacements - Minimal restoring force - For linear damper, modeling of damper is simplified. - Properties largely frequency and temperature-independent - Proven record of performance in military applications	- Activated at low displacements - Provides restoring force - Linear behavior, therefore simplified modeling of damper	- Stable hysteretic behavior - Long-term reliability - Insensitivity to ambient temperature - Materials and behavior familiar to practicing engineers	- Large energy dissipation per cycle - Insensitivity to ambient temperature
Disadvantages	- Possible fluid seal leakage (reliability concern)	- Limited deformation capacity - Properties are frequency and temperature-dependent - Possible debonding and tearing of VE material (reliability concern)	- Device damaged after earthquake; may require replacement - Nonlinear behavior; may require nonlinear analysis	- Sliding interface conditions may change with time (reliability concern) - Strongly nonlinear behavior; may excite higher modes and require nonlinear analysis - Permanent displacements if no restoring force mechanism provided

Appendix G: Location of Seismic Base Isolation Structures

Based on 1998 EERC data

Bridges

State	**# of Structures**
AL	1
DC	3
CA	19
CT	3
IL	9
IN	2
KY	2
MA	14
MO	7
NH	5
NJ	12
NV	1
JY	9
OR	4
PA	1
PR	1
RI	3
VA	1
VT	1
WA	8
WV	2

Buildings

State	**# of Structures**
CA	29
MO	2
NV	2
OR	2
TN	1
UT	1
WA	1

Appendix H: Regional Earthquake Loss Estimation-A brief Description of HAZUS-MH

A brief summary of FEMA’s regional earthquake loss estimation is presented below to further support the claim that the upfront premiums involved with implementing high performance seismic design measures are small compared to the predicted cost of repairing or replacing buildings after an earthquake event on a regional basis.

The research developments of the recent years has given scientists and engineers the abilities to analyze the effects of soil conditions on ground motion using probabilistic seismic hazard analyses (PSHA) (Chen & Wills, 2011). These analyses assess and estimate the effects of seismic events on the annual losses incurred from earthquakes. FEMA developed HAZUS-MH, a multi-hazard (MH) geographic loss estimation tool. The Annualized Earthquake Loss (AEL) estimation generated by HAZUS is used in seismic risk assessment. This estimation tool is a regional indicator of predicted and potential earthquake damage, and their economic consequences. The AEL may also be used as an annualized percent earthquake loss (APEL) to relate the annual building loss as a percentage of its replacement value (Chen & Wills, 2011).

According to a 2008 study that FEMA conducted on AEL values for the US states, the AEL to the stock of buildings in California accounted for approximately 66% of the national AEL loss ($3.5 billion of $ 5.3 each year) (Chen & Wills, 2011). The study ranked California as number one in AEL in the country (Chen & Wills, 2011). The 2010 estimated AEL resulting from building damage for regions in California by the California Geological Survey (CGS) is $2.8, with an APEL of 0.103% (Chen & Wills, 2011). Because the annual earthquake losses are greater in California than any other states, the next sections will focus on illustrating the cost reductions that structures in California can achieve using the HPSD measures detailed in the previous chapter. Since a greater number of buildings abroad, specifically Canada, Japan, and

New Zealand, are using base isolation and energy dissipating devices, some of the data used in the subsequent sections will be for buildings located in these countries.