Report Submitted to:

Professor Arthur Gerstenfeld
Professor Lok C. Lew Yan Voon

Puerto Rico Project Center

SEISMIC VULNERABILITY OF PUBLIC STRUCTURES IN PUERTO RICO

By

Michael M. Dorval	Michael M. Dorval
Timothy M. Hanley	Timothy M. Hanley
Keri E. Blauvelt	Keri E. Blauvelt
Daniel C. Nelson	Daniel C. Nelson

In Cooperation With

Dr. Fernando E. Fagundo – *Senior Technical Advisor*

CSA Group – San Juan, Puerto Rico

May 1, 2001

Abstract

The following study, commissioned by CSA Group, Inc., investigates the seismic vulnerability of public structures in Puerto Rico. The objectives provided by CSA are to determine the causes and areas of seismic vulnerability in Puerto Rico, to evaluate the cost of retrofitting the vulnerable structures, and to evaluate the social impacts that an earthquake may have on the Island. The provided information will enable CSA Group to assess the feasibility of and need for retrofitting the vulnerable structures.

Authorship Page

All members contributed equally to the completion of this project. Additionally, all members assisted with the completion of all sections of the report.

Acknowledgements

We would like to thank the following people who all played critical roles in the completion of our project:

CSA

Dr. Fernando Fagundo

Dr. Luis Daza

Mr. Herman Ramos

University of Puerto Rico - Mayagüez

Dr. Jose Martinez Cruzado

Dr. Ricardo Lopez

Dr. Ali Saffar

Others

Dr. Bernardo Deschapelles

Dr. Alberto Guzman

WPI Faculty Advisors

Prof. Arthur Gerstenfeld

Prof. Lok Lew Yan Voon

Prof. Susan Vernon-Gerstenfeld

Table of Contents

List of Tables

List of Figures

Executive Summary

The following report, commissioned by CSA Group, Inc., investigates the seismic vulnerability of public structures in Puerto Rico. The goals of our project were to determine the causes and areas of seismic vulnerability in Puerto Rico and to evaluate the cost of retrofit along with the social implications associated with a major earthquake. Furthermore, we made recommendations that we believe would save many lives and money in the event of an earthquake.

We began this project by researching general earthquake information. We examined the types of earthquakes and why they occur, how they are measured, and whether or not they can be predicted. Our main concern for this project was how often earthquakes actually occurred in Puerto Rico, and whether or not they have ever had a major impact on the Island. Therefore, we discussed the frequency and history of earthquakes in Puerto Rico in order to portray the importance of this project.

In order to show that retrofitting is needed in Puerto Rico, we compared the costs of retrofit versus the human capital costs associated with the number of lives at risk within the structure in the event of an earthquake. We compiled data on schools and residential structures and then analyzed this data in order to determine if retrofitting would be beneficial when compared to the cost of damage and loss of life from an earthquake. Factors such as earthquake probabilities in Puerto Rico, cost of human life, damage to buildings, and economic loss were taken into account in this analysis.

Our project discusses both the technical aspect and the social aspect associated with earthquakes before and after damage occurs. Our social aspect of the project compares the cost of damages from a major earthquake for a structure that was un-retrofitted versus the cost of damages for a structure that was retrofitted. After the cost of retrofit was taken in account, we determined that it is beneficial to owners to retrofit their structures.

From the technical standpoint of the project, we received significant amounts of information through literature review, interviews, and information sessions. Our project goes into detail about the types of retrofit techniques commonly used throughout the world, as well as in Puerto Rico. We also discussed the causes and modes of structural failure during an earthquake in order to address ways for retrofitting certain structures. We used a computer software program known as Visual Analysis in order to model a single-story school building in Puerto Rico. It allowed us to see where common failure points occurred from an earthquake load and enabled us to recommend various retrofit techniques through experimentation.

By using a software package known as ArcExplorer2, a Geographical Information Systems program, we were able to map out the problem areas of Puerto Rico by layering maps based on vulnerable areas due to landslide possibilities, poor soils, and high populations. An area susceptible to these three properties was considered vulnerable to seismic activities.

From our research, we found that retrofitting must be done in Puerto Rico, but currently the desire to do it does not exist for a majority of the population living in vulnerable structures. We believe that the public needs to be educated about the strong possibility of a major earthquake striking Puerto Rico in order for the public to consider the risks involved. Many people do not realize the importance of strengthening their

buildings, and by providing this report, we hope to show that “an ounce of prevention is worth a pound of cure.”

Chapter 1: Introduction

Recent tragedies such as the earthquakes in El Salvador and India emphasized the importance of the safety of the buildings in which we live and work. Because of similar tragedies, CSA Group, located in San Juan, Puerto Rico, decided that there is a need to investigate the seismic vulnerability of some of the older structures on the Island. The Department of Civil Engineering at the University of Puerto Rico – Mayagüez chose representative structures built prior to the modern code requirements for a project team from Worcester Polytechnic Institute to study in order to determine how well the structures meet the current seismic codes.

We believe that this project can serve as a model for other countries that are considered to be located in seismically vulnerable areas. Due to the infrequency of earthquakes, many people are unaware of the fact that a major earthquake can cause destruction at any given time in their area. It may actually take a large earthquake to occur in order for some people to realize how powerful earthquakes are, not only physically, but socially as well. The cost of human lives often exceeds that of retrofit when an earthquake of large magnitude occurs.

Engineers designed the provided representative structures utilizing the building codes current at the time of construction. However, technological advances and an increased knowledge regarding earthquakes resulted in improved seismic codes, requiring engineers to design future structures to a higher standard than those buildings designed in years past. The current codes are much more demanding of the properties of a structure, resulting in appreciably higher construction costs. We intended to analyze the compliance of a structure with the current seismic codes. The determination to retrofit, or bring a structure up to code, affects its residents. This procedure is time consuming, causing the displacement of the residents as well as a loss of profits for the companies affected. However, this procedure is an important step to ensure the safety of a building's occupants.

The goal of this project was to determine the need, feasibility, and cost of retrofitting inadequate structures to an acceptable seismic standard. Furthermore, the objective was to identify areas of Puerto Rico that could be susceptible to severe damage during a major earthquake. We also analyzed the social issues associated with an earthquake including lax government regulations, retrofit incentives, and an owner's decision between the costs of retrofit versus the cost of the lives within. These social implications can have an effect on how well a given area will respond to a major earthquake. The more aware a society is of its earthquake preparedness, the better it will perform in the event an earthquake were to occur.

We compiled data on schools and residential structures, and then analyzed it to determine if retrofitting was more or less economically beneficial than the damage and loss of life from an earthquake. Factors such as earthquake probabilities in Puerto Rico, cost of human life, damage to buildings, and economic loss were taken into account in this analysis. We made recommendations about what areas of Puerto Rico have a high failure potential in the event of an earthquake. From our conclusions, our model portrayed how to prioritize which of these areas were in need of the most work. Puerto Rico has had a history of earthquakes that have endangered the lives of its inhabitants.

By analyzing this problem *before* a major earthquake occurs, we believe this project shows how to minimize the cost and human suffering for the residents of Puerto Rico.

One of the graduation requirements of Worcester Polytechnic Institute is the completion of an Interactive Qualifying Project (IQP). The IQP challenges students to develop a comprehensive understanding of the impacts that science and technology can have on society. This project qualified as an IQP because of the societal impact resulting from the decisions regarding the potentially vulnerable structures. Residents of a populated building that is seismically vulnerable have a high risk of injury or death from an earthquake. We not only evaluated the number of lives at risk, but also compared that to the economic cost of retrofitting the building.

This report was prepared by members of Worcester Polytechnic Institute Puerto Rico Project Center. The relationship of the Center to the CSA Group and the relevance of the topic to CSA Group are presented in Appendix A.

Chapter 2: Literature Review

The following sections provide background information and a review of previous work related to the objectives and goals of our project. In order to provide ourselves with all of the necessary information regarding earthquake vulnerability, we reviewed many books and journal articles relating general seismic information and the probabilities of earthquake occurrences. We also looked into the social implications of earthquakes in order to compare the feasibility of retrofit versus the cost of human life. We will discuss the necessary methods, techniques, and costs used to retrofit many structures in order to meet required standards and governmental codes for seismic vulnerability.

2.1 General Earthquake Information

Many reasons exist for the occurrence of earthquakes. Additionally, there are signs that show that an earthquake has occurred, or that one may occur in the future. Puerto Rico has an extensive earthquake history and is still susceptible to earthquakes.

2.1.1 Types of Earthquakes and Why They Occur

Earthquakes, in general, occur near plate margins. Bolt (1993) classifies them into four different categories. The most common of the four, which is the primary one that occurs in Puerto Rico, is the tectonic earthquake. This type of earthquake occurs when stress buildup and other geological forces underneath the surface of the earth cause rocks to break apart. This produces seismic waves, causing the earth to tremble. Volcanic earthquakes, which accompany volcanic eruptions, are very closely related to the tectonic earthquake. The collapsing of a cave or a mine causes collapse earthquakes. The shaking is a result of the collapsing of the rocks. Finally, there is the explosion earthquake. For the most part, man causes this type of earthquake as a result of the detonation of chemical and nuclear devices.

2.1.2 Measurement Scales

Two scales, the Richter scale and the Mercalli scale, exist for the measurement of earthquake intensity. The Richter scale relies on quantitative data, while the Mercalli scale utilizes a qualitative analysis.

2.1.2.1 Richter Scale

The most widely used method of measuring the magnitude of an earthquake is called the Richter scale, or Richter magnitude. This scale does not take into account the population or the amount of construction that has taken place in an area, as did some earlier methods. Instead, it uses an instrument called a seismograph. The seismograph provides various pieces of information including the energy released in an earthquake and the amplitude of the waves. Because of the wide range of values for amplitude, scientists developed the scale using a logarithmic scale. More specifically, the Richter magnitude is the log to the base ten of the largest amplitude recorded. The Richter magnitude is measured in thousandths of a millimeter at a distance of one hundred kilometers from the epicenter of the earthquake (Bolt, 1993). The scale ranges from 0 to 10. The U.S. Geological Survey (USGS) provides a comparison of the different magnitudes and the frequency at which they occur. This information is provided in Table 2.1.

The important thing to keep in mind when looking at this table is that a rise of one in magnitude represents a change in magnitude by a factor of ten. For example, an earthquake of magnitude 7.0 is ten times stronger than one of magnitude 6.0 (NEIC, 2000).

Table 2.1 – Global Earthquake Magnitudes and Frequency

Description of the Earthquake	**Richter Magnitude**	**Number Per Year**
Great	> 8	1
Major	7 – 7.9	18
Strong	6 – 6.9	120
Moderate	5 – 5.9	800
Light	4 – 4.9	6,200
Minor	3 – 3.9	49,000
Very Minor	< 3	9,000 Per Day

Source: United States Geological Survey (2000)

2.1.2.2 Mercalli Scale

An additional method of measuring earthquakes is the Modified Mercalli Intensity Scale. This scale is purely qualitative, utilizing both the perception of the earthquake by the people who experienced it and the amount of damage produced by it. The Mercalli scale ranks earthquakes from 1 to 12, using Roman numerals. It ranges from I, an earthquake that was not felt, to XII, an earthquake that caused massive damage. Table 2.2 categorizes these intensities.

Following a seismic event, the USGS mails surveys to postmasters so that an appropriate Mercalli Intensity can be assigned to the earthquake, resulting from the peoples' responses to what they felt during the quake (NEIC, 2000). From this information, researchers produce a map of damage, allowing seismologists to determine how the earthquake affected different parts of the same area.

Table 2.2 – Perception of Damage as Related to Mercalli Intensities

Intensity	Perception and Damage
I	Not felt except by a very few under especially favorable conditions
II	Felt only by a few persons at rest, especially on upper floors of buildings
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly
XII	Damage total. Lines of sight and level distorted. Objects thrown into the air

Source : United States Geological Survey (2000)

2.1.3 Long-term Earthquake Prediction

If an area lies along a fault line, there exists a much larger chance of experiencing an earthquake (Mogi, 1985). Additionally, earthquakes tend to occur more frequently in the same locations; if a large earthquake has occurred in a particular area, it is very likely that one will occur again. Mogi says that it may be possible to estimate the amount of time between large earthquakes in an area by examining the past seismic activity. Unfortunately, accurate records do not exist for many areas. The partial information available is for only a few hundred to a few thousand years, and therefore is not reliable for making predictions.

Seismologists use various criteria to determine the probability of an earthquake occurring. In order for long and short-term prediction of earthquakes to be successful, possible precursors require examination. Researchers define precursors as an occurrence or change that takes place before an earthquake (Lomnitz, 1994; Brumbaugh, 1999). Lomnitz explains the importance of a precursor, emphasizing the need to examine what happens before an earthquake, not what happens after one.

According to Brumbaugh (1999), a seismic gap consists of an area that, when compared to the surrounding areas, has experienced little seismic activity. Lomnitz (1994) breaks up this definition into two parts. First, a seismic gap consists of an area along a seismic belt that has not experienced any large seismic activity in the recent past. Second, if adjacent areas along this belt have more recently had larger earthquakes, it is more likely for a large earthquake to occur in the seismic gap. Lomnitz asserts that, presently, seismic gaps may be one of the biggest signs that an earthquake may occur in an area. Alternatively, Mogi (1985) indicates that there are two different types of seismic gaps, called "seismic gaps of the first kind" and "seismic gaps of the second kind". Seismic gaps of the first kind are the same as the definition provided by Lomnitz. When an area frequently experiencing small earthquakes suddenly has a period when the activity drops off, a seismic gap of the second kind results, greatly increasing the probability of a larger earthquake occurring.

2.1.4 Effects of Earthquakes

Earthquakes leave behind evidence of their occurrence; besides destruction of life and buildings, they leave marks on the land. Experts concur that the largest earthquakes leave behind the most scars, resulting from faulting, tsunamis, and the liquefaction of soil.

2.1.4.1 Faulting

The most significant of the different scars left behind include the crack or the fault. When a fault appears at the center of an earthquake, a previously existing underground fault has come to the surface, as seen in Figure 2.1. Erosion often erases any sign of these faults, making them difficult to find. In addition, if the earthquake occurs on the ocean floor, the faults are nearly impossible to observe. Each time an earthquake occurs, some deformation of the land also occurs. Over time, these deformations alter the topography of the land, forming new hills and mountains. If these scars on the land can be dated, scientists may be able to determine when and where large earthquakes have occurred. From this data, scientists may be able to determine when and where other large earthquakes will strike. Dating of the land scars can be difficult, as current carbon dating is only accurate up to 40,000 years. When examining landforms that may be as old as 200,000 years, the dating may be off by as much as 50,000 years (Asada,

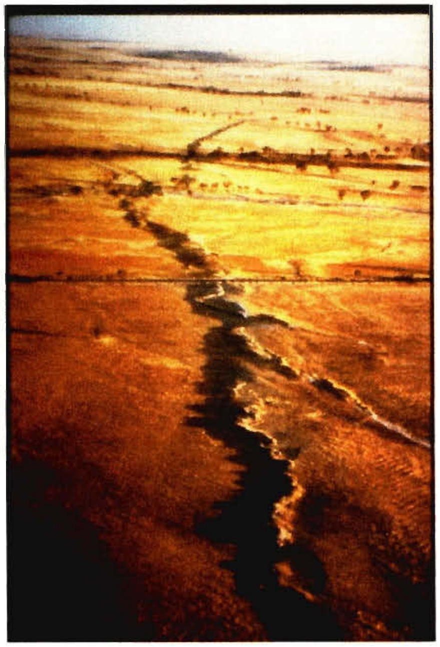


Figure 2.1: Faulting
Source: NGDC (2001b)

1992).

2.1.4.2 Tsunamis

An additional result of earthquakes that can be just as devastating as the earthquake itself is a tsunami. According to the USGS (2001), a common misconception amongst people is that a tsunami and a tidal wave are the same phenomenon when, in fact, they are quite different. An extreme case of the changing of the tides from the sun and the moon produces a tidal wave; the shaking of the earth on the bottom floor of the ocean creates a tsunami. Recorded heights of known tsunamis have reached up to eighty feet. Another misconception is that a tsunami is always a large wave. On November 18, 1929, a wave that measured one foot tall hit the east coast of the United States. Even though a very small wave, it fulfilled the definition of a tsunami because it resulted from an earthquake (USGS, 2001).

2.1.4.3 Liquefaction of Soil

In certain past earthquakes, liquefaction has been responsible for causing massive amounts of damage. This process occurs when the soil in an area assumes a quasi-liquid state due to the extreme vibrations of the ground. In essence, the soil becomes quicksand. This type of ground failure occurs in non-clay soils such as sand and silts where a deposit of water exists, located not more than thirty feet from the surface. The water pressure beneath the soil increases. When the water pressure increases to a point where it is equal to the pressure of the soil, liquefaction occurs. When the soil is in the quasi-liquid state, objects tend to sink into the soil (USGS, 2001).

2.1.4.4 Landslides

Another major effect of a seismic event includes landslides, which occur in sloped areas. A large slope provides a greater chance for the occurrence of a landslide. An earthquake may cause large rocks and soil to become loose on these slopes. If the slope is great enough to overcome the static force, the rocks and soil will then begin to slide. This avalanche of rocks and soil can be very destructive, damaging or destroying anything in its path (USGS, 2001). The most destructive landslide historically occurred during the 1970 earthquake in Peru. This landslide buried parts of two towns and was responsible for the 18,000 deaths (ACOE, 1996). The Mameyes landslide of 1985, which occurred in Puerto Rico, was the most destructive landslide in United States recorded history based on the loss of life. Although this landslide was not related to an earthquake, it demonstrates the effect that a large-scale earthquake could have in the mountainous regions of Puerto Rico. Puerto Rico is comprised of mountainous areas, putting it at extreme risk due to landslides. In the event of an earthquake of magnitude 8.0, the entire Island could be subject to devastating landslides similar to that of Mameyes (ACOE, 1996).

2.1.5 Earthquake Frequency in Puerto Rico

The University of Puerto Rico currently maintains the Puerto Rico Seismic Network. They collect data about every seismic event that occurs in Puerto Rico, the surrounding waters, and the surrounding islands. Table 2.3 provides an example of the data that the Puerto Rico Seismic Network collects each month. This table shows the seismic activity for the first four days of the month of December 2000.

This information is typical of the data provided by the Seismic Network. In just four days eight seismic events occurred. Upon further examination of the data, it is apparent that Puerto Rico experiences approximately six hundred seismic events per year. In addition to the information given in the above table, the Seismic Network possesses data for all seismic events that occurred over the last thirteen years. During this time, the earthquakes had magnitudes of up to 5.6 (UPR, 2001).

Table 2.3 – Seismic Activity in and Around Puerto Rico for December 1-4, 2000

Day	Magnitude	Depth (km)	Latitude	Longitude
1	3.5	74.6	19.64	-67.08
1	3.1	86.7	18.56	-66.69
1	4.3	55.7	19.30	-67.95
1	3.5	54.9	19.38	-68.13
2	2.8	97.8	18.47	-66.65
3	3.4	112.7	18.46	-65.49
4	2.2	20.6	18.05	-67.19
4	2.2	24.0	18.06	-67.06

Source: Puerto Rico Seismic Network (2001)

2.1.6 Earthquake History of Puerto Rico

According to José Freytes (2000) of the Puerto Rico Department of Civil Defense, there have been four large earthquakes recorded in Puerto Rico and the surrounding waters. The earliest known of these occurred in 1670, in the San German District. Although known to be a very large earthquake, no estimate of its magnitude has been determined. On May 2, 1787, the Island experienced another large earthquake with an estimated magnitude of 8.0 on the Richter scale, most likely the largest earthquake to hit the Island since the beginning of its colonization. The effects of this earthquake reverberated throughout the Island and did extensive damage to buildings including the monasteries, churches, and castles of the period. Another large earthquake struck on November 18, 1867. This earthquake centered within the Anegenda passage, located between Puerto Rico and the Virgin Islands, with an estimated magnitude of 7.5 on the Richter scale. The center of this quake was not located directly on the mainland of Puerto Rico; however, this did not prevent a resulting tsunami from traveling almost five hundred meters inland on the eastern coast. The most recent large earthquake near Puerto Rico occurred on October 18, 1918. Its epicenter was located in the Mona Canyon between Puerto Rico and the Dominican Republic with a magnitude of 7.5. This quake also created a tsunami that devastated the western part of the Island, killing an estimated

116 people and causing nearly $4 million of damage to the Island (Freytes, 2000).

Besides the four most destructive earthquakes in Puerto Rico that Freytes (2000) discusses, in the last one hundred years there have been five other earthquakes in Puerto Rico with magnitudes above 7.0 on the Richter scale. The first of these five struck in 1916, in the area of San Juan, and registered a magnitude of 7.2 on the Richter scale. Two other earthquakes of magnitude 7.0 and 7.2 struck San Juan again in 1917 and 1969 respectively. The last earthquake above 7.0 struck Ponce in 1974 and registered as 7.5 on the Richter scale (NGDC, 2001).

2.2 Social Implications of Seismic Vulnerability

Seismically vulnerable structures present a threat to their occupants. In order to reduce this threat, the building requires structural improvements. Because we are concerned with the safety of a person's life, this project has profound social implications. When making the changes to the structure, it becomes important to complete a cost-benefit analysis of the situation. This section will begin to discuss some of the different ways to assess the social costs of changing the structure, mainly by determining the value of a human life.

2.2.1 Value of Human Life

Whenever there exists a potential change to the safety of a public structure, the cost of a human life needs consideration (Arthur, 1981). A cost-benefit analysis is necessary for the building owner to complete in order to decide whether a building requires fixing. This cost-benefit analysis involves the amount of money required to retrofit a structure compared to the cost of lives that would be lost if the building collapsed. Therefore, a study of past situations involving the calculation of the cost of life will be helpful to understand this analysis.

According to Arthur (1981), structural engineers must come to an agreement on the safety features of buildings during construction. The structures must not be built so rigid that no sway is allowed, nor can they be built so weak that they may collapse in the event of an earthquake. The question that needs asking by these engineers is, "To what degree of safety should we strive for?" The United States government already defines this degree of safety by creating building codes.

Many people feel that evaluating the cost of a human being is unthinkable (Lavelle, 1988). However, companies that make products that could possibly pose some risk to a life do this analysis so that they can determine what is best for the company by maximizing profits. Bayles (1978) states that placing a price on a human life is something commonly done, especially in the area of bio-ethics and social policy. Arthur's perspective (1981) indicates that calculating the value of a life must be strictly from an actuarial standpoint, with all subjectivity removed in order to obtain an accurate assessment.

2.2.1.1 Evaluation Methods of Price of Life

According to the U.S. Department of Transportation (USDOT) (1991), there exist three different ways to place a value on the human life. These three types include a cost-benefit model, a human capital model, and a comprehensive model. The approach of placing a monetary value on human life did not begin to enter into governmental regulations until the Reagan administration. In 1981, Reagan's Office of Management and Budget (OMB) began to estimate the price of a human life using the cost-benefit model. The OMB intended to determine the value of a human life in order to compare it to the cost to society of the regulation that they desired to promote (Lavelle, 1988). Many of the proposed regulations that the agency examined included building codes, which they analyzed to prevent safety improvements from becoming too costly for the construction company, especially without a guarantee of an accident occurring. The government did not want to make the codes so strict that it would cost a fortune to build, making the price of the construction skyrocket. Once the OMB calculated the economic value of a life, they could then decide whether the cost of the regulation was economically beneficial. The approach that this committee utilized took the amount that the regulation would cost, determined the proposed number of lives the regulation could save, and then divided the cost by the number of lives saved to get the proposed value of a human life (Lavelle, 1988).

According to the USDOT (1991) and Lavelle (1988), a commonly used model when applying this calculation is the comprehensive model. This method takes into account many other factors left out by other models. It considers future income loss, medical bills, court costs, loss to the employer of the deceased, funeral costs, and even property damage. Because of all the aspects considered by this model, it typically yields a much higher estimate, making it a commonly used model. One of the downfalls to this model is that it can only be used on an individual basis, not on the populated basis that we need for this project. Another problem with this model is that it does not provide any consistency from case to case. This method takes into account a value of pain and suffering that is completely subjective. It is because of this pain and suffering value that the structural and architectural engineering profession does not use this method (Guzman, 1998). While Arthur (1981) indicated that when doing this type of calculation all subjectivity must be removed, this method of comprehensive analysis uses much subjectivity to achieve its final value. The fact that this method includes a value for pain and suffering in the final estimate causes controversy. This amount for pain and suffering varies greatly depending on the cause of death or injury, making it hard to place an actual monetary value on a human life. The USDOT (1991) says that at times, it may become necessary to separate the pain and suffering value from the overall estimate and consider a more straightforward method of calculation known as the human capital model.

Analysts utilized the human capital method for over two hundred years (USDOT, 1991). The basis of this method uses the loss of income if the person were to die. It takes the amount a person makes in a year and multiplies that value by the number of years they could have still worked had they not died. One of the downfalls of the human capital model is that it tends to place low values on older people and children. One advantage to this model is that it is easier to calculate a value based on a population as a whole, rather than on an individual basis. Another advantage to this method is that it allows for quick and easy calculations with very little information needed. The only information that a person needs to know in order to use this model are the gross per capita annual income of the area involved, the average age of the people in an area, and the retirement age of the population. Even though this method provides what may seem to be low estimates, it is the core for the method in use by the structural engineering profession (Guzman, 1998). According to the USDOT (1991), the legal profession uses this model as well, but they take it one step further and apply a value for pain and suffering.

In 1988, the National Highway Traffic Safety Authority (NHTSA) said that they refused to put a monetary value on a life. They felt that the safety of a person should be the only priority. NHTSA did calculate the number of lives saved by a certain technological advance, but said they would never translate those lives saved into any amount of money (Lavelle, 1988). A few years later this agency changed its viewpoint and began utilizing this practice as an integral part of their crash analysis (USDOT, 1991). They felt it was a necessary step to take in order to ensure a consistency across all of their decisions. Consistency would then make their safety policy more rational (USDOT, 1991).

2.2.1.2 Price of Life Estimates

This section outlines some past situations where the cost of a human life was important to consider. It looks at different case studies, and explains the difficulty related to placing a monetary value on a life.

Wrongful Death Lawsuit Estimates

Another important area where analysts frequently calculate the cost of life includes wrongful death lawsuits. Reviewing awards from many of these lawsuits occurring within the past few years, the average value of a life is approximately $3.5 million, half of which constituted retribution for pain and suffering. While there existed some awards with estimates in the $8 million to $12 million range with higher pain and suffering values, there also existed other awards with smaller pain and suffering values (Morlan, 2000).

Most government agencies utilize values similar to this wrongful death lawsuit estimate of $3.5 million. According to the USDOT (1991), in 1991, government agencies used the value of $2.39 million with $1.74 million of that in pain and suffering. After applying the calculations provided by the USDOT to account for inflation, the monetary value of a human life in the United States is currently $3.6 million with $2.72 million of that allotted for pain and suffering. This values a human life at $880,000 without the pain and suffering factor.

Ford Pinto Recall Estimate

During the late 1960's, the Ford Motor Company released a new sub-compact car called the Pinto. In an effort to compete better against foreign made cars, Ford rushed this vehicle through production in two years, as opposed to the three and a half years that new vehicles normally take. In this process, Ford overlooked many critical engineering aspects. The main problem with the automobile revolved around the location of the gas tank, between the rear bumper and the rear axle of the vehicle. When struck by another vehicle, the gasoline would often leak into the passenger compartment, ignite, and cause massive injury or even death to the occupants of the vehicle (Flores, 1980).

Ford began receiving lawsuits filed against them from many of their customers, so they performed a cost-benefit analysis of the situation. They calculated that it would cost $11 per vehicle to fix the problem. Based on the number of vehicles produced, the total amount required to move the gas tanks would be $137 million. Ford then priced the cost of a human life. The key point they explored involved the amount the lawsuits from the family of the victim would cost them. They completed a comprehensive analysis in 1965, which yielded a value of $200,725 for the cost of a human life with $10,000 accounting for pain and suffering (Flores, 1980). Translated into current values, the amount is $700,000 with $35,000 for pain and suffering.

Consumer Product Safety Commission Estimates

In one case in 1979, the Commission said a life was worth $132 million, with millions of those dollars being a pain and suffering estimate due to the gross negligence of a company. However, in a case in 1980, this same Commission found that a life was worth $70,000 with virtually no value for pain and suffering, for they felt the accident was an honest mistake and there was no wrongdoing (Lavelle, 1988). These large discrepancies demonstrate how difficult it can be to evaluate the exact value of a life depending on the situation.

2.2.2 Indirect Costs

During an information session with Dr. Ali Saffar at the University of Puerto Rico – Mayagüez, it was brought to our attention that indirect costs could be associated with an earthquake. According to Saffar, there is a big concern with the market output of firms supplying goods and services. Take, for instance, a highly populated office building located adjacent to a building with a cafeteria. This adjacent building happens to provide the only cafeteria in the area and serves many of the employees of the office building. An earthquake occurs that damages the office building in such a way that it needs major repair. This repair requires relocation of the occupants of the office building during reconstruction. Because this relocation, there will be a lack of lunchtime traffic into the building containing the cafeteria. This lack of traffic has a direct affect on the building still in operation, because the employees will not be utilizing the cafeteria, causing a reduction in the profit of the building. Because this building has fewer customers, they will have less need to buy materials from their suppliers, and this effect will have a domino effect on other businesses in the area.

If a building collapses or is damaged by an earthquake, it is often necessary to relocate the occupants of the building in order to repair or rebuild the building (Guzman, 1998). This relocation results in an additional expense for the occupants. This expense is an unexpected cost on top of the cost of the rehabilitation of the building.

Another indirect cost due to earthquake damage is also associated with the reconstruction of the building. According to Dr. Ali Saffar, repairs done to a building often need to have a certain appearance to them. The goal of the repair is to rehabilitate the building, while at the same time, restoring it to its original appearance. This can be a problem when trying to fix certain buildings. If the building that collapses happens to be a historical building, it may require a certain façade throughout the building during the reconstruction so that it looks like the original. It may be possible to repair the building with relatively little money by using modern techniques, but the changes may not match the original style of the building. In cases like these, it may become necessary to pay additional money to have the rehabilitation of the building done a certain way so that it looks like the original.

2.3 Government Regulations

During the design and construction of buildings, engineers must comply with certain standards, known as building codes. According to Breyer, Fridley, and Cobeen (1999), in order to be beneficial to the public, these codes must be written into local laws in the form of ordinances. Breyer et al. further indicate that the lengthy legislative process tends to prevent the codes from advancing at the same pace as technology.

2.3.1 History of Building Codes as Related to Earthquakes

Following major catastrophes, such as the earthquake in Northbridge, California in 1994, engineers inspect the damaged, as well as undamaged, structures in the area, with the purpose of gaining a better understanding regarding successful and unsuccessful design techniques. These methods, according to Breyer et al. (1999), tend to result in advances in building codes, which increase the protection of the public. However, the alterations made to the building codes generally apply to future construction projects only. Although the codes do not require owners of existing buildings to improve their buildings, inspectors stamp existing buildings that fail to meet the higher seismic standards account for seismic loading during the design of buildings. Before 1987, the engineers utilized the 1968 *UBC* in building design for Puerto Rico. The problem with the 1968 *UBC* was that it referred the designer to the American Concrete Institute (ACI) standards when considering the seismic vulnerability of a particular structure. Even though the seismic standards existed before 1987, designers felt that they were not required to consider these standards because the 1968 *UBC* did not directly list them.

Since many buildings in Puerto Rico were built before 1987, Deschapelles (2001) feels that many vulnerable buildings exist on the Island. Furthermore, he indicates that many of the buildings designed in rural areas after 1987 may still be vulnerable to seismic activity because the building plans do not exist for those particular structures. Therefore, no one knows for sure if these buildings are safe. However, Deschapelles believes that the least seismically vulnerable buildings are those located in the metropolitan areas of Puerto Rico that were built after 1987 because they are required to comply with the modern seismic codes.

2.3.2 Current Building Codes

Engineers within the United States employ one of three major model building codes, which are usually updated on a three-year cycle. These building codes are:

1. *Uniform Building Code (UBC)*
2. *The BOCA National Building Code/1996*
3. *Standard Building Code* (Breyer et al., 1999)

The western portion of the United States tends to rely on the *UBC* while the northern part of the country utilizes *The BOCA National Building Code* and the southern states make use of the *Standard Building Code*. Although these model codes constitute the building requirements for roughly 90 percent of the United States, many large cities write their own or modify them through legislation. According to the Multidisciplinary Center for Earthquake Engineering Research (2000), Puerto Rico employs the 1997 *UBC* in conjunction with local amendments.

Breyer et al. (1999) indicate that the *UBC* is the most widely used model building code. Because of its use in the western part of the nation, this code must include most recent seismic design requirements.

2.3.2.1 1997 UBC Seismic Zones

The 1997 *UBC* classifies all land located in the United States into five different seismic categories, zones 0 through 4. Figure 2.2 on the next page illustrates the zone distribution for the United States and Puerto Rico. Zone 2 is split up into two different zones, Zone 2A and Zone 2B. This ensures a more accurate representation of the areas comprising Zone 2. Examples of Zone 0 include North Dakota, Minnesota, and Wisconsin. In these areas, even if earthquakes do occur, the earthquakes will most likely be so small that they will cause no damage or loss of human life.

As the zone number increases, the likelihood of an earthquake occurring and the frequency at which they occur rises. An extreme danger of an earthquake occurring exists in Zone 4. Additionally, the earthquakes in this area will be large in magnitude and have the potential to cause damage and cause loss of life. An example of this type of area is the Pacific coast of California. The 1997 *UBC* classifies Puerto Rico as Zone 3. This indicates that there is potential for a large earthquake to hit the Island, which can cause damage and loss of human life. Based on the Zone classification, an area receives a seismic zone factor, which represents the percentage of gravitational acceleration, g, which the ground can expect to experience. The factor, given the variable name Z, results from multiplying gravity, g, by one-tenth the value of the zone, and is used in many of the equations that determine the building requirements for structures (*UBC*, 1997).

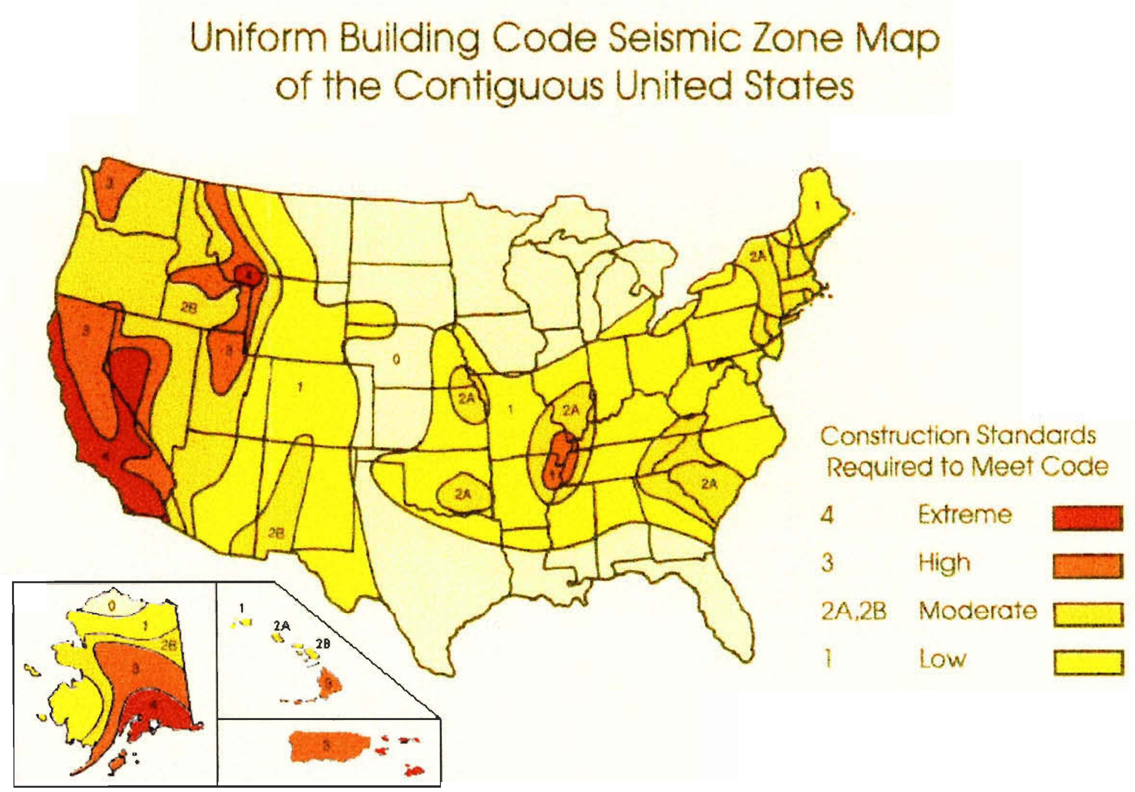


Figure 2.2: UBC Seismic Zone Map
Source: UBC (1997)

2.3.2.2 1997 UBC Provisions for Retrofit

According to the 1997 *UBC*, alterations made to a structure must meet certain requirements. The structure itself need not meet all of the seismic provisions of the current code, so long as the intended alteration complies with the codes. Furthermore, the alteration may not cause the existing structure to become unsafe. Additionally, the code allows alterations to an existing building when they result in a structure that is no less hazardous than before the alteration.

2.3.3 Future Trends in Building Codes

The organizations responsible for the three codes mentioned previously worked cooperatively to compile the 2000 *International Building Code (IBC)* (Breyer et al., 1999). This code, while very similar to the 1997 *UBC*, modified the provision for alterations allowed for existing structures. The *IBC*, like the *UBC*, allows alterations to an existing building, so long as the modification complies with the current seismic standards; however, the new code makes no provision allowing for alterations that increase the stability of the structure. Unlike the *UBC*, the *IBC* states that the forces within any element may not be increased by more than 5 percent as a result of the alteration, unless the increased forces still comply with the current standards.

2.4 Seismic Vulnerability

According to Ambrose and Vergun (1999), an examination of a structure provides an insight for much of the potential damage resulting from an earthquake. They further state that since structural engineers rarely consider the nonstructural elements of a building during design, these components fail to receive the attention they deserve.

2.4.1 Common Causes of Structural Failure

The purpose of the structural frame of a building is to serve as its skeleton. Regardless of the type of frame used, it serves to resist the various forces applied to the structure (Breyer et al., 1999). Often, the applied force on a structure affects several members. Rather than divide the force evenly among them, each structural component receives a portion of the force determined by its relative stiffness (Ambrose & Vergun, 1999).

Ambrose and Vergun (1999) indicate that a serious structural problem may result if the stiffest components resisting a load are not the strongest members. For example, although the lightweight frame braces an extensive wall, the load may be transferred to the wall rather than to the framing system. The wall, stiffer than the frame but lacking its strength, may fail before the frame receives any substantial part of the load.

Sudden changes in the relative stiffness of adjoining stories describe the situation known as "soft story". According to Denning (1993), as a result of soft story, the entire building would attempt to rotate during an earthquake, resulting in severe structural damage and increasing the potential for the loss of life. Figure 2.3 illustrates the effects of soft story after an earthquake.


Figure 2.3: Soft Story Effects on a Structure
Source: NGDC (2001b)

Similar to soft story, "weak story" occurs when the strength of one story is drastically greater or less than those it adjoins. As shown in Figure 2.4, weak story occurred within the fourth and fifth floors during an earthquake. Ambrose and Vergun (1999) indicate that both situations may result from minimum code requirements. Although elements such as interior and curtain walls may be considered nonstructural during the design phase, in actuality they resist seismic forces, altering the intended load distribution with respect to the bracing system.

Ambrose and Vergun (1999) assert that the uneven distribution of weight resulting from heating, ventilation, and air conditioning (HVAC) equipment commonly located on roofs of tall buildings may result in additional damage during an earthquake. Furthermore, they state that irregularities in the floor plan of multistory structure affect its seismic response. The location of the center of gravity of a building affects its ability to resist torsion. In an ideal situation, the center of gravity of a structure would coincide with the center of resistance supplied by the bracing system. They indicate, however, that this situation rarely occurs. In addition to an irregular floor plan, the shape of the structure, such as whether or not it is L-shaped or T-shaped, also influences its ability to resist seismic forces. Similarly, a nonparallel system of shear walls, resulting from a curved or angled shear wall or moment-resisting frame, alters the ability of the structure to withstand seismic forces (Ambrose & Vergun, 1999; DiJulio, 1989).

Figure 2.4: Weak Story Effects on a Structure
Source: NGDC (2001b)

A lateral spread results from the moving of a large block of soil beneath the surface of the earth that occurs during liquefaction. Lateral spreads generally occur when the slope of the ground is between 0.3 and 3 degrees. In general, this horizontal movement is between 10 and 15 feet, however soil has been known to move up to 150 feet horizontally. The damage produced by lateral spreads are usually not very extreme or life threatening. Often, this liquefaction may cause damage to bridges, causing them to collapse. Additionally, the horizontal movements are particularly dangerous to pipelines, such as water mains, which lie under the surface, causing them to burst disrupting the every day lives of the people in the surrounding areas (USGS, 2001).

Flow failure generally occurs when the slope of the land is greater than three degrees. This is the most damaging type of soil liquefaction, which often begins in coastal areas. In this type of liquefaction, soil and other materials in the area flow down the slope of the land anywhere from twenty feet to tens of miles. Coastal flow failure causes severe damage to buildings on the coast and create large waves, which travel inland, resulting in even more damage. An example of a flow failure on land is the 1920 Kansu earthquake, located in China. The earthquake caused liquefaction, which in turn caused many flow failures that were up to one mile long and killed 200,000 people (USGS, 2001).

Figure 2.5: Soil Liquefaction Results in Niigata, Japan
Source: NGDC (2001b)

When liquefaction occurs, the strength of the soil underneath a structure decreases. This may cause parts of the building to sink into the ground or in some extreme cases, completely tip over. Figure 2.5 illustrates an extreme case of this, which occurred in 1964, in Niigata, Japan. During this earthquake, several four-story buildings in the same area tipped as much as sixty degrees (USGS, 2001).

When an earthquake occurs, the ground vibrates at a certain frequency. The time it takes for one cycle this vibration is called the period. Additionally, all structures have periods associated with them. When a lateral force is applied to a building, the time it takes for it to rock back and forth once is the natural period (ACOE, 1996). According to Dr. Luis Daza, department manager of the structural engineering department at CSA Group, when this condition of resonance occurs, a building has a much larger chance of collapsing. When the two periods become very close or the same, structural soundness of the building no longer matters; the building will collapse. An example of this occurred with the Juarez Hospital in Mexico City. The hospital had a state of the art structural design and could withstand a very strong earthquake. During the earthquake in 1985, resonance occurred and the building collapsed as is shown in Figure 2.6.

Figure 2.6: Hospital Collapse in Mexico City due to Resonance (1985)
Source: NGDC (2001)

This collapse near the maternity wing of the building trapped four hundred patients and staff in the building for days. Additionally, the hospital shut down, preventing other injured patients of the earthquake from receiving care. Similar situations occurred in two other Mexico City Hospitals, trapping a total of eight hundred more people and causing the hospitals to shut down (NGDC, 2001).

2.4.2 Common Modes of Failure

In 1985, Mexico City suffered from a serious earthquake, which resulted in damage to many reinforced concrete structures. Numerous people researched the failures in these buildings. Aguilar et al. (1989) first wanted to determine the most common failure points of 114 different buildings. They considered nine different structure types: namely columns and waffle slab floor systems, concrete frames, masonry walls, steel frames, concrete frames in the first floor and masonry in the upper floors, concrete walls and waffle slab floor systems, concrete walls and concrete frames, and concrete frames and waffle slab floor systems.

Aguilar et al. also studied five different modes of failure. These failures included those of the vertical elements, namely walls and columns; floor systems; connections; the foundation; and the mixed failures. The main failure mode existed within the vertical structural elements. This held true for the different structure types. According to Aguilar et al. (1989), since the failures of the floor system did not occur often, one may be able to assume that waffle slab structures withstand more of a load than the concrete frame structures. Another major cause of the structural failure of the buildings resulted from incorrectly designed geometries as well as abnormal stiffness of the buildings (Aguilar et al., 1989). Aguilar et al. also concluded that the most frequent causes of damage occurred because the masonry walls in the corners of the buildings were not lined up symmetrically.

2.4.3 Common Nonstructural Failures

Many structures utilize suspended ceilings for acoustical purposes or to maintain economy. According to Ambrose and Vergun (1999) these members, unless restrained, may swing freely during an earthquake, resulting in extensive nonstructural damage. Additionally, the upward acceleration that sometimes accompanies earthquakes may result in failure of these elements. While ceiling panels may sustain damage because of either of these instances, the damage may also affect other nonstructural elements, such as the lighting system or the piping for fire sprinklers.

Many buildings have various cantilevered components, such as balconies, parapets, and chimneys. Although when designing these elements, the engineer considers gravity loads, or dead loads, these loads act in only one direction. However, seismic loads may act in directions other than those originally used during design or the loads themselves may exceed the design loads, thus causing failure (Ambrose & Vergun, 1999).

2.5 Retrofitting of Existing Structures

Breyer et al. (1999) state that, for various reasons, structures may require retrofitting, or strengthening. This necessity may be the result of new information regarding the seismic vulnerability of a particular building, the desire of the owner either to alter the existing building or to protect the property from potentially expensive damage. In addition, Breyer et al. indicate that retrofitting need not be limited to improving the structural frame of a building; excessive movement of the building may result in extensive nonstructural damage. This damage may include the failure of ceilings and the breaking of glass, which they state may not necessarily threaten the integrity of the building itself, yet it may result in severe loss of life (Breyer et al., 1999).

2.5.1 The Need for Retrofitting

Ascertaining the age of a structure allows for identifying the code to which the building originally complied. In doing so, this enables the owner to anticipate the significant alterations required for bringing the building up to an acceptable standard (Breyer et al., 1999). However, determining whether to retrofit a structure may be a very difficult decision and requires extensive consideration. According to Shepherd and Platt (1995), when an owner must decide whether to retrofit his or her building to meet safety standards or to demolish and rebuild the structure, many seriously contemplate the latter. The seismic requirements since the 1980's may be too expensive when compared to the cost of rehabilitation. Every case in which the older buildings do not meet today's required codes, the alternatives facing the owner include risking the possibility of damage during an earthquake, to retrofit the structure, or raze the entire structure.

2.5.2 Incentives for Retrofit

Dr. Deschapelles (2001) stated that many social implications occur amongst the owners of the buildings regarding the retrofitting of their structures. He indicated that in California, the government provides the owners with incentives and tax reductions if they decide to retrofit their buildings. This encourages the owners in California to keep their buildings up to modern standards because of the benefits they receive for doing so.

However, Dr. Deschapelles indicated that Puerto Rico does not provide the building owners with any added incentives or tax reductions for retrofitting their structures. Therefore, the building owners of Puerto Rico are not motivated to improve the standards of their buildings. They have no reason to do so if it is not going to save them money. Incentives exist for the owners of structures located in Old San Juan, but only for retrofitting the facades of the buildings, and not the actual structures. In reality, the owners are receiving benefits for making their buildings look nice as opposed to being safe.

2.5.3 Methods of Retrofitting for Concrete and Masonry Structures

According to Ambrose and Vergun (1999), the attempt to evaluate the seismic performance of many existing buildings today can be quite complicated. Should a large earthquake occur, many buildings that exist might cause many hazards. Many widely used procedures enable the evaluation of potential earthquake damage to a particular building.

2.5.3.1 Traditional Techniques

Several methods exist to strengthen a building, resulting in increased seismic resistance (DiJulio, 1989). Designers enlarge individual elements, allowing them to withstand greater compression and bending loads. Another option requires devising a more efficient structural system, accomplished by shortening spans, realigning members, using additional joints, or by increasing the symmetry of the support system. Similarly, improved load-transferring connections serve to improve the building.

Ambrose and Vergun (1999) feel that several factors require consideration when determining the appropriate method of retrofitting a structure. These factors include the materials that comprise the building, the amount of additional strength desired, whether replacing would be more desirable than reinforcing, and the technology available for such projects. The evaluating procedures lead to various retrofitting ideas.

Following the 1985 Mexico City earthquake, engineers considered various retrofitting techniques for the buildings. Aguilar et al. (1989) considered fifteen different possible solutions, namely the sealing of the cracks, utilizing resin injections, replacing damaged parts of structural elements, the use of hydraulic jacks to recover the original geometries of the columns, concrete jacketing of columns, steel jacketing of columns, the addition of shear concrete walls, the addition of infill concrete walls, adding of steel diagonals, the addition of concrete frames, the addition of new structural elements, straightening the building, and adding of new piles.

The study indicated that the most common retrofitting techniques used were the concrete jacketing of columns and beams and the addition of shear walls (Aguilar et al., 1989). The most useful restoration technique was the replacement of all the damaged parts. Other conclusions indicated that the most common retrofitting technique used for buildings of twelve stories or less was the concrete jacketing of the structural elements.

The concrete jacketing of the frames takes away the concentration of lateral forces on the foundation as well as retains the original architectural design of the structure with minimal amounts of change (Aguilar et al., 1989). Taller structures required the addition of shear walls, together with new piles, because the requirements of strength and stiffness are much greater in taller buildings. Shear walls reduced the lateral displacements and improved the resistance of the structures. Other results indicated that waffle slab structures required the additions of shear walls as the most prevalent retrofit technique. The concrete framed structures mainly required the use of concrete jacketing of the structural elements (Aguilar et al., 1989).

The analysis of these buildings considered five types of foundations, which included continuous footings, box type foundations, end bearing piles, friction piles, and piles with a "penetrating" point. The main conclusions drawn from the foundation research indicated that concrete jacketing was also the most common retrofit technique used for box foundations. However, a building foundation consisting of piles utilized additional shear walls and new piles (Aguilar et al., 1989).

According to Dr. Deschapelles (2001), many of the structures located in Puerto Rico are unsafe because their designs use shear walls in only one direction. When a building uses shear walls only in one direction, it can only withstand strong lateral loads that act perpendicular to the shear walls. There are many buildings designed in this manner in Puerto Rico, making them vulnerable to seismic activity and unsafe due to modern standards.

The most common major retrofit technique in Puerto Rico used to provide support for shear walls in only one direction, involves providing steel bracing on the outside of the structure. Steel bracing is commonly used because it is a cheap and effective manner. This method of retrofit consists of adding cross braces between the two shear walls on the outside of the structure. An example of this technique is illustrated in Figure 2.7. This picture was taken at an apartment complex (Balcones de Santa Maria) in Guaynabo, Puerto Rico.

Figure 2.7: Steel Bracing of Structure in Puerto Rico
Photo taken by CSA Project Team (2001)

The bonus to this retrofit technique is that the building remains in use during the retrofit process, since the construction takes place outside and the tenants can continue to use the building. The downfall to using cross bracing is that it takes away from the architect's desired design of the building. Many people feel that having steel bracing showing on the outside of a building takes away from its aesthetic appearance. However, many designers have found ways to make the building look as if the cross bracing on the outside was purposely designed by the architect for a unique appearance.

2.5.3.2 Alternative Methods of Retrofit

Advances in retrofit include the use of dampers, base isolation, and composite reinforcement. While engineers in the United States frequently employ these methods, they do not prove to be cost effective when considered for use in Puerto Rico (Daza, 2001).

Dampers

Reinhorn, Manolis, and Wen (1986) discuss one particular way to retrofit a large flexible structure such as a tall building or a long bridge. They felt that the use of tuned mass dampers (TMDs) and rubber bearings would lessen the chances of earthquake damage to certain structures. The dampers and bearings would lessen the impact of seismic forces during an earthquake since the elasticity of the structure increases.

TMDs can still be an effective and practical means for reducing vibration in structures and are still widely used today (CSA Engineering, 2001). A TMD is a modular device composed of a spring, mass, and dashpot, as pictured in Figure 2.8. The dashpot is a device used to cushion or dampen movement caused from the seismic shock. The TMD adds a mode of vibration to the base structure. CSA Engineering, Inc. also discusses various features of the TMD that help reduce vibration. They are compact devices with many uses, they can be readily added to a base structure that is already designed or even built, and they can add high damping for a structure with adding minimal weight if they are designed correctly.

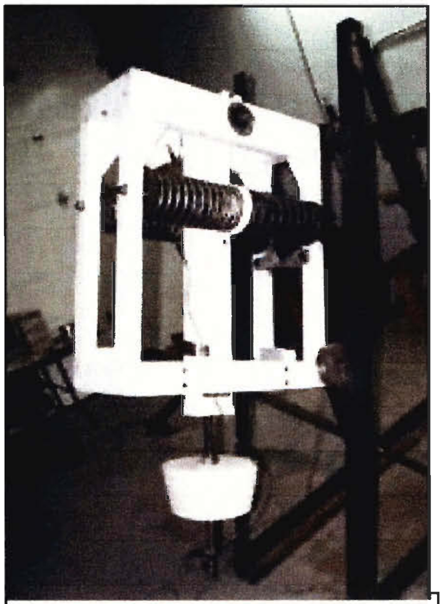


Figure 2.8: Tuned Mass Damper
Source: RWDI (2001)

Rubber bearings are designed in order to carry the weight of the structure, provide an elastic restoring force for the structure, and provide the required damping necessary for the structure (Robinson-Seismic Co., 2001). The rubber isolators used in this process may cause a substantial increase in the side sway of the building, still leaving a high possibility of earthquake damage depending on the size of the earthquake (Reinhorn et al., 1986). This procedure for retrofitting attempts to decrease the tension and/or compression responses to seismic loads of many buildings so that they meet the required design codes.

Reinhorn et al. (1986) devised an algorithm still frequently used today that would calculate the response limits of certain structures with the rubber bearings and dampers. These ideas were later used in the retrofitting process of the Foothill Communities Law and Justice Center in San Bernardino County, California. The retrofitting process in this situation utilized ninety-eight seismic isolation bearings, each containing three hundred pounds of rubber and eight hundred pounds of steel. The bearings were designed to reduce the base accelerations of the building by more than 50 percent.

Base Isolation

Another common form of retrofitting techniques for structures consists of seismic base isolation. The idea behind base isolation revolves around the possibility of removing the direct force of the earthquake on the actual structure by applying the bulk of it into the added base support.

According to Mosteghel (1993), three different methods of analysis exist for the effects of earthquakes on structures. The first method utilizes the release of seismic energy from the earthquake, the second method utilizes the distribution of the energy from the earthquake into the location of the structure, and the third method utilizes the distribution of the energy from the location into the actual structure. Of these steps, only the third provides the opportunity for control (Mosteghel, 1993). An example of this particular retrofit technique is the Resilient-Friction Base Isolator, also known as the R-FBI, which is composed of a set of rings that lie flat on top of each other. Teflon composes each ring, which contains a rubber core that helps protect the rings from wearing away. The added rubber helps absorb most of the seismic shock from the earthquake in order to lessen the force on the actual structure (Mosteghel, 1993). A diagram of the mechanics of a base isolation system can be seen in Figure 2.9.

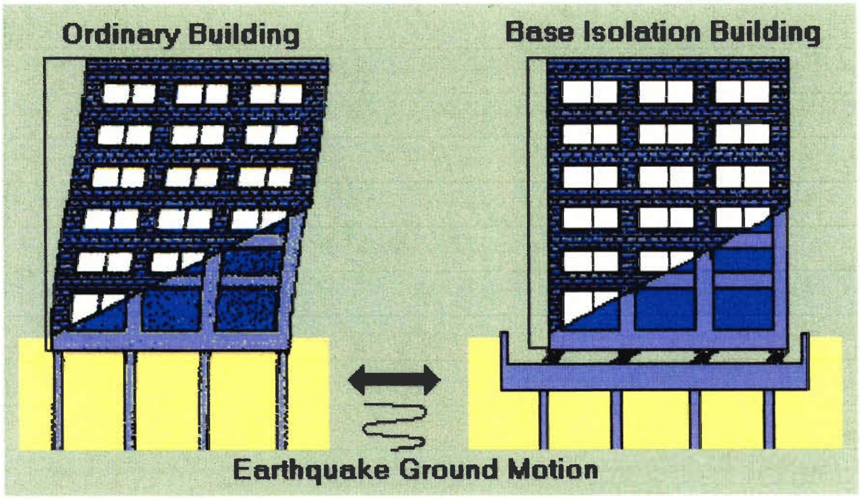


Figure 2.9: Diagram of Base Isolation System Mechanics

Composite Reinforcements

According to Emmons, Thomas, and Vaysburd (1998) and Seible and Karbhari (1996), fields involving aerospace and military defense readily utilized advanced composites. However, due to the cost of these materials, their use within the area of civil engineering developed slowly. Despite the advantages presented by these composites, such as high strength to weight ratios and stiffness to weight ratios, Seible and Karbhari further indicate that the costs of materials and manufacturing outweighed the possible benefits.

When discussing the causes of the more widespread use of advanced composites within the area of civil engineering in recent years, Seible and Karbhari (1996) identified several developments. First, advances in the manufacturing of the composites resulted in considerably reduced costs. Additionally, because of the reduced demand within the defense industry and an expanded market that includes the sporting goods industry, manufacturers continue to search for new outlets, encouraging lower costs. Furthermore, the use of these materials, in conjunction with traditional methods, allowed for efficient designs at competitive costs.

Hamilton and Dolan (2000) describe one of the advanced composites, fiber-reinforced polymers (FRPs) as a combination of a high strength fiber reinforcing material woven into a mesh and a polymer binder. The fibers support the majority of the structural load received by the composite while improving the stiffness of the mixture. The most commonly utilized fibers include glass, aramid, and carbon due to their high strength to weight ratio, a ratio comparable to that of steel at a fraction of the weight (Hamilton & Dolan, 2000).

According to Neale (2000), in recent years the number of civil engineering projects utilizing FRPs increased dramatically. Although more expensive than traditional materials, Neale asserts that, the savings in labor expenses may offset the cost of using of FRPs for retrofitting, resulting in FRPs becoming the material of choice for repair and strengthening in the future. Similarly, Emmons et al. (1998) indicate that the labor costs associated with FRPs range from 20 to 30 percent lower than those resulting from conventional retrofit techniques.

Using FRP jackets to retrofit reinforced concrete columns, says Neale (2000), continues to be a topic of interest among researchers. Although tests indicate that the ductility and strength of columns increase when wrapped in FRP, the author points out that these tests involved small-scale specimen and require more research for large-scale columns.

Research attempting to increase the flexural strength of beams and columns by using FRP laminates began over fifteen years ago (Neale, 2000). The studies indicated that the polymer bonding with steel plates successfully provided strength. Neale indicated the problems associated with the plates, which included the handling of these heavy objects and providing clean surface between the plates, prompted the investigation of the feasibility of utilizing lightweight carbon FRP laminates rather than steel plates. The research demonstrated that the use of FRP wraps resulted in increased strength accompanied by a loss of ductility (Neale, 2000). In order to provide the necessary flexural strength, laborers apply the composite with the filaments in the mixture placed in the direction of the tensile stresses within the member (Hamilton & Dolan, 2000). As well as increasing flexural strength, the application of FRPs substantially increased the shear capacity of the member. Furthermore, the studies developed an axial reinforcing method providing nearly a 40 percent increase in the wall-column strength (Neale, 2000).

Due to the success of FRPs in studies, Neale (2000) states that the implementation of this method of retrofitting increased at an accelerating rate. Meier in Neale (2000) affirms that since 1991, more than one thousand structures throughout the world utilized FRP laminates for strengthening. Hamilton and Dolan (2000) cite a strengthening project of a parking structure in Sherbrooke, Canada, in which engineers utilized various FRP composites. Bending strength increased of the building by 15 percent while the percent shear capacity increased by 20 percent (Hamilton & Dolan, 2000).

According to Emmons et al. (1998), Japan and Europe utilized carbon fiber-reinforced polymers (CFRPs) successfully within the past decade while use of the material in the United States is limited to research. A National Science Foundation study completed at University of California – San Diego established the effectiveness of carbon-fiber composite overlays used for the retrofit of masonry walls (Seible & Karbhari, 1996). The carbon fabric utilized by the study consisted of horizontal fibers that limited the shear deformation of the structure. The study concluded that the material provided an efficient method for repair.

For several reasons, Emmons et al. (1998) indicate that the widespread use of CFRPs face many obstacles. Before full-scale implementation occurs, standards, specifications, and detailing procedures that differ from current reinforced concrete design need to be developed.

2.5.4 Seismic Vulnerability Analysis

In order to determine whether a structure requires retrofitting, engineers employ various methods. They use the vulnerability index method, the qualitative estimate method, and the hybrid procedure method. The most common method used is the vulnerability index method.

Benedetti et. al. (1988) describes the vulnerability index as one method of determining the seismic vulnerability of a structure. The first step of this method is to list the significant structures in need of assessment. Then a field inspector examines each significant structure and associates it with a vulnerability parameter in the form of a numerical value, which determines the need for retrofit. The inspector must consider the characterization of ground motion, the characterization of the state of damage, and the definition and characterization the building's structural quality. The parameters usually range from a scale of one to ten, having the highest values refer to the most significant structures (Benedetti et al. 1988).

An example of retrofitting old, un-reinforced masonry occurred in Italy. According to Benedetti et al., (1988) the idea was to reduce the seismic risk of old, un-reinforced masonry buildings. Benedetti et al. (1988) analyzed old buildings having rigid floors, old buildings with flexible floors, new buildings with rigid floors, and new buildings with flexible floors using the vulnerability index method. The method of analysis consisted of a numerical evaluation of the existing buildings. Each value assigned to the existing structures was determined by the weight of the building, the materials used in construction, and soil conditions. Weighting the seismic quality of each building with a numerical value helped determine the necessity of retrofit. To be considered safe, each building would have to meet a certain value. After performing the vulnerability index method using numerical analysis, Benedetti et al. (1988) state that the next steps after the evaluation involve deriving strengthening techniques for the building. The main problem, however, for masonry structures is that they may be too costly in order to retrofit.

Similarly, Augusti and Ciampoli (2000) also discuss the approaches for evaluating the vulnerability of several buildings. Each building is divided into a typological class, which is determined by the characteristics of the building, materials of construction, technology used, structure type, and the age of construction. Each category is then classified along with a particular type of earthquake with a certain estimated intensity. This approach groups the buildings together according to similar vulnerabilities. Each typological case should be distinguished in every region. For example, like Italy, Puerto Rico may consist of mainly un-reinforced concrete structures, whereas the United States may consist of mostly reinforced steel and concrete structures. Therefore, the ideas for retrofit and reconstruction vary in every region.

Inspectors also utilize qualitative estimates to determine the vulnerability of a structure. Qualitative estimates evaluate the structural engineering aspects of the building in order to determine its vulnerability. However, according to Augusti and Ciampoli (2000), researchers often use inaccurate and incomplete information in the qualitative analysis of buildings. The age of certain structures may not allow a modern inspector to evaluate accurately the seismic performances of structures not designed to meet current seismic codes. Newer buildings would allow an inspector to update the structure in order to meet certain seismic criteria if he or she knew the original code standards used to design the structure (Augusti & Ciampoli, 2000).

Augusti and Ciampoli (2000) also discuss another method, which they feel is the most commonly used and the most useful technique for evaluating historical buildings, the hybrid procedure. It combines multiple techniques used to evaluate a certain structure, enabling an inspector to obtain the most possible amount of information needed to properly assess the vulnerability of a particular building. Even though many methods may be used to evaluate seismic response, it is very difficult to evaluate old buildings. Each building is unique in its own way, which leads to incorrect assumptions based on comparisons to other similar structures (Augusti and Ciampoli, 2000).

Deschapelles (2001) states that Puerto Rico is least vulnerable to seismic activity in its metropolitan areas because the building plans for a structure are required during construction, enabling the designer to meet the seismic requirements for a particular structure. Having the plans for a particular structure will also enable a designer to retrofit the structure in the future as the building becomes more vulnerable to seismic activity.

2.5.5 Cost of Retrofitting

According to Denning (1993), in addition to saving lives, retrofitting saves the owner money if the structure remains intact or is repairable following an earthquake. It may be easy to estimate the cost of a building, but it is not as easy to predict the cost of retrofit. The only way to make a prediction of the cost of retrofitting a structure is to look at any previous cases of retrofit. According to Shepard and Platt (1989), the larger the building, the less the unit cost of retrofit. Several factors require consideration when estimators attempt to determine the cost of retrofitting include the type of property, the purchase price, and the future structure value. In addition to these costs, the owner need consider the investment options for retrofit versus reconstruction as well as the cost of constructing a new building. Although a very long and complicated process for one to consider, Shepherd and Platt (1989) contend that it will ultimately lead to the most rational decision for the owner.

F. Nateghi-A (1995) also states that the cost to retrofit a project should remain below 25 percent of the cost for reconstruction and replacement. In the case of these buildings, the cost of repair was much greater than the total demolishing costs for the walls, where 240 different five-story buildings were retrofitted in order to meet certain standards and codes, and the cost was only 8 percent of the total project. However, according to Benedetti et al. (1988), retrofitting of un-reinforced masonry may cost up to 60 percent of the total cost of reconstruction, making it difficult to decide whether or not retrofitting would be the ideal process.

Chapter 3: Methodology

The objective of our project was to study the seismic vulnerability of various structures throughout Puerto Rico and to identify possible retrofitting techniques. Furthermore, our aim was to evaluate the impact of an earthquake on the amount of deaths, injuries, and costs associated with it. In this chapter, we present our methodology for carrying out the project.

3.1 Interviews

In preparation for this project, we conducted interviews with three seismic and structural professionals at WPI. These interviews enabled us to determine our plans for research. We determined whom to interview based on their knowledge of seismic vulnerability. Our objective for these interviews was to gain basic knowledge of general earthquake design procedures and to obtain the names of other seismic experts. We intended to learn who decides whether a structure is deemed seismically vulnerable and how complicated this process is.

We first interviewed Professor Leonard Albano because of his experience in structural engineering and design loading. We were mainly concerned in obtaining information on what factors affect seismic vulnerability. He indicated that, in order to determine the seismic vulnerability of a given structure, many aspects related to the structure, such as the shape, size, location, age, and the type of materials for construction, require consideration.

Next, we met with Professor Robert Fitzgerald, who is experienced in the structural and fire protection engineering fields. Professor Fitzgerald is knowledgeable in the area of code design and we intended to gain information on seismic requirements for building design. Professor Fitzgerald also provided us with numerous contacts that would be useful, both in the United States and in Puerto Rico.

Finally, we interviewed Professor Jayachandran, who has participated in various courses offered by the Federal Emergency Management Agency (FEMA) regarding the determination of seismic vulnerability of structures and methods of retrofit. Professor Jayachandran is an expert in concrete design and we wanted to determine the seismic vulnerability of concrete as opposed to steel, wood, or masonry since Puerto Rico mainly consists of reinforced concrete structures. In addition, since Professor Jayachandran participated in the various seismic courses offered by the FEMA, we felt that he would be able to provide us with any other important seismic information that he received from FEMA that we might have not yet researched.

3.2 Information Sessions

During our first few weeks in Puerto Rico, we attended five information sessions arranged by CSA Group in order to increase our seismic knowledge. These sessions provided information regarding structural systems and code regulations, general aspects about seismic analysis and design of buildings, as well as discussed post earthquake procedures and the minimization of social impacts of earthquakes.

Dr. Luis Daza, the Structural Engineering Department Manager of CSA Group, also a professor at the University of Puerto Rico in San Juan, conducted our first information session. The aim of the session was to provide information about the nature of earthquakes and the response of a building to earthquake loads. We analyzed various seismic code requirements necessary for building design, common causes of structural failure, and frequently used retrofit techniques.

During our first week in Puerto Rico, we traveled to the University of Puerto Rico – Mayagüez to meet with three professors in the civil engineering department who are experts in seismic engineering. Dr. Jose Martinez Cruzado conducted the first of the three information sessions that we attended. His session provided seismic information specific to Puerto Rico. The goal of the session was for us to learn about the history of earthquakes and the common modes of failure within structures on the Island.

Dr. Ali Saffar, a civil engineering professor at UPR-Mayagüez, conducted the second information session. His presentation focused on the history of seismic codes in Puerto Rico and the social impacts related to earthquakes. We wanted to obtain information from this session that would allow us to compare the seismic restrictions of Puerto Rico to that of an area with strict code requirements, such as California. Dr. Saffar also discussed a study that he conducted at UPR – Mayagüez that determined the seismic vulnerability of certain representative structures on campus.

Dr. Ricardo Lopez, a civil engineering professor at UPR – Mayagüez, conducted our final information session at the university. The purpose of this session was for us to obtain the representative structure that was necessary for our seismic analysis using the computer software package, Visual Analysis. He informed us that Puerto Rico lacks a design earthquake necessary to assist seismic experts in determining the vulnerability of its structures. Design earthquakes are past earthquakes that are frequently used to enable seismic experts to make recommendations and assumptions for ways to retrofit and design. Therefore, it is necessary to use the computer software, which allows you to analyze a particular structure using various earthquake loads that occurred in other countries. At the conclusion of the session, Dr. Lopez provided us with the set of building plans that we subsequently used in developing a model for analyzing seismic vulnerability.

Dr. Bernardo Deschapelles, of Molina, Garcia, and Associates, and the president of the Seismic Commission in Puerto Rico, provided the fifth information session that we attended. This session was necessary for us because we wanted to learn whether seismic retrofit was common in Puerto Rico. The information that he provided included a history of the current seismic building code, an explanation of the different seismic hazard zones, common methods of retrofit for concrete structures, and the areas of Puerto Rico that may be susceptible to earthquake damage. This information allowed us to concentrate on specific areas of Puerto Rico, based on population density, soil conditions, and the topography of the land.

In order for us to study the social implications of our project, it was necessary for us to determine the number of seismically vulnerable structures located in Puerto Rico's rural and metropolitan areas. This was achieved by using a model study developed by Dr. Luis Daza in his doctoral dissertation (1996), which focused on the seismic vulnerability in Puerto Rico. We used data from Dr. Daza's study, such as the number of housing units and condominiums located in the rural and urban zones of Puerto Rico and their respective ages in order to determine the percentage and of various structures that were considered unsafe. This information allowed us to evaluate the social implications of improving those structures. These numbers enabled us to create a model, which compared the cost of human capital associated with a structure versus the cost of retrofitting the structure.

We also obtained a seismic vulnerability dissertation written by Dr. Alberto Guzman (1998), a civil engineer for the architectural and engineering firm, Unipro. His doctoral dissertation consisted of the social implications associated with earthquakes in Puerto Rico. The study provided a second model that we used in order for us to recommend whether or not a building should be retrofitted. This dissertation assumed that an earthquake occurs causing damage to buildings. In order to make a decision on retrofit, this study used two sets of equations, one for an un-retrofitted structure, and one for a retrofitted structure. After comparing the values calculated by each equation, a decision can be made as to the needs of retrofit for the building. These equations were very comprehensive in that they took into account many factors including the cost of a human life, the cost of retrofitting, the cost of repairing the building, and even the cost of clean up for a demolished structure. We used these particular equations and applied them to residential buildings and schools based on the data that we received from Dr. Luis Daza's dissertation.

We also obtained a seismic vulnerability study from Dr. Alfonzo O'Neil of the Army Corps of Engineers, which discussed vulnerable areas such as bridge locations, dam locations, utility damage, and hazardous waste areas. This study was used in order to determine the seismically vulnerable areas located in the San Juan metropolitan area.

3.3 Software

In order to analyze the seismic vulnerability and to recommend possible retrofit techniques for certain structures, we used the software package, Visual Analysis, produced by Integrated Engineering Software Inc. This program allowed us to determine the ways a building will deflect under certain applied loads, such as wind or earthquake loads. The program allowed us to reconstruct the frame of a particular structure based on its dimensions and materials.

In our model, we reconstructed the frame of a single story school building from the building plans that we received from UPR-Mayagüez. The building plans allowed us to determine the exact sizes and material used in the construction of the school. We then entered the building frame into the Visual Analysis program. Once the frame of the school was modeled three-dimensionally, the program allowed us to apply the same loadings that occurred from previous earthquakes in order to determine how our particular structure would have reacted to the given earthquake load. Once we determined where the failure points existed in the structures, we strengthened the necessary areas by using common methods of retrofit, such as steel bracing, strengthening of columns, and the addition of concrete shear walls. We then applied these retrofit techniques to the structure modeled in Visual Analysis. Once retrofitted, the earthquake loadings were reapplied to the improved structure in order to establish whether the changes in deflection were significant. If these deflections were significantly minimized, we provided a cost analysis to calculate whether the retrofit technique was feasible, using our results to formulate our recommendations to retrofit.

We also used a Geographic Information Systems (GIS) software package known as ArcExplorer2 in order to generate a map of the areas that need the most attention before the occurrence of a potentially disastrous earthquake. ArcExplorer2 allowed us to create different layers of maps and superimpose them onto one other in order to portray common areas associated with the various map layers. In our study, we obtained map layers from the GIS Department of CSA Group representing the population density, soils, and landslide hazards of the entire Island.

Our objective was to layer a map with the soils in order to determine what areas in Puerto Rico were most susceptible to liquefaction during an earthquake. Areas with sandy regions were considered more vulnerable than those areas containing clay soils. We also added the layer of landslide hazard order to determine the areas that were vulnerable to landslides during an earthquake. The population density layer was added so that we could pinpoint any problem areas containing many people. If we noticed an area that was vulnerable to liquefaction or landslides that also contain numerous amounts of people, we determined that this is the area of most concern and would require a more comprehensive study in the future. Figure 3.1 represents our methodological flow chart.

CSA Group Methodology Flowchart

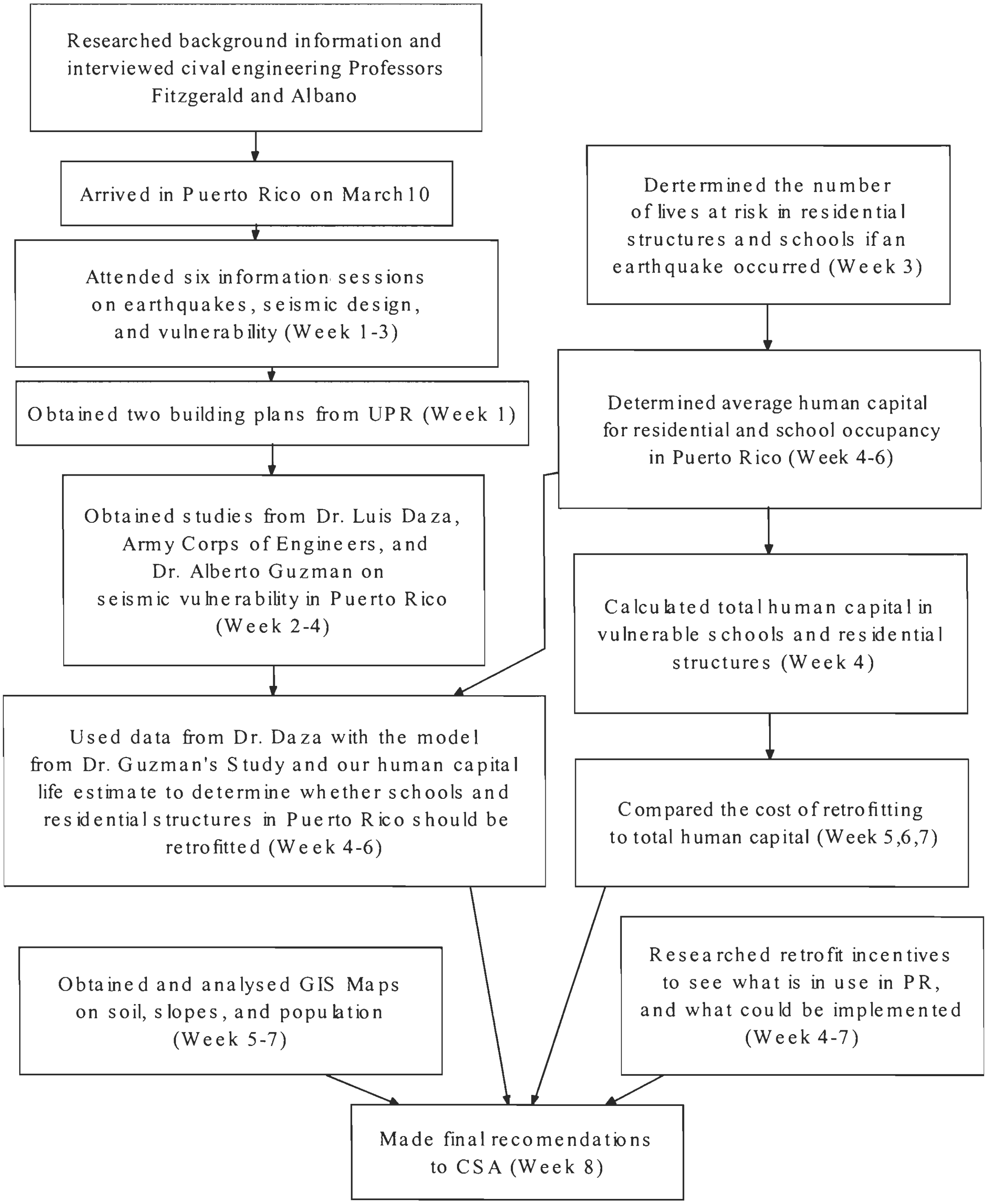


Figure 3.1: Methodology Flowchart

Chapter 4: Data Presentation and Analysis

In this section, we present data we collected regarding the seismic vulnerability of structures in Puerto Rico, as well as some of the social implications resulting from a potentially dangerous seismic event. This chapter also includes our analysis of the collected data.

4.1 Earthquake and Retrofit Information

The information presented in this section resulted from an information session with Dr. Luis Daza, the CSA Group Structural Engineering Department General Manager. Dr. Daza provided us with numerous amounts of general information about earthquakes, along with specific information about earthquakes that only pertained to Puerto Rico.

Of all the retrofitting techniques discussed in section 2.5.3, only concrete shear walls and steel bracing are implemented here in Puerto Rico due to their relatively inexpensive costs. There are major code requirements needed for seismic design, but many owners cannot afford to retrofit their structures. *UBC* regulations imply that a building should be able to resist minor earthquakes without damage, resist moderate earthquakes without structural damage but some nonstructural damage, and resist major earthquakes without collapse but some structural and nonstructural damage. According to Dr. Daza, the main objective of the code is not to protect the structure, but rather it is to avoid loss of life.

One common cause of failure within a building is torsion. Torsion is the tendency of any floor or roof system to rotate, and occurs when the center of mass of the building does not coincide with its center of stiffness. The distance between the center of mass and the center of stiffness in a building is known as the eccentricity of the building. A low eccentricity in a building is good for resisting torsion due to seismic loads. A high eccentricity in a building means that the center of stiffness is much further from the center of mass, causing the building to twist and rotate and may lead to failure of the structure.

4.2 Areas of Susceptibility in Puerto Rico

The vibrations due to earthquakes may result in other natural hazards that can often cause as much damage as the earthquake itself. Landslides, tsunamis, and liquefaction are just a few of these other hazards. After researching these hazards, we used GIS maps to pinpoint the areas of concern in Puerto Rico where multiple vulnerabilities may exist. Based on our results, recommendations are made in Chapter 5 as to which areas need further examination. By using a study by the Army Corps of Engineers, we decided on areas that were vulnerable.

4.2.1 Analysis of Puerto Rico's Infrastructure

The information presented in this section resulted from a study conducted by the U.S. Army Corps of Engineers in 1996 that performed an analysis of how an earthquake would affect Puerto Rico. The study examined how many key structures would stand up to seismic forces resulting from an earthquake with the magnitude of 8.0. They looked at representative structures in general, as opposed to specific structures so that they could draw conclusions as to seismically vulnerable structures. From their study, we are able to point out areas of Puerto Rico that may deserve closer attention. We focused our study on the San Juan metropolitan area because of time constraints on our project. It is not possible to perform a complete analysis of the Island, so we adopted many of the findings of the Army Corps related to the San Juan metropolitan area.

Based on the information that we obtained from the U.S. Army Corps of Engineers (1996), Puerto Rico is considered to be seismically vulnerable in the areas containing bridges. Many of the bridges on the Island are made of reinforced concrete, which is the most seismically vulnerable type of bridge due its low capability to deform or bend without collapsing. Bridges are an important aspect in seismic vulnerability here in Puerto Rico because their failure during an earthquake could lead to the loss of necessary emergency relief routes, and the loss of lives.

Another major seismically vulnerable area in Puerto Rico is along the rivers containing major dams. There are major dams located on four different rivers in the San Juan metropolitan area. They are the Comerio and La Plata dams on the Río de la Plata, the Cidra and San Juan dams on the Río de Bayamón, the Carraízo dam on the Río Grande de Loíza, and the Las Curias dam on the Río Piedras. These dams are areas of concern because if they experience any damage during an earthquake they may cause large amounts of flooding which could result in significant amounts property damage and loss of lives.

According the U.S. Army Corps of Engineers, the failure of the Cidra and San Juan dams would lead to flooding all the way down to the Bayamón area in San Juan. The Corps also feels that the failure of the Comerio and La Plata dams would result in the flooding of Dorado, and the failure of Carraízo dam would result in the flooding of the Carolina area. The failure points in these dams would most likely occur from landslides causing the dams to collapse, and from foundation liquefaction.

The Comerio dam is a major power generator and its failure would cause substantial loss of power in the San Juan metropolitan area. The failure of the domestic water supply dams, mainly the La Plata and Carraízo dams, would cause great difficulty because they would add tax increases to the water supply system of San Juan due to lack of the water supply.

Puerto Rico also leads all other islands in the Caribbean in external trade by a substantial amount, and a resulting flood from an earthquake may wipe out a large industry in the San Juan harbor. This would provide a major financial downfall on the international side of external trade.

Utility damage is also another major seismic concern in Puerto Rico. Underground utility lines are susceptible to damage during earthquake due to the ground vibrations underneath the surface. The vibrations may cause the lines to crack or even break during an earthquake. Underground utilities are areas of concern because they provide the area with water, gas, fuel, and power. Without access to these particular sources, many harmful effects can occur, such as a lack of water.

Water is necessary for drinking or fire fighting during the aftermath of an earthquake. The Corps suggested that automatic shutoff valves for the water supply reservoirs would help preserve most of the water that may be lost during an earthquake. San Juan is compared to Kobe, Japan because of its similar location to the water, along with very similar soil types, and even similar structures. The U.S. Army Corps of Engineers used the results of the Kobe earthquake of 1995 in Japan in order to portray the possible effects of waterline damages. Kobe had 2,000 waterlines break during the earthquake and since there were no shutoff valves on some of the water tanks, the water drained within eight hours after the earthquake. As a result, Kobe went nine days without access to water. It is possible that a similar situation could occur in San Juan.

Gas lines in Puerto Rico may also be subject to damage. Most of the power supply provided in Puerto Rico is electric, but the natural gas plant located near the Kennedy Avenue Bridge in the San Juan area is cause for concern because it could explode during an earthquake. Another anticipated problem in Puerto Rico is the main electric power plant for San Juan located in Palo Seco. This area is highly susceptible to tsunamis and liquefaction and a major power outage in San Juan for a few days would cause many problems among businesses and residential facilities. Puerto Rico also has an oil refinery located near Ft. Buchanan in the San Juan area and two petroleum tanks located in the Port of San Juan and at the Palo Seca Power plant. The location of these structures is in a vulnerable area, in that they are located above soil that is susceptible to liquefaction, and are located near a fault line. This could lead to a hazardous material spill if an earthquake were to hit.

4.2.2 Earthquake Recovery Response Plan

A major goal for the U.S. Army Corps of Engineers was to implement recovery operation programs in Puerto Rico that would help during the aftermath of a disastrous earthquake. The Corps is very concerned with the Island's relief efforts and earthquake knowledge. They feel that they are going to be one of the first agencies to assist in the recovery efforts on the Island. Some potential programs that may be implemented by the Corps consist of:

- Establishing an emergency operations center away from areas subjected to liquefaction, flooding, or structural collapse.
- Obtaining contracts for debris removal, heavy equipment, fuel supply, water supply, and repairs.
- Constructing temporary housing facilities.
- Acquiring boat and helicopter services.
- Obtaining legal services and cost estimating support.
- Establishing engineer design services and geo-technical inspection teams.

4.2.3 GIS Software Analysis

In order to determine the seismically susceptible areas of Puerto Rico, we used the GIS software package known as ArcExplorer2. We combined the information obtained from this mapping system with the information that we obtained from the U.S. Army Corps of Engineers' study. We layered maps that allowed us to determine what types of soils are found on the Island in order to determine liquefaction hazards, and what areas are susceptible to landslides. The map shown in Figure 4.1 shows the soils on the Island that may be vulnerable to liquefaction. These areas would need further study to check on their vulnerability. These vulnerable soils, which are comprised of sand and silts, are shown in dark green.

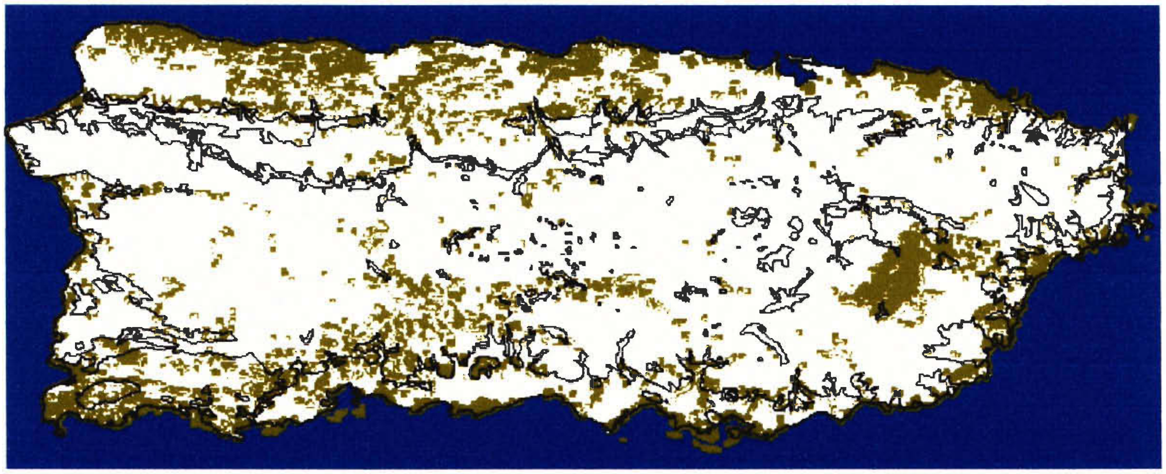


Figure 4.1: Map of Soils Most Vulnerable to Liquefaction in Puerto Rico

The majority of the areas with vulnerable soils lie on the coasts, however, there are also some areas of concern inland. The map of the landslide hazards was portrayed in a similar manner, and is shown in Figure 4.2. On this map, the landslide hazards are represented by hash marks. The red areas are high landslide risk while the green areas are moderate landslide risk.

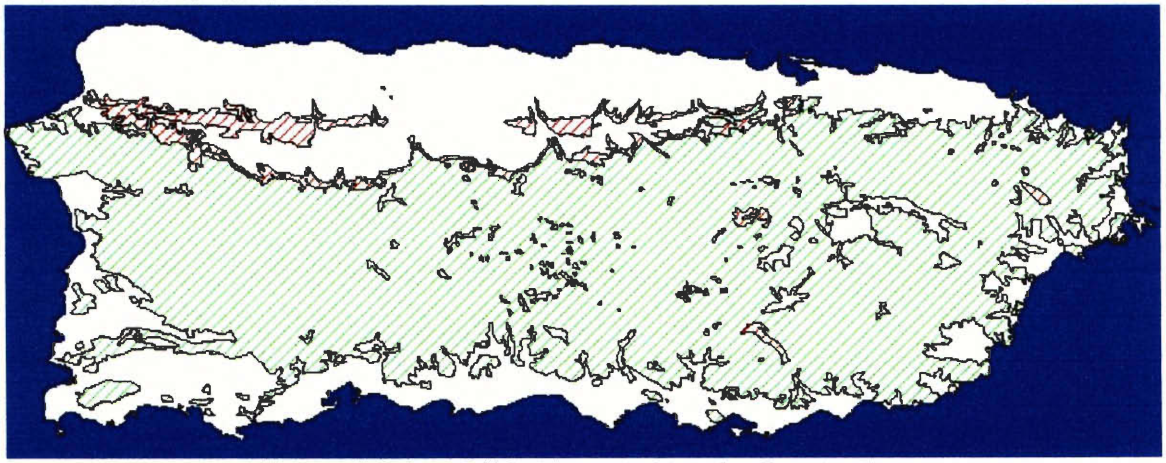


Figure 4.2: Landslide Hazards Map for Puerto Rico

We also layered a map of the population density, shown in Figure 4.3, of Puerto Rico in order to determine whether many people were located in these susceptible areas. The highest densities are shown in dark red, while the lowest densities are shown in yellow.

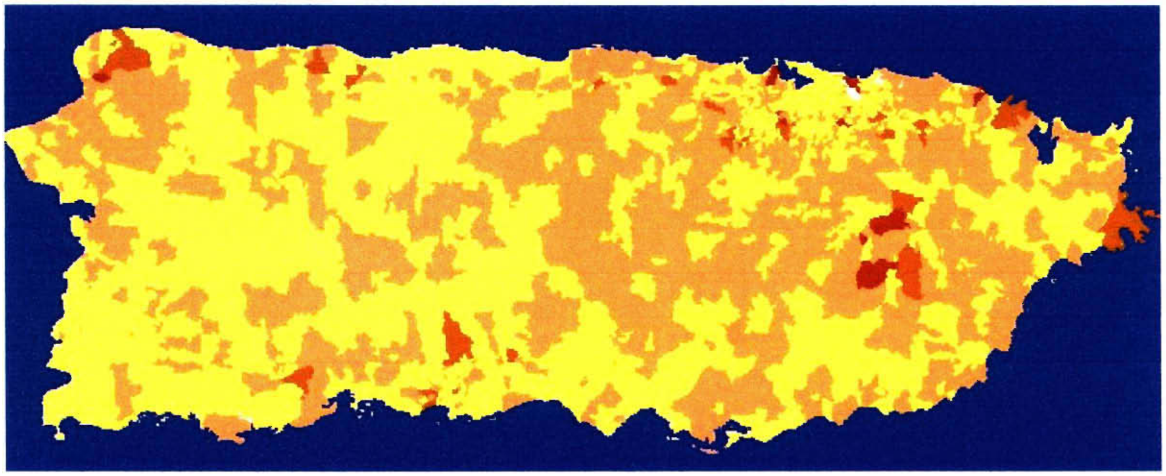


Figure 4.3: Population Density Map for Puerto Rico

Once we overlaid these three maps onto each other, we were able to make conclusions or recommendations based on the seismic vulnerability of a particular area. The map of the three layers is shown in Figure 4.4. For this final layering of the maps, the only visible population areas are those that have sandy soils. On top of this is the landslide hazard map with the high-risk areas in red dashes and the moderate risk areas in dark blue dashes.

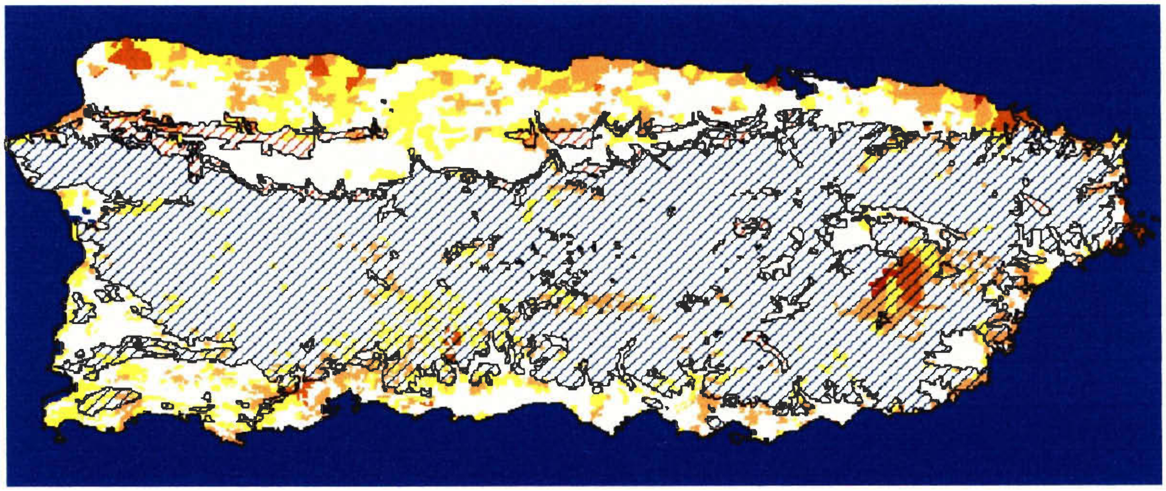


Figure 4.4: Overall Seismic Hazard Map for Puerto Rico

Areas that may be more vulnerable during an earthquake can now be seen on this layered map. From these maps, we saw that many of the areas that have vulnerable soils lie along the coast. Additionally, these areas are vulnerable to tsunamis, making most of the coast of Puerto Rico a very hazardous area. The west coast may be especially vulnerable because a large part of it also has a moderate landslide risk. Ceiba is one of these areas on the west coast, which also has a high population density. The area on the map that encompasses Juncos, Caguaus, Gurabo, and San Lorenzo have dense population, a moderate landslide risk, and vulnerable soils. This creates the possibility of this area being a very hazardous area. Because this area is inland, we do not know if there is water within thirty feet of the surface. Therefore, this area needs further study for liquefaction. Some areas on the northwest to central part of the Island have both vulnerable soils and high landslide risk. These include northern Moca, southern Isabel, southern Quebradillas, southern Camuy, southern Hatillo, southern Arecibo, southern Manatí, southern Vega Alta, and northern Corozal. This area does not have a high population density, but the people that are there are at extreme risk because of the other two hazards. All of these areas are ones that should be looked at when determining which parts of the Island are most vulnerable during an earthquake.

4.3 Cost Analysis of Seismic Retrofitting

There are several methods of evaluating the costs associated with an earthquake. We chose two different mathematical models to demonstrate how a decision regarding the retrofit of a building can be made. Both of these models require a calculation of the cost of a human life in Puerto Rico. Depending on the types of buildings that are analyzed, this value may be different.

Model #1 is a straightforward comparison of the total cost of human lives in vulnerable buildings to the cost of retrofitting those buildings. This model will consider the worst-case scenario that the expected building populations are present and will die when the building collapses. This model will be applied to all of the vulnerable residential structures in Puerto Rico as well as the vulnerable schools in Puerto Rico. From this model, it will be shown that the cost of the human lives at risk is much larger than the cost of retrofitting the structures. The reason for choosing this model was that it represents the worst-case scenario for the Island, and is very illustrative in showing the overwhelming need for retrofit in Puerto Rico.

Model #2 (Guzman, 1998) is a very in-depth model that involves many different factors leading to a conclusion on whether or not it is beneficial to retrofit a building. This model uses the probabilities and expected damage costs associated with different size earthquakes. The costs associated with the unretrofitted structure are then compared to costs for the structure if it were to be retrofitted. This particular model is generally used by an owner of a building to determine if it is economically feasible for him to retrofit his building. This model was chosen because of all of the factors that are included. It is a business-oriented model that allows us to make a more realistic recommendation as to whether or not a building needs retrofitted.

4.3.1 Model #1 – Human Capital vs. Cost of Retrofit

Model #1 is a straightforward model that consists of comparing the human capital within all the respective occupancy type buildings, to the cost of retrofit for those particular buildings. Calculations based on this model amounts to validating the following inequality:

$$\text{Net HC} > \text{RC}. \tag{4.1}$$

For this inequality, if the calculated total human capital, Net HC, is greater than the retrofit cost, RC, then it is economically advantageous to retrofit. RC is calculated by multiplying the area of a structure by the current cost of retrofit per square foot, C_U. This value of C_U is calculated using an equation provided in Dr. Alberto Guzman's 1998 Ph.D. dissertation. An explanation of this equation can be found in section 4.3.2, Equation (4.5). Using Equation (4.5), the calculated current retrofit cost is \$17.67 per square foot.

Model #1 was applied to two different occupancy types, one was a residential type occupancy, while the other was a school occupancy. The reason for concentrating on these two types of occupancies was due to the fact that we were provided with a study done by Dr. Luis Daza which gave the numbers of schools and residential buildings in Puerto Rico that were considered unsafe. The analysis that we preformed using his numbers was done in order to show the need for retrofit in Puerto Rico. We assumed that all buildings would have all of their respective occupants in the building at the time of the earthquake, and that everyone in the building would be killed. The calculation for each occupancy type was done for all of the structures on the Island in order to show the existing need for retrofit. The values that are given in the end of this analysis are a total for all of the at-risk structures of that occupancy type, which is why they may seem large. The first structures that we looked at were the at-risk residential structures on the Island. We then analyzed the at-risk schools on the Island.

In order to begin to satisfy Equation (4.1), we first calculated the left side of the equation, Net HC. Because we are dealing with placing a monetary value on a group of people, and we are working with a structural engineering firm, we need to use the human capital method of evaluating the cost of a human life in Puerto Rico, for reasons stated in section 2.2.1.1 of our literature review. This method is based on the average income of the people most likely to populate the building at the time of an earthquake, and their average age. The human capital method in equation form is:

$$\text{HC} = \textit{(Average income of population)} \times \textit{(Number of work years left)}, \tag{4.2}$$

where HC represents the calculated value for the human capital. We would like to point out that the value obtained from Equation (4.2) is a purely economic value.

4.3.1.1 Residential Occupancy Analysis

This section outlines our analysis for the at risk residential occupancy structures for the Island. We first present the value that we obtained for HC, and then we demonstrate how the RC value was calculated. At the end of this section, we put both the Net HC value and the RC value into Equation (4.1) so that we can show the need for retrofit.

Average Human Capital for Puerto Rico

The average human capital was first calculated for the population of the entire Island. The average per-capita income in Puerto Rico is $9800 as obtained from the Central Intelligence Agency (2000). The average age of the entire population is 33 years old, as obtained from the projected 2000 census data provided by the Census Bureau (United States Department of Commerce, 1990). The recognized retirement age in Puerto Rico is 65 years old, obtained from the Social Security Administration (SSA, 2001). Using these values, and Equation (4.2), the average value of a human life in Puerto Rico was found to be $313,600:

$$HC = \$9{,}800 \times (65\text{-}33) = \$313{,}600.$$

Total HC Value for Residential Occupancy

From Dr. Daza's dissertation (1996), it is known that 75% of the total population lives in reinforced concrete structures. Furthermore, his study indicates that 10% of the reinforced concrete structures on the Island are at risk. Based on the projected 2001 population of 3,967,527 provided by the census bureau, that means there are 297,565 people who reside in at risk residential structures. For the purpose of the residential type occupancy calculation, we used the average human capital value of the entire population, $313,600, as calculated above. Multiplying this HC by the number of people that are living in inadequate housing units, a total value of the lives at risk, Net HC, was calculated to be $93.32 billion for all of the affected occupants of residential housing:

$$\text{Net HC} = \$313{,}600 \text{ per person} \times 297{,}565 \text{ persons} = \$93.32 \text{ billion.}$$

Retrofit Cost Value (RC) for Residential Occupancy

We next examined the cost that would be required to retrofit these inadequate structures up to the current seismic codes. According to Dr. Daza (1996), the average size of a residential structure is 1200 sq. ft. Furthermore, he states that the total number of inadequate housing units was calculated to be 89,174. The structures that Dr. Daza investigated were built before 1990. For our study, we assumed that the number of inadequate housing units has remained constant, because anything built after 1987 should be up to the 1987 Puerto Rico building code, which was the first to incorporate provisions for seismic forces. If we use the retrofit cost per square foot of $17.67 as calculated in Equation (4.5), the total number of housing units, and the average size of each structure, we get the total amount required to retrofit all of the at risk residential structures in Puerto Rico, RC, to be $1.89 billion. The results of this analysis can be seen in Table 4.1.

Table 4.1 – Residential Occupancy Analysis Results

Cost of Life Data	
Number of affected people	297,565
Average value of a human life	$313,600
Total cost of lives at risk (Net HC)	**$93,316,384,000**
Retrofit Cost Data	
Average building size (sq. ft.)	1,200
Reinforced Concrete retrofit cost per sq. ft.	$17.67
Inadequate housing units	89,174
Total retrofit cost (RC)	**$1,890,845,496**

As can be seen by the above table, Equation (4.1) holds true. Since Net HC > RC, it is economically beneficial to retrofit the structures. The RC value is about 1/50 of the Net HC value. This calculation shows that the cost of retrofit is a very small price to pay as opposed to the amount it would save due to the loss of life. One thing to remember, is that the values in the table are for all of the at risk residential structures on the Island. This analysis was done to show that with a comparatively high cost of the loss of human capital, the retrofit cost is relatively low. In reality, not all of this damage will occur, and not all of these lives will be lost, but in order to show an overall need for retrofit in Puerto Rico, the data was presented in this fashion.

4.3.1.2 School Occupancy Analysis

This section outlines our analysis for the at risk school buildings on the Island. We first describe how we calculated the Net HC factor for the schools. There were different values for this depending on whether the person was a teacher or a student. Then we show the RC value required to retrofit the schools to the acceptable current seismic standard. From this, we put both the Net HC value, and RC value into Equation (4.1) to make a conclusion on whether retrofit is economically beneficial.

Human Capital Analysis for Schools in Puerto Rico

It is possible for certain buildings to have a higher human capital value than others. Because Equation (4.2) is dependent upon age and average income, the HC values for a particular structure can vary. Schools typically have a larger human capital value than the overall population because the students have more years left to work than the average aged person does. Since our study involves analyzing a school building, it is necessary for us to refigure the human capital value for the schools in Puerto Rico. To do this, we calculated two different values. One value is for the students while the other is for the teachers. This was done in order to get a more accurate representation of the human capital value within a school. Since the students have a larger human capital value, they were considered separate from the teachers.

Human Capital Value for Students

For this study, we assumed that the average age the students entered the work force was at age 20. We also assumed that once the students joined the work force, they would make the current per-capita income of $9,800, as well as retire at the current retirement age of 65. By using these values and assumptions, the average value of the life of a student in Puerto Rico is calculated by substituting these values into Equation (4.2), resulting in a value of $441,000:

$$HC = \$9,800 \times (65-20) = \$441,000.$$

Human Capital Value for Teachers

We then calculated the value of life for a teacher. For this we needed to calculate the average age of a teacher. We took the current Census Bureau demographic data broken up into age categories. We dropped out anyone over the retirement age of 65, and anyone younger than the age of 22. This left the age group representative of the working class. We assumed that this group was representative of the teachers on the Island. From here, we found the average age of a teacher in Puerto Rico is 40 years old. Using this age, along with the average per-capita income of $13,500 for teachers, obtained from the Puerto Rico Department of Education, the value of a teacher in Puerto Rico is calculated to be $337,500:

$$HC = \$13,500 \times (65-40) = \$337,500.$$

Total HC Value for School Occupancy

According to Daza (1996), in 1990, there were 110,860 students at risk in vulnerable structures. With the assumed average class size of 20 pupils per class, that means there are 5,543 teachers at risk in 1990 as well. We assumed that the number of teachers has remained constant over the past years, but applied the population growth in Puerto Rico, of 11.79% since 1990 (United States Department of Commerce, 2001) to the number of affected students. This means that there are currently 123,930 students, and 5,543 teachers located in at risk school buildings. We now apply the same analysis to this situation as was done to the residential occupancy type. With 123,930 students being affected with an approximate value of $441,000 each, and 5,543 teachers being affected with an approximate value of $337,500, there would be a total loss of $56.5 billion in human capital if the buildings were to collapse with everyone in them.

Retrofit Cost Value (RC) for School Occupancy

The study done by Dr. Daza gives the amount of money it would cost to retrofit all of the at risk schools in Puerto Rico. The values he gives are in 1996 dollars, so we needed to apply an inflation calculation. An inflation rate of 5.2% was used because it is currently Puerto Rico's inflation rate (CIA, 2001). After applying a yearly 5.2% inflation calculation to Dr. Daza's study (1996), the amount of money required to retrofit the at risk schools in Puerto Rico, RC, in 2001 dollars is about $155 million. The results of this analysis are seen in Table 4.2.

Table 4.2 – School Occupancy Analysis Results

Cost of Life Data	
Number of Students	123,930
Average value of a student	$441,000
Number of Teachers	5,543
Average value of a teacher	$337,500
Total value of occupants (Net HC)	**$56,524,066,254**
Retrofit Cost data	
Total retrofit cost (RC)	**$155,022,757**

Similar to the analysis of the residential type occupancy, Equation (4.1) holds true for this case as well. The RC value is less than the Net HC value, as seen in Table 4.2. The RC value is only around 1/360 of the Net HC value. This ratio shows that there is a huge gain in spending the money for retrofit, versus the human capital that would be lost if the building collapsed, killing all of its occupants. Once again, for this analysis, we assumed a worst-case scenario that all of the people accounted for are in the building at the time of a total collapse in order to show the maximum losses possible.

Both, the analysis of the residential structures, and school buildings, show that there is a need of retrofit here in Puerto Rico. In each case, there was a large discrepancy between the retrofit costs (RC), and the net human capital (Net HC) values, seen in Figure 4.5.

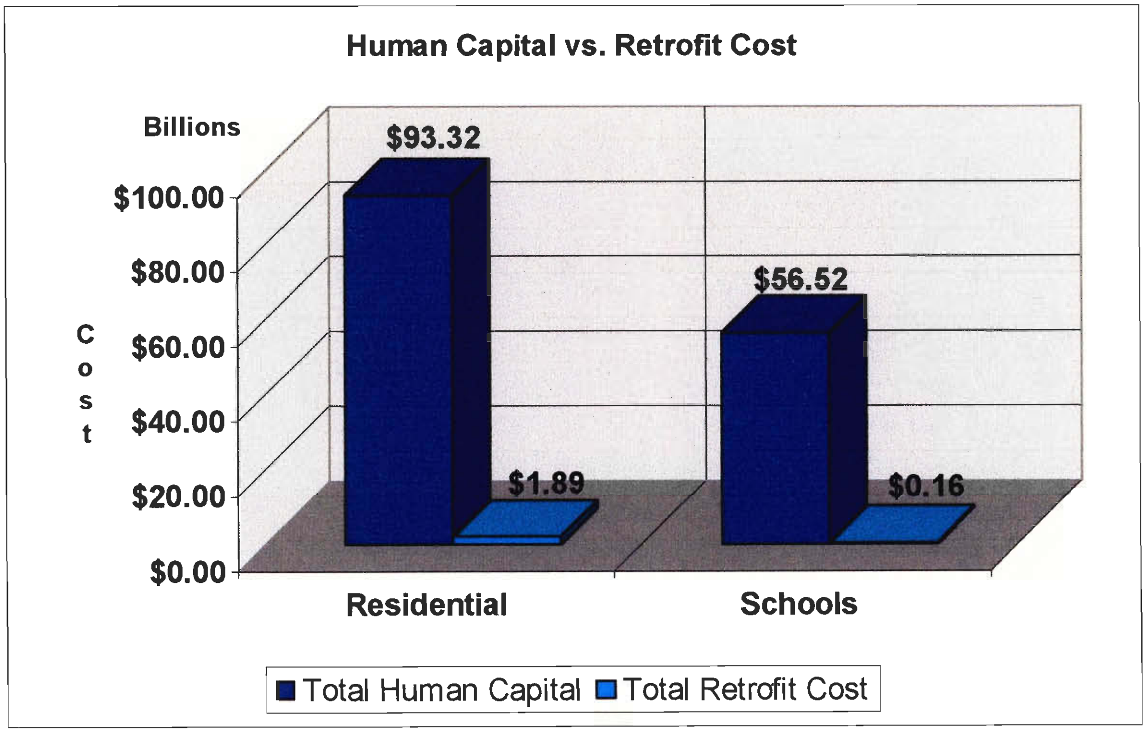


Figure 4.5: Human Capital vs. Retrofit Cost for Puerto Rico Structures

This discrepancy in the values is important in order to bring attention to the fact that retrofit needs to be done. Currently there are very few people concerned about the retrofitting of structures, but the fact is, something needs to be done before a major catastrophe that could have been avoided has a chance to occur.

Looking closely at the residential occupancy type analysis, it was found that the number of people whose human capital value was equal to the cost of retrofit was 4,172 people, or about 1.4% of the at risk residential population. This indicates that if more than 4,172 people died, retrofitting the structures would be beneficial. Since earthquakes have been known to kill thousands of people at a time, it is very important for these structures to be retrofitted in order to save lives.

Studying the school occupancy analysis in order to find the same break-even value as in the residential occupancy analysis, we find that 246 people have the same human capital value as the total cost of retrofit. This number represents only 0.19% of the students and teachers that are in the schools. Given the concerns expressed by various structural engineers regarding the safety of the schools in Puerto Rico, it would be very easy for 246 people to die in the collapse of even one school building. This percentage demonstrates how important it is to retrofit the schools on the Island.

This analysis was completed in order to demonstrate the need for retrofit on the Island, and to better emphasize the discrepancies in the cost of human capital that could potentially be lost and the retrofit cost. In each case, only a relatively small number of people would have to die before the retrofitting costs would be beneficial. By making the initial investment of retrofitting the at risk structures, not only can money be saved, but also the lives of many of the buildings occupants.

4.3.2 Model #2 – Cost-Benefit Analysis of Retrofitting

Model #2 came from a Ph.D. dissertation completed by Dr. Alberto Guzman (1998) of Unipro, a civil engineering firm in San Juan. In this study, he discussed a cost-benefit model that allows a person to make a decision on whether or not to retrofit a building. This model conducted a cost-benefit analysis that detailed many of the economic factors associated with an earthquake, such as the cost of a human life and retrofit cost. Unlike Model #1, this model took into account expected damage to buildings, construction costs, building repair costs, cost of injuries, economic loss, and earthquake probabilities. Since this study was conducted in 1998, an inflation calculation was used to update cost values to 2001 dollars. An inflation rate of 5.2% was used because it is the current inflation rate in Puerto Rico (CIA, 2001). Since some numbers used for this model came from Dr. Daza's 1996 Ph.D. dissertation, inflation was applied on a case-by-case basis and not at the end of the calculation. Additionally, a reconstruction period of one year was assumed for this model.

In this model there are four cost values, C_R, C_C, C_H, and C_E. The value C_R is the total repair cost for a building after an earthquake. C_C represents the loss of content in a building. The contents of a building are the non-living items in a building, such as desks and computers. C_H is the total cost associated with human capital. This value includes the cost of a human life if people were to die, the cost of injuries, the cost of hospitalization, and emergency room costs. Finally, C_E is the economic loss of a building due to the earthquake, such as rent required to temporarily relocate a business, or family. When all four of these values have been calculated, they are added together into one total damage cost called C_D:

$$C_D := C_R + C_C + C_H + C_E \; . \tag{4.3}$$

A final inequality compares the expected cost of damage associated with an unretrofitted building to the expected damage costs if the same building were to be retrofitted:

$$E(C_D)_{\text{unretrofitted}} > E(C_D)_{\text{retrofitted}} + A \times C_U \; . \tag{4.4}$$

This inequality states that if the cost of damage to an unretrofitted structure, $E(C_D)_{\text{unretrofitted}}$, exceeds the cost of damage to a retrofitted structure, $E(C_D)_{\text{retrofitted}}$, plus the total retrofit cost of the building area multiplied by the retrofit cost per square foot, $A \times C_U$, then the building should be retrofitted. The E function in this inequality associates four different earthquake probabilities. The earthquakes that produce more damage are given a lower probability. This process is further explained in Appendix B. The last value that is calculated before using the final equation is C_U, the retrofitting cost per square foot. This value is a product of five costs:

$$C_U := C_1 \cdot C_2 \cdot C_3 \cdot C_L \cdot C_T \; . \tag{4.5}$$

C_1 is the building group mean cost. It represents the estimated retrofit costs per square foot of a reinforced concrete frame based on Missouri dollars as suggested by the FEMA-156 document entitled *Typical Costs for Seismic Rehabilitation of Existing Buildings*. This value is then adjusted by the other four cost values included in C_U. C_2 is the floor adjustment factor, which takes into account that a larger building has a lower retrofit cost per square foot. C_3 is the seismicity/performance objective adjustment factor, which considers the type and quality of the materials used for retrofit. C_L is the location adjustment factor, which converts the Missouri dollars of value C_1 to that of any other location. C_T is the time adjustment factor, which considers inflation, converting 1993 dollars to 2001 dollars. Finally, C_U is multiplied by A, and this value is used in Equation (4.4). A more detailed discussion of this model is included within Appendix B.

Dr. Guzman's study went through examples of three, five, and seven story buildings. In each case, the model was used for a single building at a time. Instead of applying the model to single buildings, we took the process one step further and applied it to an average building in Puerto Rico. We applied the model to the average residential structure on the Island, as well as a one-story school building. The plans for the one-story school building were given to us by the University of Puerto Rico – Mayagüez. We also took information from Dr. Daza's dissertation about the average size of a residential structure, as well as the number of people located in at risk structures, and applied it to the Guzman model. Once we obtained the damage costs for an unretrofitted building, and compared it to the damage costs of the same building if it were retrofitted before the earthquake, as demonstrated in Equation (4.4), we made generalizations about the structures on the Island. The analyses of these structures are in the following sections.

In order to make generalizations about the structures in Puerto Rico, certain assumptions about their properties had to be made. We used data that we had collected from our information sessions from seismic professionals in order to make these assumptions.

4.3.2.1 Calculations for Residential Structures in Puerto Rico

For residential structures, we took the model that was created by Dr. Guzman, and applied it to an average residential structure for Puerto Rico. For these calculations, we assumed an average square footage of twelve hundred ft^2. We then proceeded to calculate the cost values, which are shown in Table B.8. As previously discussed, four different earthquakes and damage amounts were used. These four damage amounts were applied to both the unretrofitted structure and the structure if it were to be retrofitted, to give a total of eight values for each cost. Corresponding costs were then added to obtain eight C_D values. These eight costs, four for each side of Equation (4.4), were then weighted according to their damage amounts. These damage costs along with the retrofitting costs were then plugged into Equation (4.4) and the following inequality was obtained:

$$\$16,004.18 > \$9,253.93.$$

This shows that by retrofitting residential structures, money will be saved on average if a large earthquake was to occur. Additionally, the probabilities that injuries will occur will be greatly reduced by making the structure stronger. A more detailed explanation of these calculations is shown in Appendix B.

4.3.2.2 Calculations for Schools in Puerto Rico

We also applied Dr. Guzman's model to schools in Puerto Rico. For these calculations, we used properties from the schools building plan that we obtained from the University of Puerto Rico – Mayagüez. The cost values were recalculated for the school and are shown in Table B.10. The C_E values are approximated to be zero because there is no economic loss from a school, since it is a non-profit organization.

Finally we plugged in our numbers into Equation (4.4) again and obtained the following inequality:

$$\$29150.09 > \$17168.51.$$

This again shows that by making an initial investment, money will be saved by retrofitting in the event of a large earthquake. Additionally, making the building stronger will reduce injuries. A more detailed explanation of these calculations are shown in Appendix B.

After applying Model #2 to schools and residential structures, it was shown that it is economically beneficial to retrofit the buildings. Figure 4.6 shows a comparison of the left and right sides of Equation (4.4). The costs on the graph are shown in 2001 US dollars. The damage cost for the unretrofitted schools and residential structures are larger than the retrofitted damage cost plus the cost to retrofit the buildings. While money is saved in both cases, more money is saved in the retrofitting of schools. On the other hand, there are many more people at risk in residential structures. These are the two major issues to be considered if a decision were to be made on which types of structures should be retrofitted first.

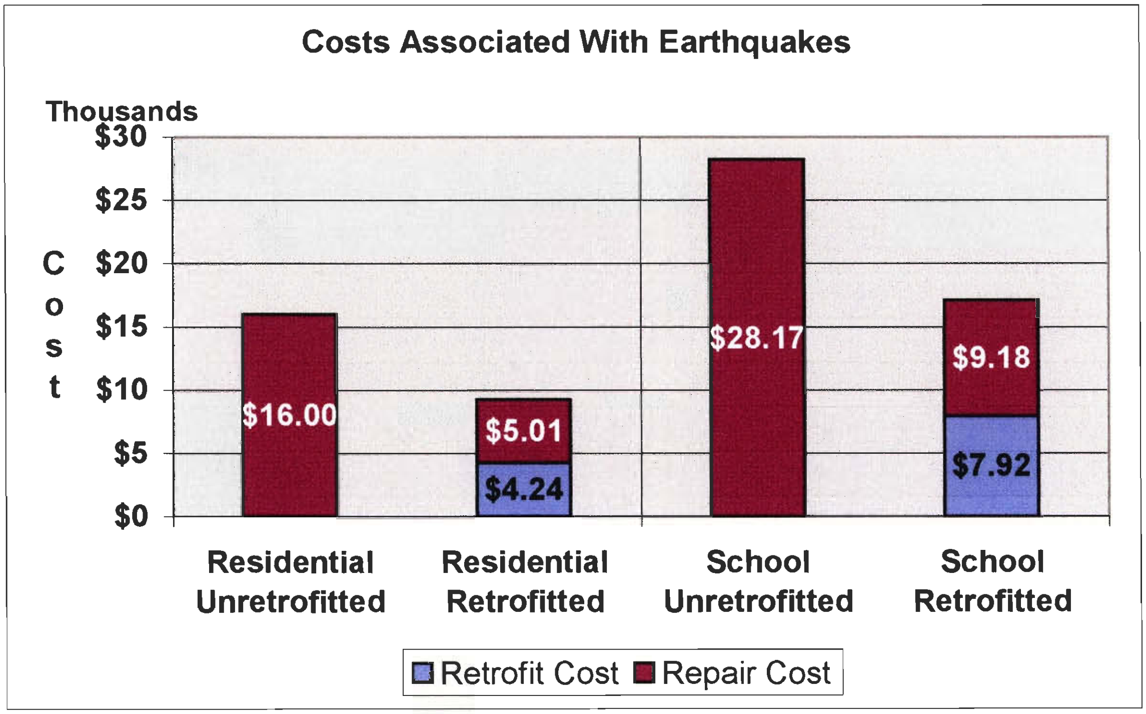


Figure 4.6: Costs Associated with Earthquakes

4.4 Earthquake Awareness

Throughout our conversations with various structural engineers in Puerto Rico, a concern has been expressed concerning the awareness of the Puerto Rican people regarding the potential hazards related to earthquakes in their area. Many of these experts believe that very few residents of the Island are currently aware of the earthquake response plan described in section 4.2.2. In order to develop an educational program designed to educate the citizens of the Island, we used information provided by Mr. Bill Wood, of the California Secretary of State's office, regarding two community action programs currently in existence in California. An analysis of these programs served as a foundation for our proposed community education program.

4.4.1 Sunnyvale's Sunnyvale Neighborhoods Actively Prepare Program

The Sunnyvale Neighborhoods Actively Prepare (SNAP) program combines the efforts of the government and citizens of the city. This program works with residents of the city to ensure that they will be able to cope with the aftermath of an earthquake. Developed on a neighborhood-by-neighborhood basis, SNAP provides self-reliance through a system of training and communications. Neighborhoods are self-defined and are composed of approximately 35 to 50 homes. Within each of these neighborhoods, committees are formed which reflect the key concerns in the event of a disaster, namely communications, damage assessment, first aid, safety and security, search and rescue, and sheltering and special needs. These committees utilize citizen resources in time of need, yet are directly associated with city staff. Although training provides education and information, these committees represent joint government-citizen involvement, allowing citizens to participate in decision-making and community improvement. SNAP receives funding from local tax dollars and currently 22 percent of the city's households participate. FEMA utilizes this program as a model for residential emergency preparedness.

4.4.2 Albany's EarthQuake Preparedness Program

The EarthQuake Preparedness Program (EQPP) relies on the efforts of community volunteers. The city fire department supervises the training and education program of the residents of Albany, California, by offering various courses related to disaster preparedness and emergency response. Because of the limitations of government response, the program has developed a network of volunteer support. In the spring of 1995, the program organized a citywide earthquake drill, involving over 70 percent of the organized neighborhoods. Additionally, using informational activities, the EQPP encourages earthquake preparation on the individual household level.

4.4.3 Educational Programs for Puerto Rico

At this time, Puerto Rico is not ready for the implementation of a program similar to SNAP or EQPP. Without proper education regarding the potential for serious damage, people may be hesitant and unwilling to set aside tax money to fund such programs. Furthermore, citizens may be hesitant to volunteer their time and efforts to participate in these programs, unless the need for such programs could be made evident. Utilizing the influence of the media, residents could be informed of the potential danger posed by earthquakes through commercials, televised special reports, documentaries, and any other form of educational medium. However, after properly educating the people of the Island, convincing them of the importance of preparation, a similar program could prove to be an effective tool to prepare citizens of Puerto Rico.

In order to implement a similar program, the cooperation of the government of Puerto Rico would be required. The support of the government would provide credence to the claim of the seismic vulnerability of the Island. Furthermore, the government could provide the necessary funding for the education programs required to increase the awareness of the public. Once educated, the public would be more willing to participate in volunteer programs designed to assist emergency response policies, allowing for the development of a plan based on the SNAP and EQPP programs.

4.5 Retrofit Incentives

As a result of our various interviews in Puerto Rico, it has been expressed that many of the building owners on the Island do not feel that they would benefit in any way, mainly financially, if they took the initiative to retrofit their structures for seismic loads. Some experts even believe that the only way to convince owners to retrofit is to actually have an earthquake strike Puerto Rico so that people can see the current need for improvements. Retrofit incentives do not currently exist in Puerto Rico, which is why not many buildings are currently being retrofitted. However, Mr. Bill Wood, of the California Secretary of State's office provided information about both private and public organizations, located within his state, that have implemented incentives in the forms of both grants and low-interest loans. Analyzing these programs will provide a basis for proposed retrofit incentive programs in Puerto Rico.

4.5.1 Incentives Available in Puerto Rico

Before compiling information about the retrofit incentive programs available in California, our main concern was to determine whether Puerto Rico provided incentive programs for its building owners. We decided that by randomly contacting various homeowner insurance companies in Puerto Rico, we would be able to examine the possibilities of different retrofit incentive programs that exist on the Island. One company with whom we conducted a phone interview was John W. Winegar Insurance, located in San Juan. They informed us that earthquake insurance is offered in Puerto Rico because mortgages require it. However, their company does not provide discounts for retrofitting. We also conducted a phone interview with Mr. Rafael Gil of the Financial Examiner's Office, a branch of the Office of the Insurance Commissioner of Puerto Rico. Mr. Gil informed us that insurance companies are free to decide whether they wanted to underwrite catastrophic events, such as earthquakes. Also, should the insurance companies decide to underwrite policies, they must maintain reserve funds in the case of the occurrence of such an event, such as an earthquake. Mr. Gil also informed us that although no incentives are provided directly, domestic insurance companies are allowed to claim the taxes paid on their premiums for the catastrophic events coverage as a deduction on their income taxes paid to Puerto Rico. However, foreign companies, including those from the United States, cannot claim this deduction.

4.5.2 Santa Cruz County – Brace for the Quake Program

A few years after the Loma Prieta earthquake of 1992, Santa Cruz County implemented the Brace for the Quake Program. This program allows retroactive funding for work already completed. It reimburses homeowners for half the cost, but only up to $10,000. This program received funding from FEMA's Hazard Mitigation Grant Program as a result of the Loma Prieta earthquake.

4.5.3 City of Los Angeles – Seismic Mitigation Loan Program

In February 1998, the City of Los Angeles Housing Department began working with the Bank of America in order to subsidize interest rates for retrofit work. Federal Community Development Block Grant funds were utilized to decrease the interest rates by approximately 1 percent.

4.5.4 City of Oakland – Project SAFE

In January of 1998, the City of Oakland began a project piloted by FEMA known as Project SAFE, Safety and Future Empowerment. This program is a partnership between the residents and business owners of Oakland. It was intended to reduce the loss of lives and property as a result of natural disasters, including earthquakes. It also provides grants and low interest loans to eligible homeowners and businesses with the stipulation that the funds be used to make their property more resistant to natural disasters.

Homeowners may utilize the funds from the grants or loans to strap water heaters, upgrade security bar releases, upgrade downspouts, gutters, and drains; install smoke detectors, bolt foundations, and install plywood for cripple wall bracing. Apartment building owners may use funds from low interest loans to strap hot water heaters, upgrade downspouts and drainage, build retaining walls, and install seismic retrofit work. Businesses qualifying for low interest loans may use the funds to install seismic retrofit work, purchase earthquake kits, enhance equipment, and train employees. Small businesses may receive special program rebates, incentives, or discounts.

4.5.5 City of Berkeley – Seismic Retrofitting Incentive Program

This program acts as a cooperative effort amongst the departments of Planning, Housing, and Finance. It provides two economic incentives for homeowners. The first being a local ordinance waiving permit fees for seismic retrofits on un-reinforced masonry structures and single family and multifamily residences. The second incentive is that 0.5% of the value of your property can be applied towards seismic upgrades for newly purchased homes. This amount can be applied towards seismic upgrades during the sale of the property. Qualifying upgrades include, foundation repair or replacement, mudsill repair or replacement, wall bracing in basements, foundation-to-mudsill bolting, shear wall installation, water heater anchoring, and the securing of chimneys.

4.5.6 California Earthquake Authority – Residential Retrofit Program

The California Earthquake Authority (CEA) is regulated as a private insurer by the California Department of Insurance, but publicly managed by a five-member Governing Board consisting of the Governor, the Treasurer, the Insurance Commissioner, the Senate President, and the Assembly Speaker.

The CEA Residential Retrofit Program refers homeowners to trained professionals who will strengthen their homes against earthquake damage and secure water heaters to reduce the risk of fire. Homeowners are referred to an approved engineering firm that will inspect the foundation of the home and prepare a report showing the weaknesses that can be corrected through retrofitting. The homeowners are then referred to a contractor who will perform the work described by the engineering report. All contractors are pre-screened and only those contractors who are financially secure, trained, and licensed are eligible to participate in this program. The CEA then arranges low-interest loans, 8.0% for non-CEA policyholders and 7.5% for CEA policyholders, through participating banks to enable the homeowner to pay for this retrofit. CEA policyholders become eligible for an insurance premium discount of 5% upon completion of the retrofit.

This program is open to California homeowners in nine counties and has strict eligibility requirements. Eligible homes consist of:

- Only wood-frame homes (or stucco over wood stud walls) built prior to 1979
- Only homes with a crawl space or an unbolted foundation
- Only homes without pre-existing earthquake, water, or pest damage

4.5.7 California Department of Insurance – Loan Program

The California Department of Insurance (CDI) offered a low-interest retrofit program to qualified borrowers in partnership with the Bank of America. This program assisted single family through four-plex properties located in one of fourteen counties, but was originally slated to end July 1, 2000. This program did not require the property owner to actually reside on the property and could be applied to mobile homes. The bank charged an interest rate of 4.5%. Funds could not exceed:

- $6,000 for a mobile home
- $8,000 for a single family home
- $10,000 for a duplex
- $12,500 for a triplex
- $15,000 for a four-plex

Eligible procedures for site-built homes include bracing the hot water heater, bracing the cripple wall, anchoring the foundation to structure, installing automatic gas shut-off valves, repairing the foundation to accommodate earthquake retrofit.

Eligible procedures for mobile homes include bracing hot water heater, anchoring fuel storage if applicable, installing an “Earthquake Resistance Bracing System”.

4.5.8 California Department of Insurance – Grant Program

The CDI offers a limited number of earthquake retrofit programs to low-to-moderate income homeowners. Funds can only be used for owner-occupied single family site-built or mobile homes and are administered directly by the Department of Insurance.

Aspects of this program include the following requirements:

- Homeowners must live in selected counties and submit grant applications during a narrow time window
- Grants cannot be used to upgrade previous FEMA recognized retrofitting of site-built or mobile homes
- A site-built home has a maximum grant limit of $8,000 and a mobile home

has a maximum grant limit of $6,000

- Grantees must be low-to-moderate income homeowners and must have lived on the property for at least two years.
- Extra consideration given to the financially neediest applicants who are on a fixed income, permanently disabled, or are 55 years or older

4.5.9 ABAG Finance Authority for Nonprofit Corporations

The ABAG Finance Authority for Nonprofit Corporations is a Joint Powers Agency whose objective is to assist eligible nonprofit organizations and other borrowers in obtaining tax-exempt debt financing for projects that demonstrate public benefit.

Projects have been financed on behalf of hospitals, health care clinics, retirement facilities, nonprofit housing developers, multifamily housing partnerships, private schools, behavioral health care agencies, substance abuse facilities, and community service organizations.

Projects have involved the acquisition and rehabilitation of facilities, the acquisition of equipment, and new construction. The program does not have any capacity limits on either the dollar amount of an individual financing project or the number of projects financed.

4.5.10 Retrofit Incentives for Puerto Rico

While an incentive program would be beneficial to the residents of Puerto Rico, the Island is not ready for such a plan. In order to implement a retrofit incentive plan similar to those listed, various preparatory steps need be undertaken. Once the residents of the Island have been educated regarding the importance of retrofit, an incentive plan would encourage residents to strengthen their homes and business against seismic forces.

Several of the programs mentioned previously provide reimbursement for retrofit work. Given the relatively low average income of the population of Puerto Rico, this type of incentive would assist those residents who could not afford retrofit work on their own to strengthen their homes. Unfortunately, without the support of the government, it is unlikely that such a plan would be implemented.

Until the residents of the Island are properly educated regarding the dangers of earthquakes, low interest loans, such as those offered by the CEA, would not be an appropriate form of incentive. While low interest loans would provide a financing option for those interested in strengthening their buildings, few people will be interested in this type of program unless they understand the necessity of these actions. Furthermore, considering the relatively low incomes of individuals on the Island, this option would not be suitable for homeowners, but perhaps would be most suitable for business owners.

Once ready for retrofit incentives, a plan must be developed that accounts for the common shortcomings of structures on the Island. Without professional consultation, home and business owners would not know where to begin the process of retrofit. The cost of obtaining the opinion of a consultant could be subsidized through the implementation of incentives. Assistance must then be provided to enable home and business owners to correct problems resulting from inadequate design. Too often, engineers have designed structures with shear walls located in only one direction; this problem requires correction, which requires funds.

Consideration must be given to the introduction of insurance discounts. While this type of incentive has proven effective in California, it may not be the best form of assistance in Puerto Rico. Although mortgaged homes must be covered with some type of disaster coverage, non-mortgaged homes are not required to carry this type of insurance. Since earthquake of 1918 was the last time the Island experienced extensive damage as a result of an earthquake, residents may be reluctant to request this type of additional coverage. However, those that currently carry this type of protection may rely too heavily on it; retrofit may not be deemed necessary since the insurance company will cover the damages sustained in the event of an earthquake. While this may be true, residents need to realize that insurance will not cover the social costs, such as mental anguish and trauma, related to the earthquake. Additionally, the insurance companies should realize that, by encouraging their subscribers to retrofit their structures, they would also save themselves money. As indicated previously, in section 4.3.1, once a building is retrofitted, it will sustain significantly less damage, requiring less money to repair, which would be beneficial to the insurance company.

In addition to financial assistance for retrofit, incentives should be implemented to encourage citizens interested in constructing new homes to build them up to the current codes. A common problem in Puerto Rico revolves around the fact that building plans are not required for those homes built in the rural areas. Financial assistance, however, may prevent the construction of less than adequate homes, further limiting the damage incurred as a result of an earthquake.

However, although retrofit incentives could be a useful tool in the fight against seismic vulnerability, without a complete education regarding earthquake preparation, citizens will be hesitant to spend money to prevent against a disaster that may never occur.

4.6 Visual Analysis Modeling

In order to demonstrate the effectiveness of retrofit of a structure in relation to experienced seismic forces, we modeled a single story school utilizing Visual Analysis on the one story school. The appropriate building plans were obtained from UPR-Mayagüez. This school was designed prior to 1987, the year when Puerto Rico adopted a building code with more stringent seismic provisions. Due to liabilities and other legal repercussions, the location of this school has not been provided.

The school was reconstructed within the program with the same properties as the original building. After creating a three-dimensional model consisting of the beams, columns, and girders, the connections were imposed upon the structure. Once the frame was completed, diaphragms were inserted into the appropriate planes, modeling the masonry walls and concrete floor. However, only the structural drawings were available for the school; therefore, we modeled this school both with and without short columns.

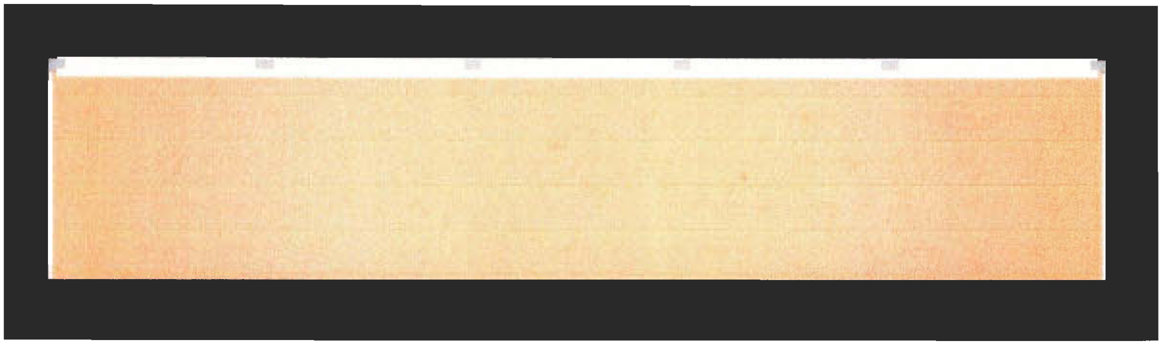


Figure 4.7: Single Story School without Short Columns (NSC)

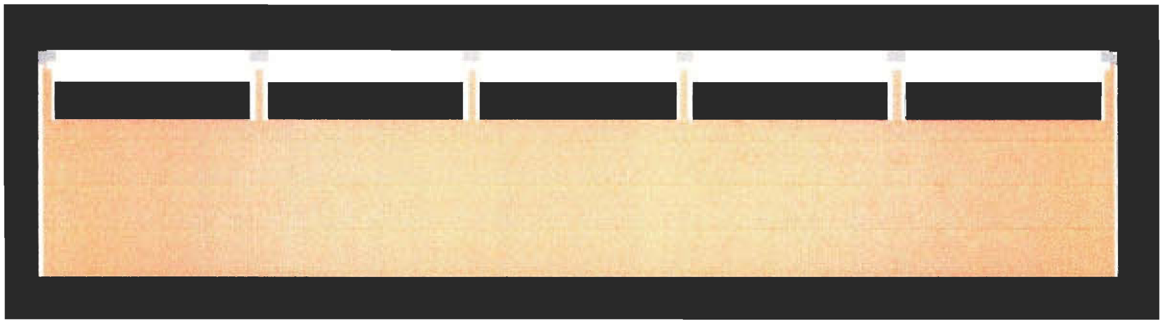


Figure 4.8: Single Story School with Short Columns (SC)

Creating a 3 ft space between the masonry walls and the roof in both the front and rear walls resulted in these short columns, as demonstrated in Figures 4.7 and 4.8.

4.6.1 Determination of Seismic Loads

Once both structures had been completely modeled, a value for the seismic loading was required. Since the purpose of this model was to demonstrate the effectiveness of simple retrofit techniques, the value of the load itself was not critical, so long as the selected value both represents a possible seismic loading and results in a deflection in our structure. Rather than select a loading at random, we calculated the seismic forces using the 1997 *UBC*, which provides the equations for the seismic loads that must be used in the design of current structures. Although the seismic forces depend upon the weight of the building, we assumed the weight of the building with short column to be approximately the same weight of the structure without short column.

According to Section 1630.2.1 of the *UBC*, the design base shear in any direction, V, is defined by the formula:

$$V = \frac{C_v I}{R T} W. \qquad \textbf{(4.6)}$$

C_v represents the seismic coefficient, as presented in Table 16-R of the Code, which provides a value of 0.45 for our model. I describes the importance factor of the structure, as given in Table 16-K of the Code. This value ranges from 1.0 to 1.5, increasing the safety of certain types of structures, such as hospitals and fire departments, and supplies a value of 1.0 for our model. R corresponds to the inherent strength of the structure, depending on the type of provided system for resisting lateral forces, as established in Table 16-N of the Code, or 4.5 for our model.

W represents the weight of the structure. The school building consists of various components and the weight of each must be considered. In order to calculate the weight of the concrete components of the structure, we applied the equation for weight:

$$W_{solid} = \text{Length} \times \text{Width} \times \text{Average Height} \times \text{Density}. \qquad \textbf{(4.7)}$$

For all calculations, the density of the reinforced concrete was assumed to be 150 pcf. From the building plans, the concrete slab was determined to be 5 inches thick, 60 feet long, and 30 feet wide. Substituting our values into Equation (4.7), we obtained a value of approximately 112.50 kips, where one kip (k) is equivalent to 1000 pounds, for the weight of the concrete slab.

In order to support the concrete slab, the structure contains six beams, running the width of the building. These beams consist of two separate components. The first part of the beam is 1 ft wide, 1.67 ft in depth, and 24 ft long. The second section of the beam consists of a trapezoidal shape 6 ft long, 1 ft wide, a $base_1$ of 1.5 ft, and a $base_2$ of 0.33 ft. Substituting both sets of these values, along with the density of concrete, into Equation (4.7), we obtain the values of 6.0 k for the first section and 0.825 k for the second section. The sum of these two sections yields a value of 6.825 k per beam. Multiplying this value by the number of beams in the structure, 6, we obtained a value of 40.95 k for the weight of the beams.

Girders extend the entire length of the structure, one located in the front of the structure and the other in back, serving to support the beams. These two girders are approximately 60 ft long, 1 ft wide, and 1.8 ft in depth. Substituting these values, along with the density of reinforced concrete, into Equation (4.7), we calculate a value of 16.2 k per girder, or 32.4 k for both girders.

There exist two separate types of columns within this structure. Although both consist of reinforced concrete, their dimensions differ. Even though both columns are 12 ft long, the columns at the rear of the structure are 1 ft wide and 0.67 ft deep while those located at the front of the structure are 1 ft wide and 1 ft deep. Substituting these values, along with the density of concrete into Equation (4.7) provides the values of 1.206 k per rear column and 1.8 k per front column. Multiplying each of these values by the number of columns present, 6 for each, we evaluated the total weight each columns. The rear columns weigh approximately 7.236 k; the front columns weigh approximately 10.8 k.

The walls of this structure are composed of masonry walls, serving as partitions rather than as shear walls. From the model in Visual Analysis, the weight of the masonry wall was determined to be 0.0625 ksf, or kips per square foot. To evaluate the weight of the masonry walls, we multiplied the areas of the walls by the weight of the walls as indicated:

$$\text{Weight} = \text{Length} \times \text{Width} \times \text{Density}. \qquad \textbf{(4.8)}$$

In order to simplify the structure, the walls composing this building will be divided into two categories, long walls and short walls. The long walls extended along the length of the front and rear of the building and, for simplicity, neglected the openings for windows.

These walls are 60 ft long and 12 ft high. Substituting these values along with the weight of the masonry into Equation (4.8), we calculated the weight to be 112.5 k per long wall. Multiplying this value by the number of walls, 2, we obtained a value of 225.0 k for the long walls. The short walls, however, were 24 ft long and 12 ft high. Substituting these values, along with the weight of the masonry, into Equation (4.8), we calculated the weight to be 18.0 k per wall. Multiplying these values by the number of walls, 6, we determined the weight of the total weight of the short walls to be 108.0 k.

The calculated weights of each component of the structure are summarized in Table 4.3.

Table 4.3 – Component Weights of One Story School Building

Component	**Weight (k)**
Concrete Slab	112.50
Concrete Beams	40.95
Concrete Girders	32.40
Concrete Columns – 1 ft × 0.67 in	7.24
Concrete Columns – 1 ft × 1 ft	10.80
Masonry Walls – Long Walls	225.00
Masonry Walls – Short Walls	108.00

Taking the sum of the component weights, the weight of the entire structure was determined to be 536.89, or 537 k. However, as this is a one-story building and the tributary area of each floor is one half the height of each story, only one half of the weight was considered. Therefore, the weight that was used in our calculations was 268.5 k.

T describes the period of the structure, as defined by the equation:

$$T = C_t\ (h_n)^{3/4}\ . \qquad \textbf{(4.9)}$$

In this equation, C_t is 0.030 for reinforced concrete. The term h_n represents the height of the structure, or 12 ft in our model. Inserting our values into the above equation, we obtained a period of 0.19 s.

Table 4.4 summarizes the values used when calculating the base shear of the structure.

Table 4.4 – Variables Substituted into Equation (4.6)

Variable	**Value Used**
C_v	0.54
I	1.0
R	4.5
T	0.19
W	268.5

Substituting the values into Equation (4.6), we obtain a value of 169.58, or 170, k for the base shear experienced by the structure.

The Code also provides that the value for the design base shear shall be located within the given boundaries, defined by:

$$0.11\,C_a\,I\,W < \frac{C_v\,I}{R\,T}W < \frac{2.5\,C_a\,I}{R}W\,. \qquad \textbf{(4.10)}$$

C_a represents the seismic coefficient as presented in Table 16-Q in the Code. In our model, a value of 0.36 was used. The variables used in Equation (4.9) are summarized in Table 4.5.

Table 4.5 – Variables Substituted into Equation (4.10)

Variables	**Value Used**
Cv	0.54
Ca	0.36
I	1.0
R	4.5
T	0.19
W	537

Substituting these values into Equation (4.6), we determined the minimum boundary value to be 44 k and the maximum boundary value to be 220 k. Since our calculated value of 170 k for the base shear falls between these values, we adopted this value.

In accordance with the Code, the forces are distributed over the height of the structure utilizing the equation:

$$V = F_t + \sum_{i=1}^{n} F_i\,, \qquad \textbf{(4.11)}$$

where F_t represents the force present at the top of the structure, and is defined by the equation:

$$F_t = 0.07\,T\,V\,. \qquad \textbf{(4.12)}$$

However, the Code states that when T is less than 0.7 s, which is true in our case, F_t may be considered to be zero. This reduces Equation (4.10) to:

$$V = \sum_{i=1}^{n} F_i\,. \qquad \textbf{(4.13)}$$

Solving Equation (4.11) for F_x, the Code distributes the base shear over the height of the structure using the formula:

$$F_x = \frac{(V - F_t)\,w_x\,h_x}{\sum_{i=1}^{n} w_i\,h_i}\,, \qquad \textbf{(4.14)}$$

where w_x represents the weight of a particular level and h_x corresponds to the height of a particular floor. However, because F_t is zero it dropped out of our equation. Since our model is of a one story school building, then:

$$w_x\,h_x = \sum_{i=1}^{n} w_i\,h_i\,, \tag{4.15}$$

and Equation (4.14) simplified to:

$$F = V = 170 \text{ k}.$$

We applied the 170 k seismic force to the center of the mass of the structure in both the x and the y directions to ensure that the building would be able to withstand seismic forces in both of these directions.

4.6.2 Deflections Resulting from Seismic Forces

Once the seismic loads were applied to the models, the program was executed in order to determine the resulting deflections. Due to the seismic loading, the both structures shift both laterally as well as towards the front.

Forward deflections experienced by the school structures are shown in Figures 4.9 and 4.10. This shift resulted from the additional weight of the reinforced concrete cantilevered section of the roof, located along the front of the building. As a result of the additional weight, the center of mass was transferred towards the front of the structure. The forward deflection of the structure increases with the presence of short columns, as indicated in the figures.

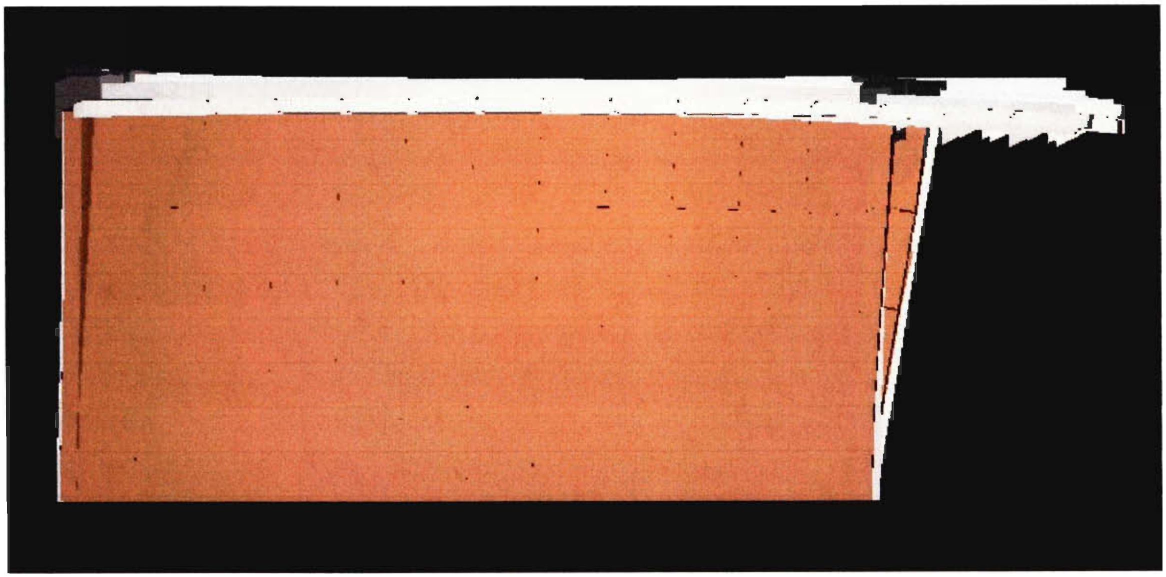


Figure 4.9: Forward Shift of NSC School

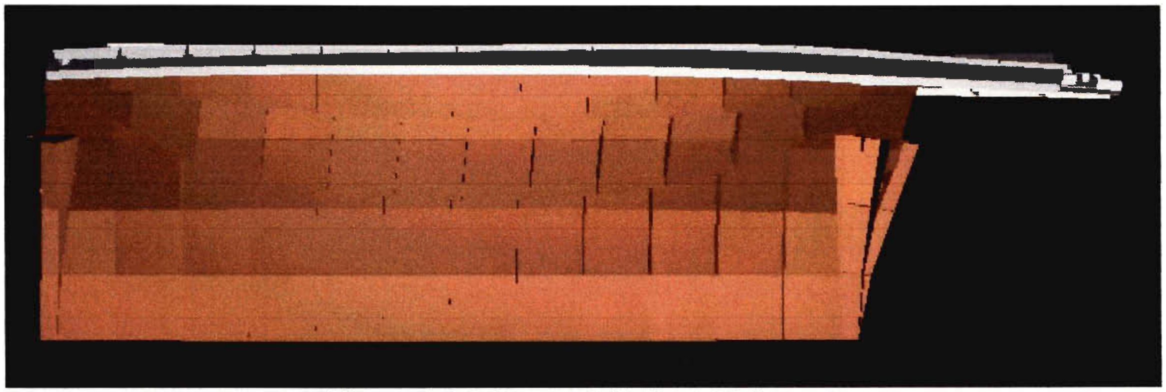


Figure 4.10: Forward Shift of SC School

The reinforced concrete elements of the structure failed to support the applied forces, resulting in damage to the masonry wall partitions.

Similarly, the lateral shift experienced by the structures also increases dramatically with the presence of short columns. Figures 4.11 and 4.12 indicate that, although both structures experience deformation, the presence of short columns greatly reduced the ability of the structure to withstand lateral forces.

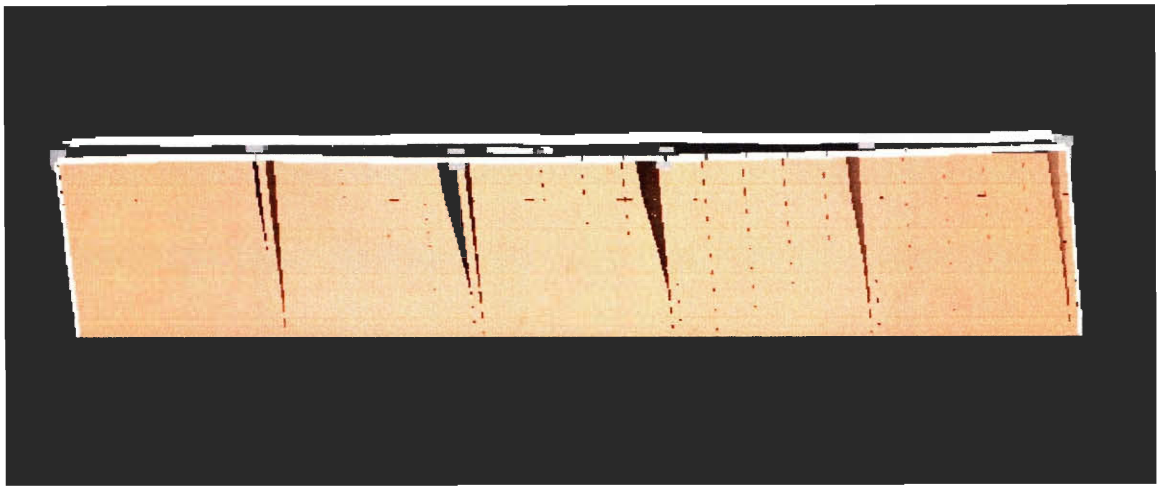


Figure 4.11: Lateral Shift of NSC School

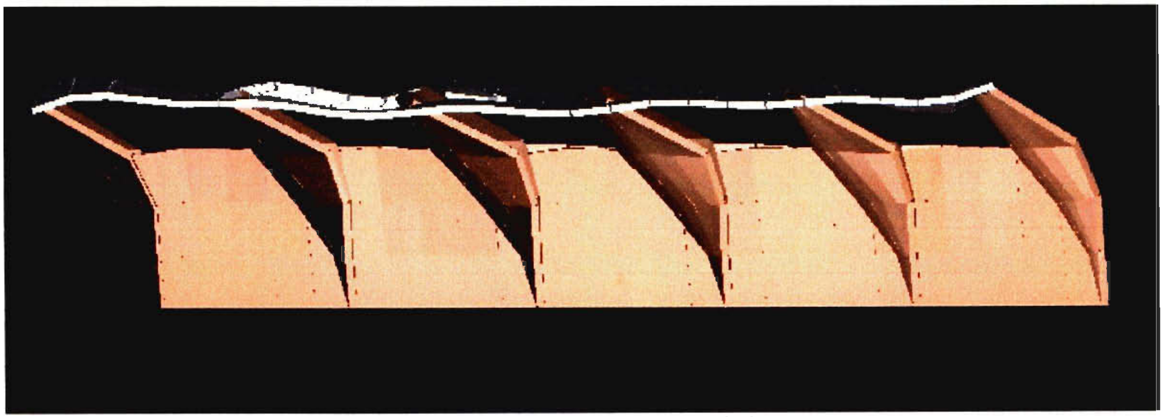


Figure 4.12: Lateral Shift of SC School

Examination of Figure 4.12 indicated that the transition between the masonry wall and the space provided for the window was the area of greatest concern. We concluded this because the deformation increased significantly in the location above the height of the masonry wall. Deformation of this degree presented a very serious problem; shattered windows and a collapsed roof would place the lives of each of the occupants in grave danger. This demonstrated that, in future design, structures that commonly utilize short columns require great consideration. To better resist lateral forces, short columns should either be designed with a greater factor of safety or be avoided altogether.

In addition to forward and lateral deflections, the interior walls of the structures may experience deflections resulting from the seismic loads, as demonstrated in Figures 4.13 and 4.14.

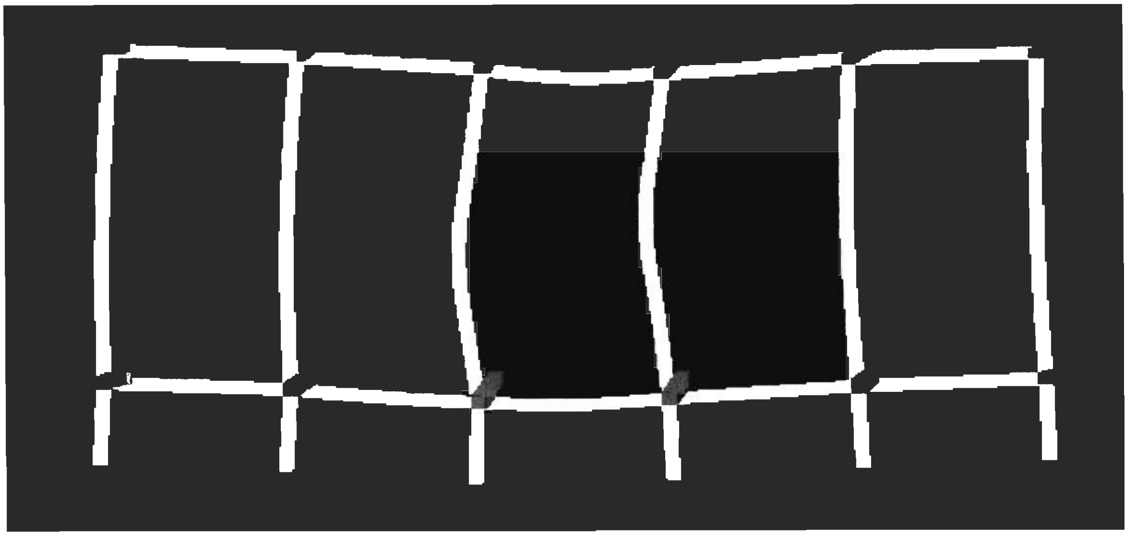


Figure 4.13: Floor Plan of NSC School

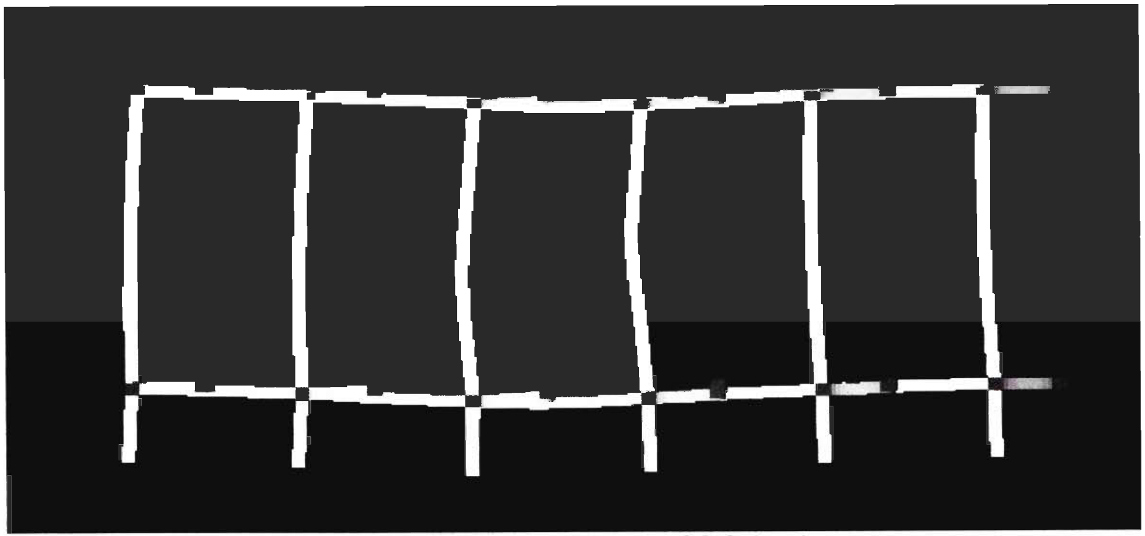


Figure 4.14: Floor Plan of SC School

The gray squares indicate the resulting position of the columns. The columns of the NSC school shifted in the direction of the resultant of the two seismic forces, while the columns of the SC structure deflected in the direction of the walls containing the short columns. Furthermore, the several of the walls buckle in response to the applied seismic forces. Although these situations would not threaten the lives of the occupants, they would adversely affect the future use of the buildings.

4.6.3 Results of Various Retrofit Techniques

Since the walls of the structure experienced the greatest deflections, we explored various methods of strengthening these weak areas. Shear walls could be inserted into the structure, steel bracing could be placed along the exterior of the walls, or a combination of the two could be implemented. While each of these methods has its advantages, the corresponding disadvantages need also be considered.

4.6.3.1 Addition of Shear Walls

The addition of shear walls requires that the school be closed for a long enough period of time to allow for the construction of these walls. It may be possible, however, to coordinate the necessary activities with the summer or other vacations of the school.

In order to implement this technique, in both models the exterior walls as well as the two middle interior walls were thickened, doubling the thickness of the wall to 12 inches utilizing additional masonry bricks. This assumes that the new layer of masonry is adequately anchored to the existing reinforced concrete beams, girders, and floor slab and the original masonry wall. Without sufficient connections, the wall would fail to act as a single unit, as assumed in this model.

Once the appropriate walls were strengthened, the previously calculated seismic loads were reapplied to the model in order to determine the effectiveness of retrofit. As demonstrated in Figures 4.15 and 4.16, this method of strengthening proved successful.

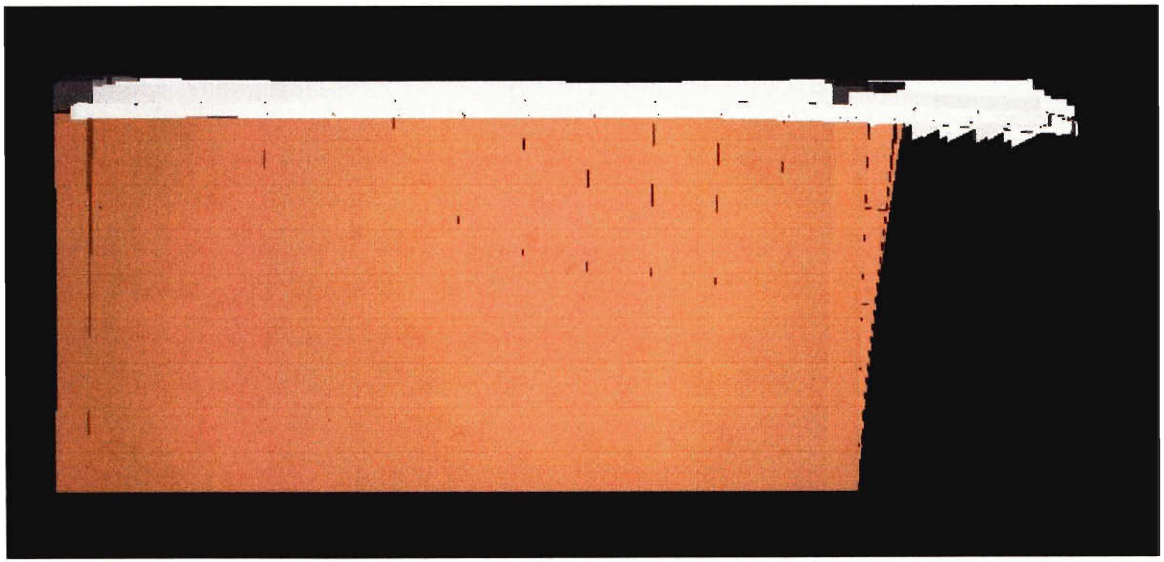


Figure 4.15: Forward Shift of NSC School with Shear Walls

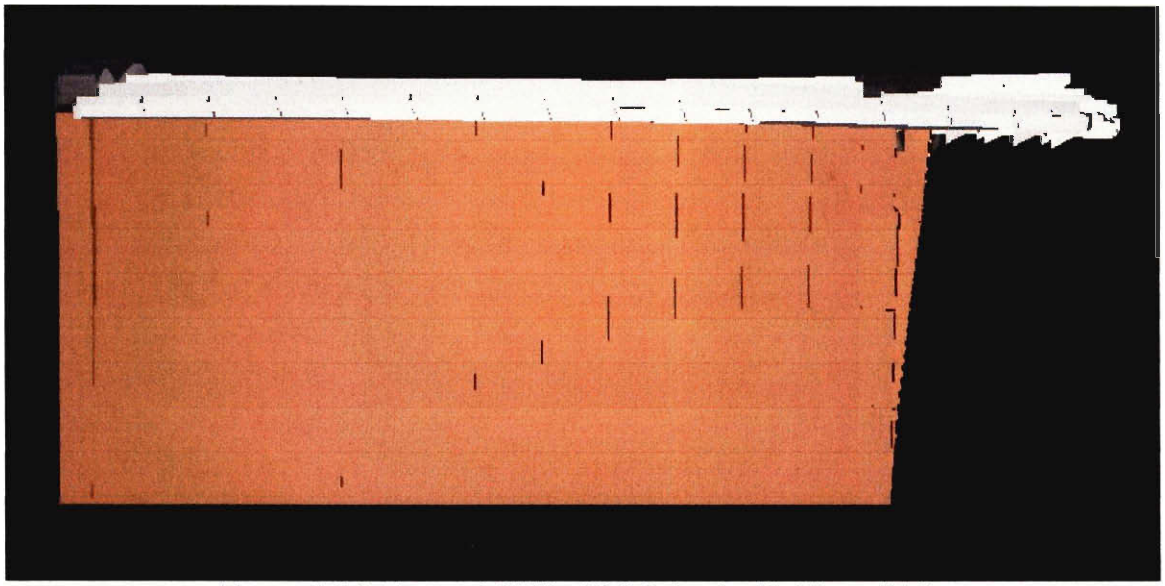


Figure 4.16: Forward Shift of SC School with Shear Walls

Strengthening the four short walls resulted in a decrease in the lateral deflections of the originally unretrofitted structures. Only slight deflections were observed in both structures. The SC structure still sustained greater deflection than the NSC structure, however this damage was much less dangerous than the original deformations. As a result of the shear walls, relatively small damage occurred to the walls and roof, a vast improvement from the original deflections presented in Figure 4.10.

Despite the improvements in the forward shift of the structure, room for improvement still existed in regards to the lateral shift of the structures. Figure 4.17 indicated that the addition of shear walls in the long direction of the NSC school, while it did reduce the amount of deflection experienced, it did not significantly increase the ability of the structure to resist the applied seismic forces.

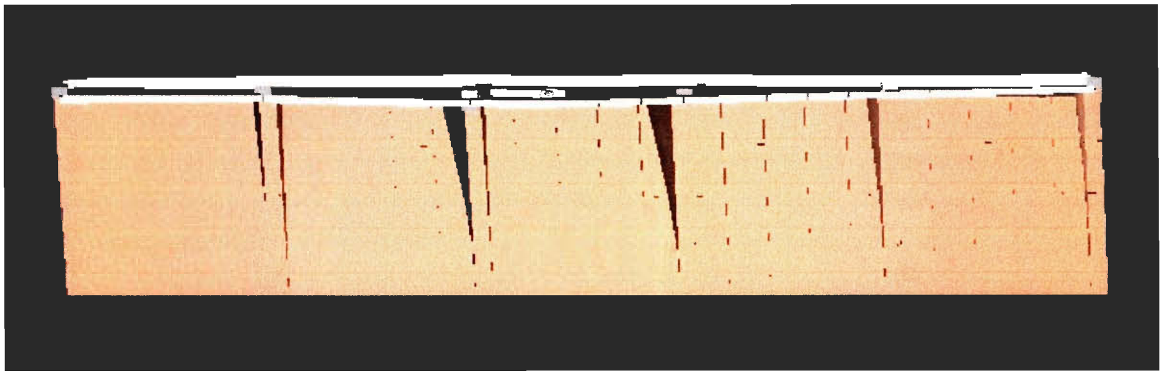


Figure 4.17: Lateral Shift of NSC School with Shear Walls

The addition of shear walls in the long direction of the SC building required consideration of the columns supporting the roof, as this is where the failure in Figure 4.12 occurred. To provide additional support for this vulnerable area, the thickened masonry wall was extended to the roof for 3 ft on either side of each column, as can be seen in Figure 4.18.

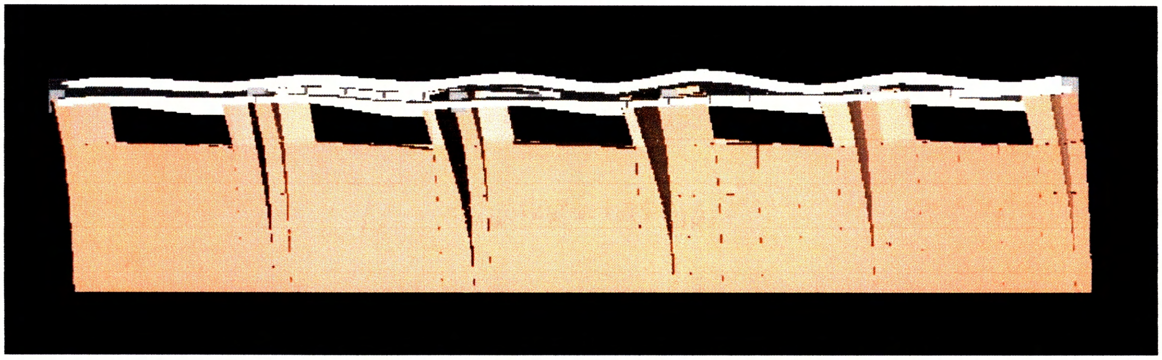


Figure 4.18: Lateral Shift of SC School with Shear Walls

As a result of these precautions, the lateral shift of the SC structure decreased dramatically. The roof was no longer in danger of a sudden collapse, however the distortion would still cause the windows to shatter and the concrete to crack. In this structure, the addition of the shear walls in the long direction proved to be very effective in increasing the safety of the occupants and reducing the amount of damage experienced.

Although the introduction of shear walls reduced the lateral deflection of the structures, the buckling of the interior walls was not reduced. Figures 4.19 and 4.20 provide the floor plans of the structures after the seismic forces have been applied.

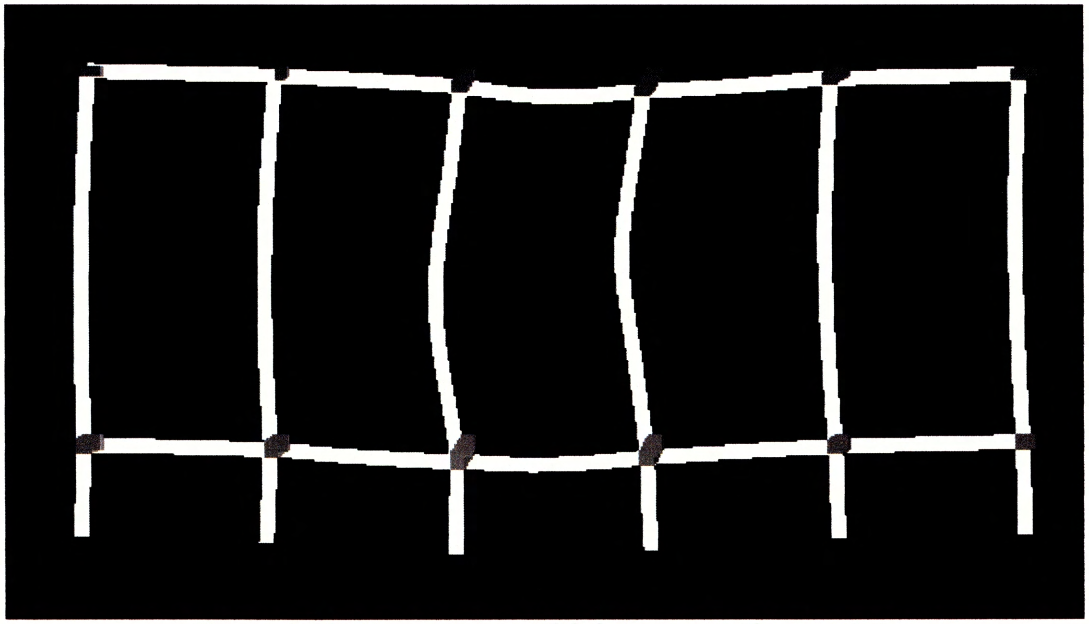


Figure 4.19: Floor Plan of NSC School with Shear Walls

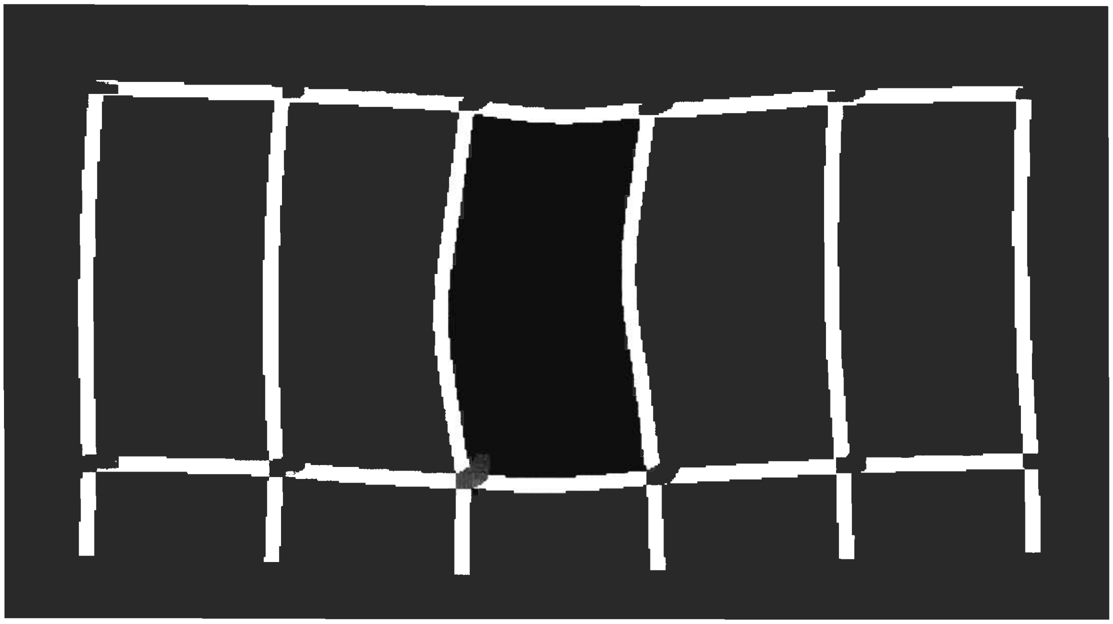


Figure 4.20: Floor Plan of SC School with Shear Walls

The columns in Figure 4.20 do, however, deflect in a manner similar to that of those in Figure 4.19. Unlike the unretrofitted structure, whose columns deflect along the walls containing short columns, the columns in the retrofitted structure shifted in the direction of the resultant of the applied seismic forces.

Adding shear walls to both of the structures provided adequate strength to the structures to decrease the experienced deflections. However, this technique of retrofit requires skill; the masonry must be properly secured and the walls must not deviate from the plumb line, or vertical axis. Nevertheless, this method does have benefits; the aesthetics of the structure would not be affected, as it would appear to maintain its original exterior.

4.6.3.2 Addition of Steel Bracing

Steel bracing could be mounted to the exterior of the structure while still allowing it to remain functional, not requiring displacement of the occupants. Unfortunately, this technique may detract from the original aesthetics of the building. The importance of the appearance of the building requires consideration when utilizing this method of retrofit.

In order to employ steel bracing, steel structural tubing was placed along the exterior walls utilizing mostly a simple truss formation, as demonstrated in Figure 4.21.

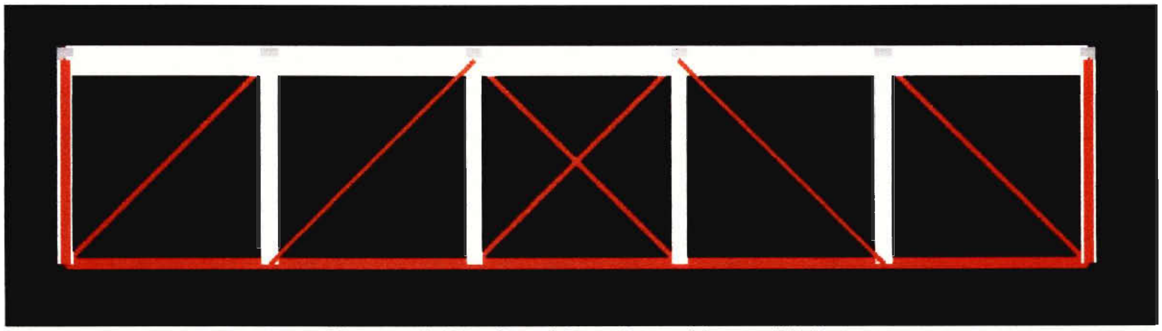


Figure 4.21: Steel Bracing of Long Walls

In this picture, the white elements represent the reinforced concrete columns, girders, and beams supporting this single story school building. The elements in red correspond to the structural steel tubing used to brace this structure. A single compound truss exists in the center of the long walls, forming a large "X". On either side of this compound truss, two simple trusses can be seen in each bay, identified by the existence of two triangles. The lines forming the compound truss appear thicker, indicating that a larger structural steel tube was used; more resistance was necessary in the center bay, as this is where the seismic loads act. Although not seen in this diagram, steel members were placed along the top of the structure as well as along the columns. Along the exterior short walls, a K-truss was utilized, as seen in Figure 4.22.

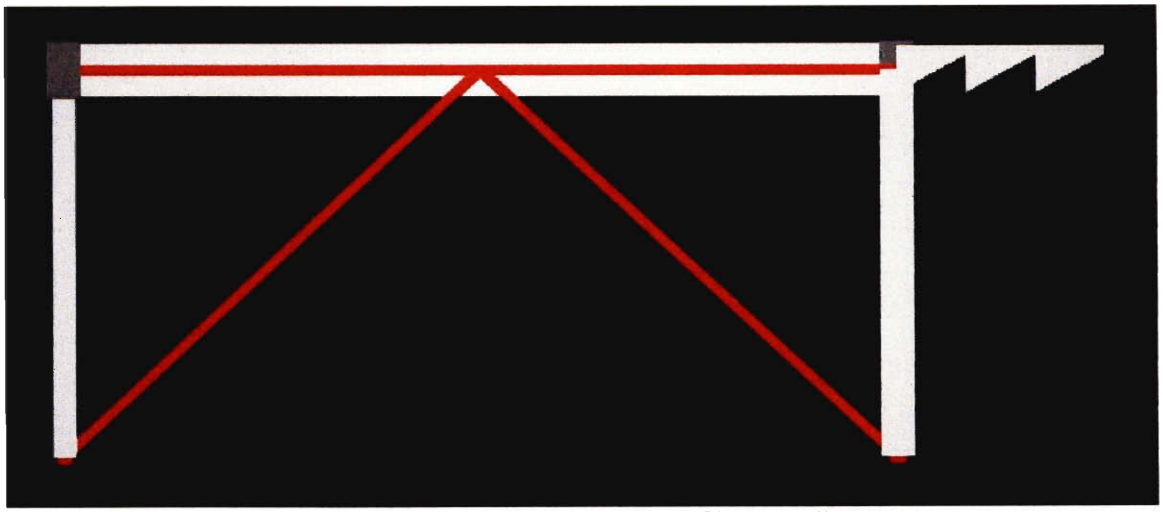


Figure 4.22: Steel Bracing of Short Walls

These formations were utilized in both structures.

Once the steel bracing was applied to the models, the seismic loads calculated in section 4.6.1 were applied at the appropriate location. The program was then re-executed in order to determine the effectiveness of this method of retrofit. Figures 4.23 and 4.24 indicated that the steel bracing located on the exterior short walls adequately strengthened the wall, almost eliminating deflection in either building.

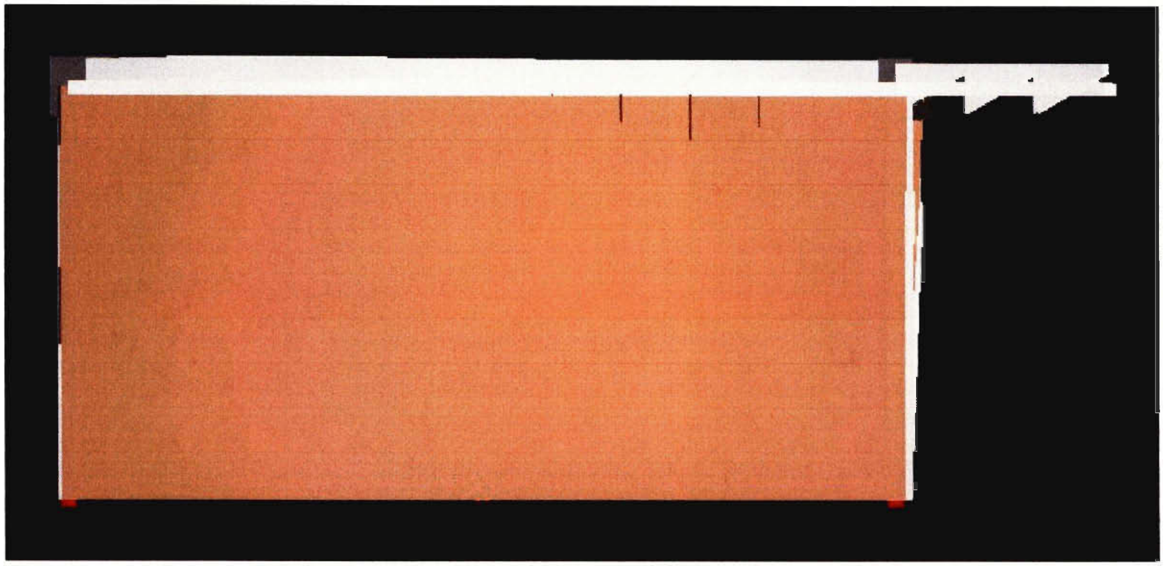


Figure 4.23: Forward Shift of NSC with Steel Bracing

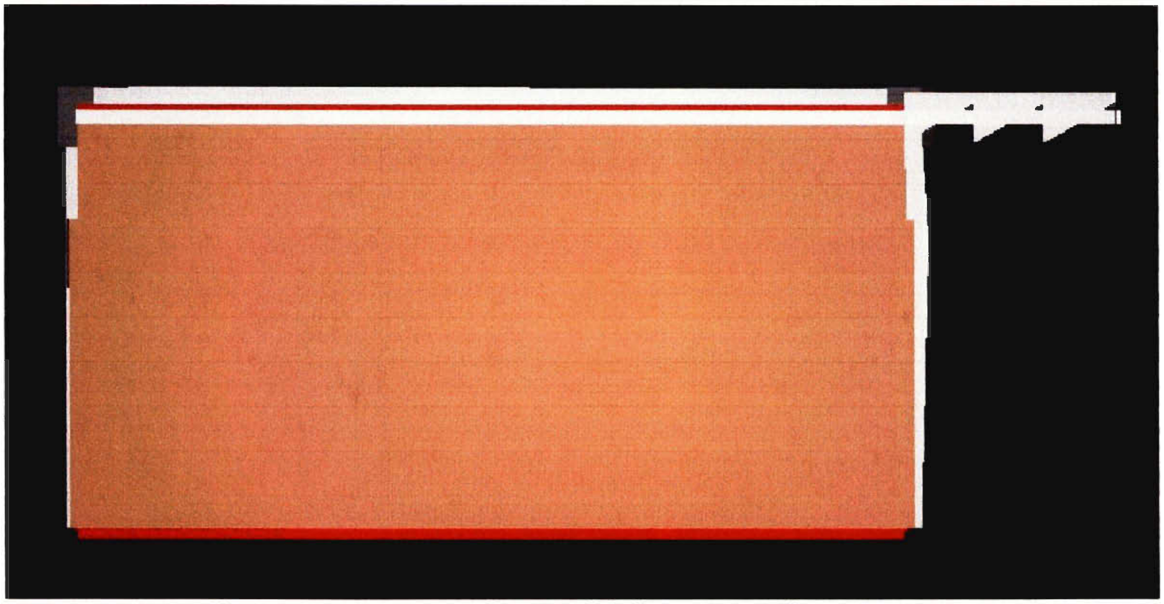


Figure 4.24: Forward Shift of SC School with Steel Bracing

Similarly, the steel bracing along the long walls provided sufficient strength to resist the applied seismic loads. Figures 4.25 and 4.26 demonstrate the improved resistance to lateral shift. The increased resistance to lateral forces and the ease of mounting steel bracing serve to justify considering this technique for retrofit.

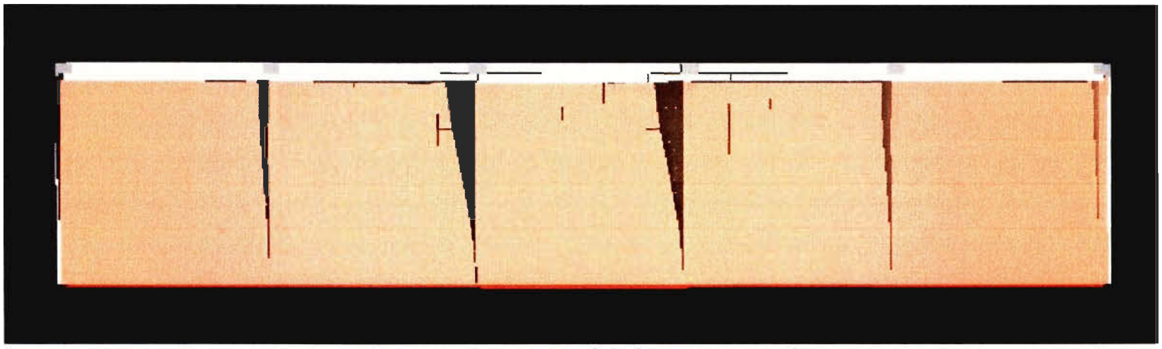


Figure 4.25: Lateral Shift of NSC School with Steel Bracing

As can be demonstrated in Figure 4.22, the seismic forces were transferred through the steel bracing to the foundation of the structure. As a result, the windows were relieved of the original forces to which they were subjected, thereby preventing them from failing.

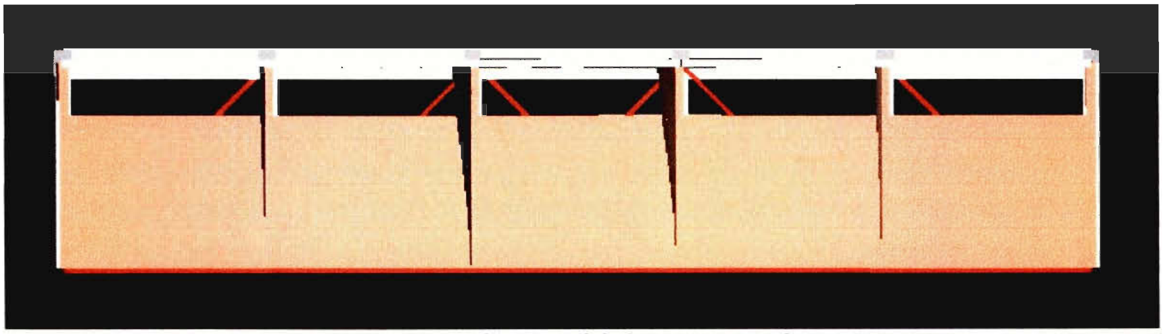


Figure 4.26: Lateral Shift of SC School with Steel Bracing

The additional strength experienced by the long walls also prevented the complete failure of the reinforced concrete slab. Instead, this slab experienced cracking over the two center columns, as indicated by the horizontal lines located directly above these members.

The steel bracing provided for these structures did not reduce the amount of buckling experienced by the interior walls of either structure. Figures 4.27 and 4.28 demonstrate the effect of steel bracing on the interior walls of the structures.

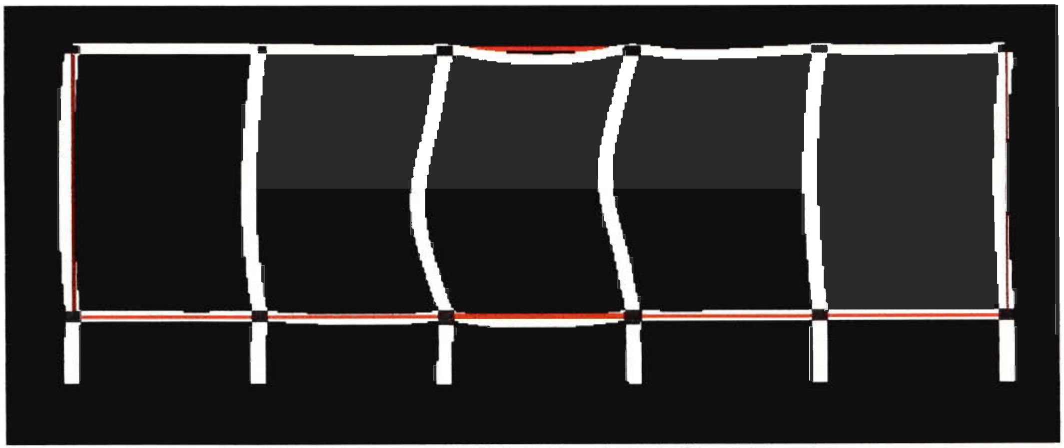


Figure 4.27: Floor Plan of NSC School with Steel Bracing

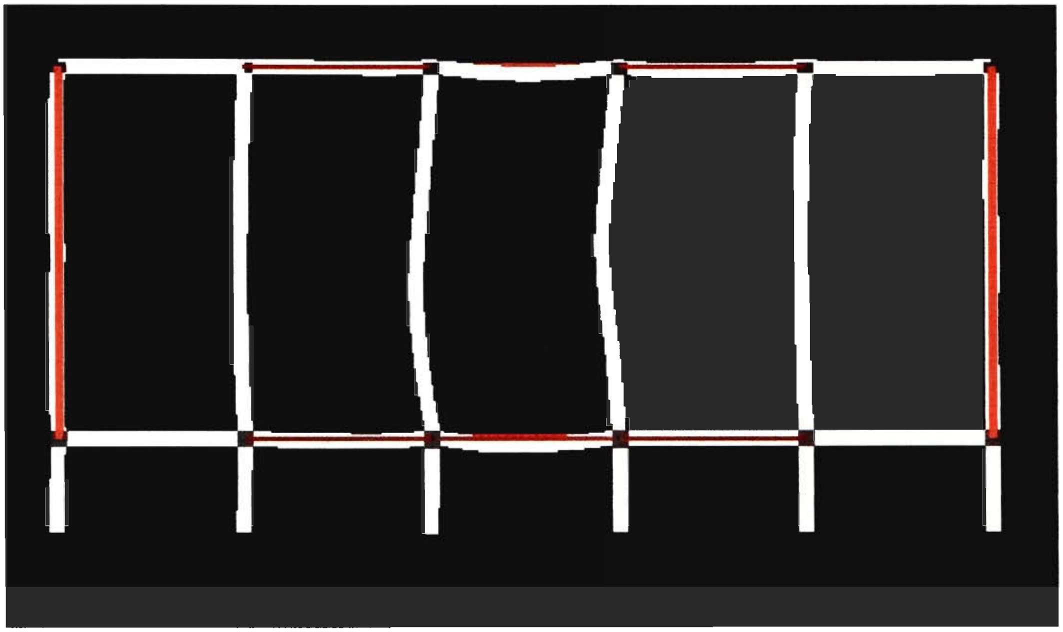


Figure 4.28: Floor Plan of SC School with Steel Bracing

This technique of retrofit did, however, prevent the columns of each structure from shifting out of their original locations.

Mounting steel bracing to the exterior of the building increased the strength of the structure, enabling it to resist the applied seismic forces. However, this method is usually only applied to the exterior of the structure; interior walls may not experience significant strengthening. This technique could be implemented without causing the displacement of the occupants. Unfortunately, this method of adding strength may compromise the aesthetic value of the structure.

4.6.3.3 Combining Steel Bracing with Shear Walls

Steel structural bracing strengthens the exterior walls of a building, while the addition of shear walls requires the presence of existing walls. Combining these two techniques allows for the strength of one method to compensate for the weakness of the other.

In order to implement a combination of steel bracing and shear walls, steel structural tubing was applied to the exterior long walls of the structures as described in section 4.6.3.2 while shear walls were constructed along the two exterior short walls and the two center walls, as described in section 4.6.3.1. Once the modification was completed, the seismic loads calculated in section 4.6.1 were reapplied to the structure.

As can be seen in Figures 4.29 and 4.30, the forward shift of the structures is greatly reduced. Nonstructural damage may be sustained by the exterior walls, as indicated by the vertical lines appearing in the walls.

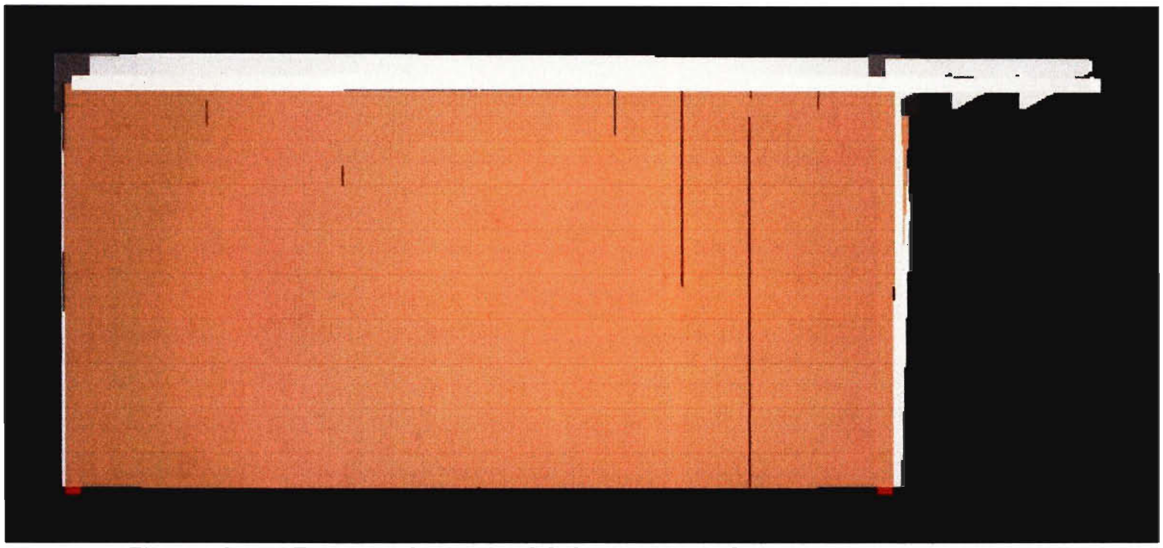


Figure 4.29: Forward Shift of NSC School with Combination of Methods

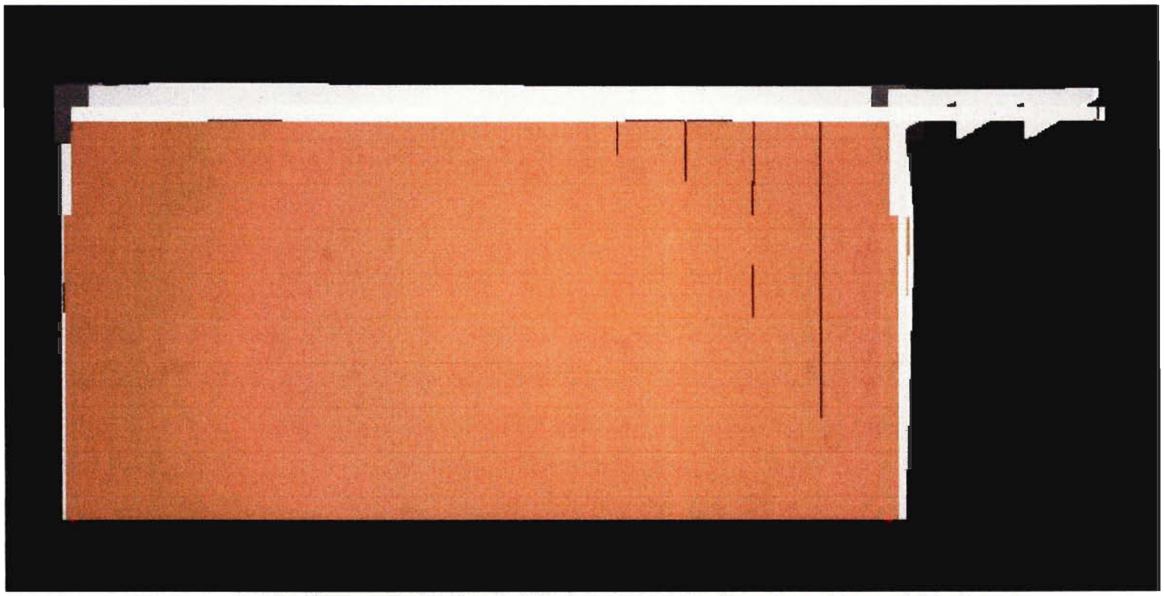


Figure 4.30: Forward Shift of SC School with Combination of Methods

Although the structures may experience cracking within the walls, the amount of damage is significantly less than that represented in Figure 4.10 and will not affect the structural integrity of the building.

The combination of the shear walls and steel bracing reduced the amount of deflection experienced by either structure, as demonstrated in Figures 4.31 and 4.32. As a result of this added strength, the windows in the SC school would not shatter and the roof would not be in danger of collapse. By eliminating these two problems, the safety of the occupants of this building has been greatly increased.

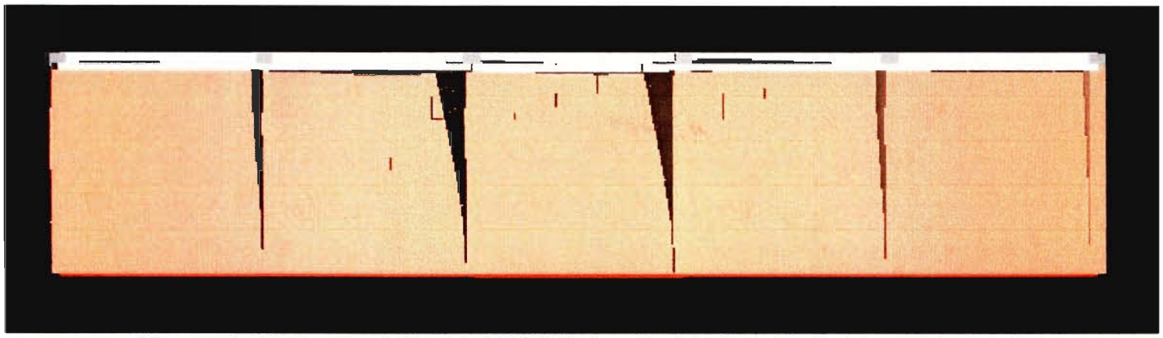


Figure 4.31: Lateral Shift of NSC School with Combination of Methods

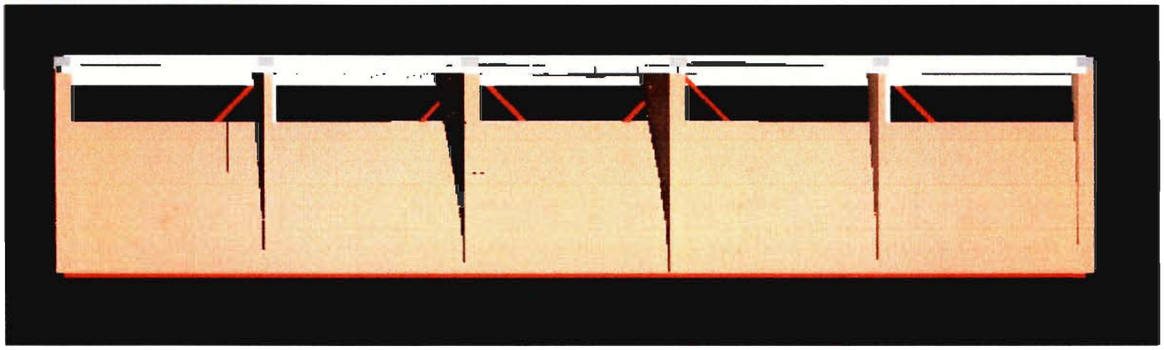


Figure 4.32: Lateral Shift of SC School with Combination of Methods

This added strength, however, did increase the amount of cracking experienced by the roof slab, as indicated by the horizontal lines appearing in both structures. More cracking would be experienced as a result of this method than as a result of steel bracing, as can be determined when comparing these buildings to those in Figures 4.21 and 4.22.

The combination of steel bracing and shear walls did prevent the shifting of the columns from their original locations, as Figures 4.33 and 4.34 demonstrate.

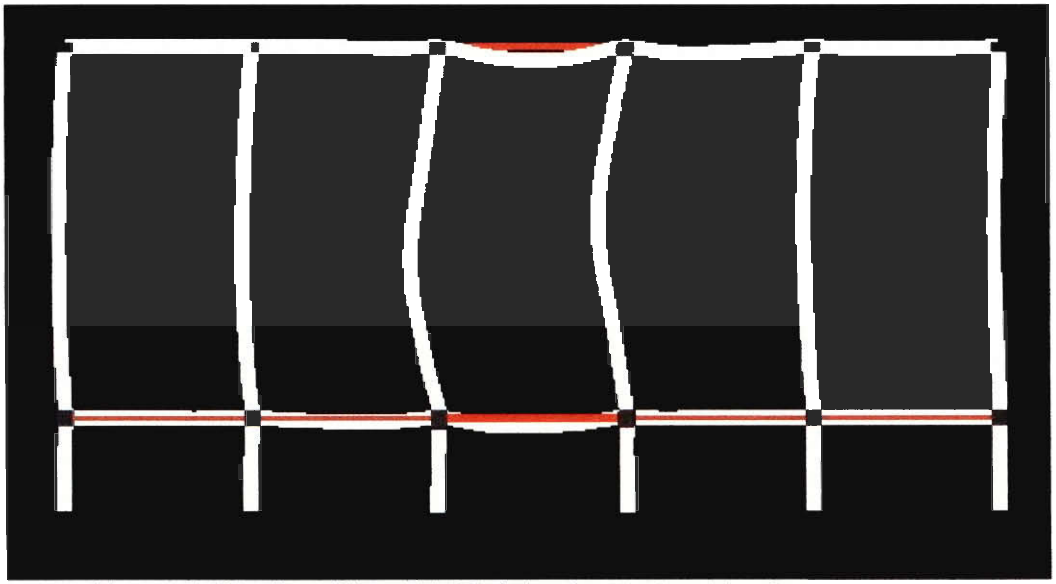


Figure 4.33: Floor Plan of NSC School with Combination of Methods

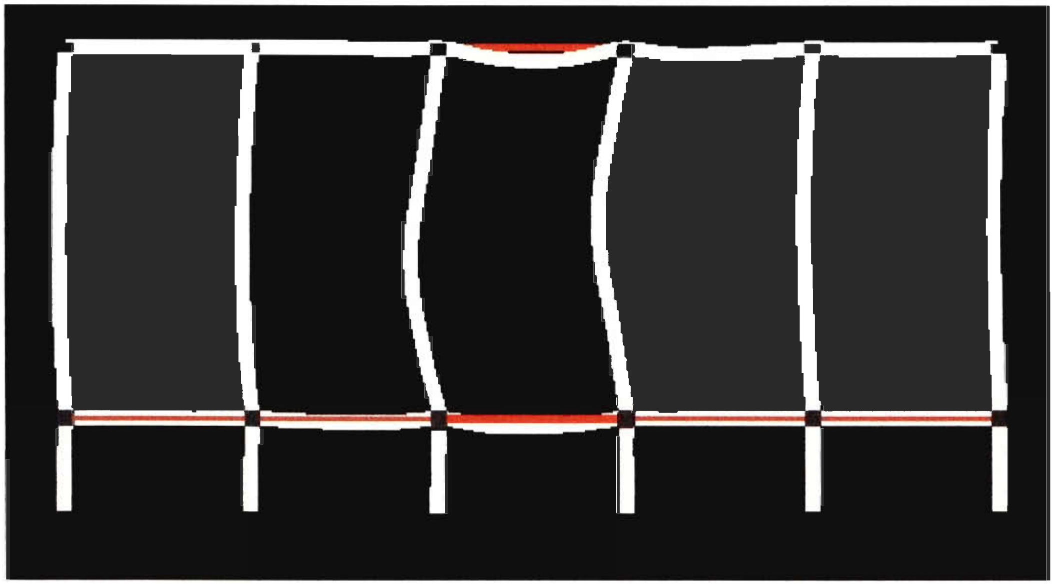


Figure 4.34: Floor Plan of SC School with Combination of Methods

However, this combination of retrofit techniques did not provide any additional resistance to the interior walls. In fact, the interior walls in Figure 4.34 deflected more than those strengthened using steel bracing alone, as was determined by comparing this figure with Figure 4.28.

This technique could not be completed without disrupting the use of the structure. However, the use of this method provides the owner of the structure with the ability to reduce the effect of steel bracing on the aesthetics of the building since steel bracing can be replaced by adding shear walls. While a combination of methods may be appropriate for other structures, this technique does not appear to be the most favorable option for strengthening this building. An additional concern would be related to the connections of the retrofit; proper connections between the masonry and the steel would need to be guaranteed in order to provide the appropriate strength.

4.6.4 Limitations of This Analysis

A more accurate analysis of this structure would require the distribution of horizontal shear forces as described in Section 1630.6 of the Code. Similarly, the horizontal torsional moments would be calculated according to Section 1630.7. An investigation into the overturning effects of each element, as described in Section 1630.8, would also be required. Due to the time constraints on the project, this analysis, while important in a detailed investigation, was not considered.

According to Sections 1630.9 and 1630.10 of the Code, limitations are placed on both the allowable drift of the structure and the specific stories. A more accurate analysis of this structure would require calculation of these limits; however, time constraints prohibited these calculations. Therefore, we limited our investigation to both a simple visual analysis of the resulting deflections.

Chapter 5: Conclusions and Recommendations

The goal of our project was to determine the feasibility of retrofitting inadequate structures to an acceptable seismic standard. By identifying areas of Puerto Rico that were susceptible to severe damage during a major earthquake, we were able to come up with conclusions and recommendations that would enable Puerto Rico to seriously consider improving the safety of public structures on the Island.

5.1 Conclusions

- Using GIS, several areas have been shown to be seismically vulnerable when examining the sandy soil composition, landslide susceptibility, and dense population. The combination of these factors will pose a major problem for disaster if a large earthquake were to strike Puerto Rico. However, the level of the water table must be determined in order to more accurately determine the seismic vulnerability of the proposed areas.
- Other vulnerable areas include rural areas. Due to the lack of laws, structural plans do not need to be provided for structures built in these areas, making retrofit nearly impossible.
- Within each analysis, the cost of lives outweighed the cost of retrofit for the buildings by a substantial amount; a small investment for the retrofit of a structure would not only save owners money, but also many lives, if an earthquake were to damage their building.
- Based on performance, relative cost, and ease of construction, steel bracing would be the best method for retrofitting the typical school structure in Puerto Rico.
- Due to the prolonged period of time without the experience of a damaging earthquake, many people on the Island are unaware of its seismic risk. We believe that this is the major reason why many building owners do not consider retrofitting to modern earthquake standards.
- Retrofitting needs to be done in Puerto Rico, but currently the desire to do it does not exist for a majority of the population living in vulnerable structures. Many people do not realize the importance of strengthening their buildings, and by providing this report, we hope to show that "an ounce of prevention is worth a pound of cure."

5.2 Recommendations

- From our analysis using GIS, we recommend further seismic vulnerability investigation of the area southeast of Caguas, the coastal area near Ceiba, and the strip of land from Moca east to Vega Alta.
- Implement a law requiring building plans to be provided in order to create a new structure.
- Retrofit each of the at-risk structures.
- Utilize steel bracing when retrofitting the typical school structure in Puerto Rico.

- Promote the following ten-step Earthquake Awareness Program:
    1. Form an earthquake awareness committee at the highest level in government, with the cooperation of insurance companies, whose goal is to actively encourage funding of earthquake education programs and to establish earthquake awareness committees in each municipality.
    2. Provide citizens of the Island with information regarding the potential for damage due to earthquakes, taking advantage of media coverage available from the 1985 Mexico City earthquake, the Kobe earthquake, and the more recent earthquakes in San Salvador and India.
    3. Begin the evaluation and retrofit of emergency structures, such as hospitals. Such actions would further reinforce the importance and necessity of retrofit.
    4. Send information pamphlets to homes of residents as well as to business owners, discussing the importance of earthquake preparedness, i.e. retrofit.
    5. Follow up pamphlets by offering informational seminars for communities, allowing residents to have their questions answered and concerns addressed.
    6. Provide necessary emergency response information regarding communications, damage assessment, first aid, safety and security, search and rescue, and sheltering and special needs to interested citizens.
    7. Organize communities into blocks of 25 – 30 homes. These committees will utilize citizen resources in time of need, yet will be directly associated with city staff. Although training will provide education and information, these committees will represent joint government-citizen involvement, allowing citizens to participate in decision-making and community improvement.
    8. Provide subsidized, or partially subsidized, consulting services to determine the seismic vulnerability of homes and businesses, enabling owners to make informed decisions regarding the strengthening of their property.
    9. Implement a variety of retrofit incentive programs to assist in the financing of retrofit work.
        a. Insurance discounts for retrofit
        b. Low-interest loans
        c. Grants for low-income homeowners
    10. Implement annual earthquake response drills to prepare all members of society to deal with the aftermath of a major disaster.

Appendix A: CSA Group Information

Dr. Fernando Fagundo, senior technical advisor of CSA Group located in San Juan, Puerto Rico, provided the following information. This information is also available at http://www.csagroup.com.

CSA Mission Statement

To transform the customers' needs into reality by supplying full project delivery capability.

CSA Group Background

The Puerto Rican operations of CSA Group began in 1956, as the Burns and Roe Group. In 1981, this company merged with Custodio and Associates, resulting in Custodio, Roe, and Associates. Roe exited the company in 1989, leaving the company as Custodio and Associates. As a result of a merger with Belcan and Suarez in 1991, the company became CSA.

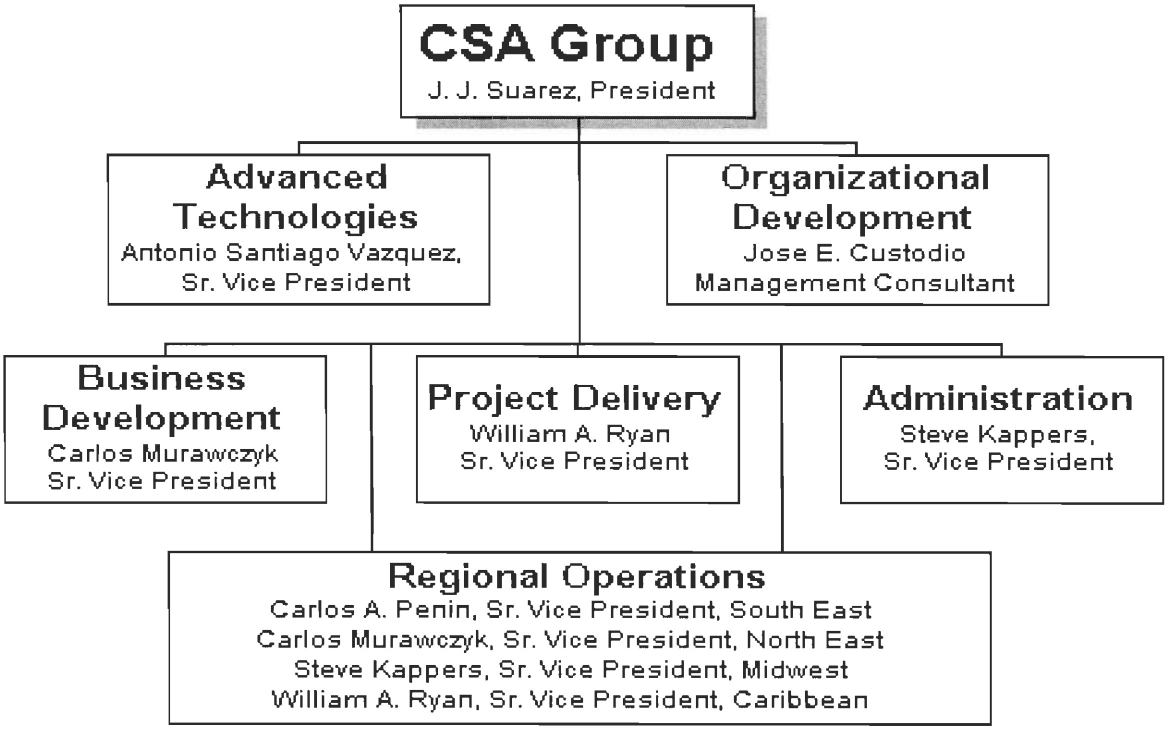
According to the 1996 Engineering News-Record, CSA Group is among the leading design and environmental engineering firms. The company has rapidly expanded from twenty-five employees in 1995 to over five hundred professionals today. They currently employ 395 people at their headquarters in San Juan and 186 people throughout their other offices in the United States. These professionals include engineers, scientists, technicians, architects, and construction managers.

CSA Group is the largest Hispanic-owned architectural/engineering firm in the United States, offering services in more than thirty disciplines. Offices are located in Atlanta, Cincinnati, Miami, Philadelphia, Panama City, and San Juan, working with both the public and private sectors on projects varying from transportation to communications, and from bio-pharmaceuticals to real estate development.

The San Juan office of CSA Group employs a variety of engineering disciplines, concentrating in civil engineering. Most of the engineers are concentrated in structural, bridge, and architectural design. Recent projects include the Guajataca Canal Rehabilitation, located in Isabela, Puerto Rico, and the Rio Mar Beach Resort, located in Rio Grand, Puerto Rico.

CSA Group has adopted a corporate philosophy that enables them to provide their clients with the best possible solutions. They instituted a Total Quality Management Leadership system that they feel allows them to often exceed clients' expectations.

CSA Group Organizational Chart



Appendix B: Model #2 Detailed Analysis and Calculations

B.1 General Model #2 Explanation

Before starting the calculations, the global damage index, D_m, must be examined. This number is assigned to a building based on its status after an earthquake. The more damaged a building is, the higher the D_m. The study used the Park–Ang model to calculate these indices. Dr. Guzman used the Taft earthquake model and amplification factors to decide on values to use for Puerto Rico. Table B.1 shows the result of this for three story buildings.

Table B.1 – Global Damage Indices for Three Story Building Prototypes

Factored intensity for Taft Earthquake	***Dm* for Buildings Constructed under 1968 Code**		***Dm* for Buildings Constructed under 1987 Code**	
	Unretrofitted	Retrofitted	Unretrofitted	Retrofitted
1.94 (2%)	0.4265	0.1823	0.222	0.0882
1.73 (5%)	0.3949	0.1626	0.1826	0.0801
1.59 (10%)	0.3598	0.1494	0.1717	0.0735
1.22 (50%)	0.3539	0.1146	0.1552	0.0565

Source: Guzman 1998

The damage index for an unretrofitted building is much higher than the value for a retrofitted building. This is because an unretrofitted building will experience more damage during an earthquake. The damage index ranges from zero to one. It is widely accepted that a value of 0.4 means a building is irreparable and needs reconstruction (Guzman, 1998).

Once the damage indices are known, Dr. Guzman's model can then be used. The equation used to calculate C_R is given by:

$$C_R := \left(1 + \rho_t\right) C_0 \cdot D_m \quad ; \quad 0 \le D_m < 0.4 \tag{B.1}$$

where ρ_t, the total repair-to-initial cost factor is:

$$\rho_t := \rho_o + \rho_d + \rho_e + \rho_c \tag{B.2}$$

Equation (4.1) is only valid when the damage index is less than 0.4, or in other words, when the building is not completely destroyed. Table B.2 summarizes the meanings and values calculated for Puerto Rico for the different ρ's.

Table B.2 – Values for ρ

Symbol	Meaning	Value for Puerto Rico
ρ_o	% Loss of Productivity Cost	70%
ρ_d	% Site Demolition and Cleanup Factor	7%
ρ_e	% Cost of Inspection and Testing for Repair or Remodeling	15%
ρ_c	% Increase in Labor and Material Costs After an Earthquake	43%

If we add up these values, we obtain 135% or 1.35 for ρ_t. If this is plugged into Equation (B.1), we obtain the following new equation for C_R, specific to Puerto Rico:

$$C_R := 2.35 C_0 \cdot D_m \quad ; \quad 0 \le D_m < 0.4 \tag{B.3}$$

When the damage index is greater than 0.4, the only ρ value that matters is the site demolition and cleanup factor. If a value of zero is used for the other ρ's, a value of 7% is obtained for the new ρ_t. If we plug this new value into Equation (B.1), the following equation is obtained:

$$C_R := 1.07 C_0 \quad ; \quad D_m > 0.4 \tag{B.4}$$

The damage index is left out of this equation because of the assumption that the building is destroyed and the D_m can be considered to be one.

The value C_C represents the loss of content for a building and, is given by the following equation used as a minimum for Puerto Rico:

$$C_C := \frac{C_0 \cdot D_m}{4} \tag{B.5}$$

The value C_0 is the total construction cost for a building and can be calculated by multiplying the area of a building by the cost to construct per unit area.

The most complicated of the four values is C_H, given by the equation:

$$C_H := R_f \cdot \left(\lambda \cdot N_D\right) \cdot \sum_{i=1}^{4} \mu_i \cdot C_{hi} \tag{B.6}$$

where:

$$R_f := e^{11.2 \cdot \left(D_m - 1.12\right)} \tag{B.7}$$

R_f is the fatality rate of a given earthquake. The floor area of a building, A, is divided into a number of different load cells called λ, which is found by:

$$\lambda := \sqrt{\frac{A - 155}{6.3}} \qquad \textbf{(B.8)}$$

The value for N_D is the number of people associated with each of these load cells. This value can be taken from Table B.3, which was created by Dr. Guzman for use in Puerto Rico. There are different percent fractiles included. A higher percent places a higher priority on life safety.

Table B.3 – People Load Statistics

Occupancy	N_D (90% Fractile)	N_D (95% Fractile)
Offices	7.29	8.65
Residential	6.29	7.65
Hotels	4.65	5.33
Retail Stores	7.29	8.65
Schools	7.29	8.65

Source: Guzman 1998

A combination of both the λ value, and the N_D value, determine how many people will be in the building at a given time. Values for μ_1- μ_4 are severity factors, which take into account different costs for different size earthquakes. Values of thirty, three, one, and one are used respectively. These μ_i values are multiplied by the C_{hi} values, which also correspond to different size earthquakes. Table B.4 summarizes the costs and meanings associated with C_{h1}-C_{h4} in 1990 U.S. dollars,

Table B.4 – C_h Values

Variable	Meaning	1998 Value	2001 Value (with inflation)
C_{h1}	Average cost of emergency treatment	$200	$221.74
C_{h2}	Average cost of hospitalization for non-disabling injuries	$3742	$4,356.63
C_{h3} Residential	Cost of retraining and pay cut over years remaining in service	NA	$125,440
C_{h3} Schools		NA	$174,628
C_{h4} Residential	Cost of human fatality	NA	$313,600
C_{h4} Schools		NA	$436,569

C_{h4} is our cost of life estimated which was previously calculated using Equation (4.1) located in section 4.3.1. According to Dr. Guzman, C_{h3} is very hard to calculate, and is usually assumed to be equal to 0.4* C_{h4}.

The final cost value to be calculated is the economic loss factor, C_E. This value takes into account rent, operating expense factors, payroll factors, and gross income. This equation assumes a rent value of $19.20 per square foot in 1998. If the inflation rate of 5.2% is applied to this value, $22.35 is obtained for 2001. This will then yield the following equation for the economic loss for residential structures only:

$$C_E := 22.35 \cdot A \cdot D_m^{\,2} \qquad \textbf{(B.9)}$$

Once all four of these values are calculated for a certain damage index, they are added together:

$$C_D := C_R + C_C + C_H + C_E \qquad \textbf{(B.10)}$$

The final inequality that is used to decide whether to retrofit or not is given as follows:

$$E(C_D)_{\text{unretrofitted}} > E(C_D)_{\text{retrofitted}} + AC_U \qquad \textbf{(B.11)}$$

These two equations state that if the cost of damage to an unretrofitted structure exceeds the cost of damage to a retrofitted structure plus the retrofit cost, then the building should be retrofitted. This part of the model associated different probabilities with different damage indexes. In total, eight damage index values are used for these calculations, four calculated for each of these retrofitting situations.

Table B.5 shows the probabilities of damage that is associated with each D_m value.

Table B.5 – Damage Index Probabilities

Damage Index Unretrofitted	**Damage Index Retrofitted**	**Probability**
0.4265	0.1823	0.04
0.3949	0.1626	0.06
0.3598	0.1494	0.1
0.3539	0.1146	0.8

These probabilities are then multiplied by the present worth factor R_D, which is dependent on to which area of the world the equation is being applied. According to Dr. Guzman, a value of 0.20 is assumed for Puerto Rico.

The final value that is calculated before using the final equation is C_U, the retrofitting cost per square foot. This value is a product of five costs:

$$C_U := C_1 \cdot C_2 \cdot C_3 \cdot C_L \cdot C_T \tag{B.12}$$

C_1 is the building group mean cost, and in 1998 had a value of \$18 per square foot. C_2 is the floor adjustment factor, whose values are listed in Table B.6.

Table B.6 – Floor Adjustment Factor

Building Size	Area (sq. ft)	Area Adjustment Factor, C2
Small	Less than 10,000	1.09
Medium	10,000 - 49,999	1.06
Large	50,000 - 99,999	1.01
Very Large	100,000 or more	0.84

Source: Guzman 1998

C_3 is the seismicity/performance objective adjustment factor. Typical values for C_3 range from 0.70 for life safety to 1.40 for immediate occupancy. C_L is the location adjustment factor and is assumed to be 0.91 for Puerto Rico. Finally, C_T is the time adjustment factor, which considers inflation. After doing this, the C_U is multiplied by the total area of the structure and R_D. R_D, which has a value of 0.2, is used to deflate the final cost values for Puerto Rico. The final equation can now be stated as:

$$0.2 \cdot \left(0.8 \cdot C_{D0.3539} + 0.1 \cdot C_{D0.3598} + 0.06 \cdot C_{D0.3949} + 0.04 \cdot C_{D0.4265}\right) > 0.2\left(0.8 \cdot C_{D0.1146} + 0.1 \cdot C_{D0.1494} + 0.06 \cdot C_{D0.1626} + 0.04 \cdot C_{D0.1823} + A \cdot C_U\right) \tag{B.13}$$

In this equation, the subscripts on the C_D values represent different damage indexes. If this mathematical statement becomes true, then the building should be retrofitted.

B.2 Residential Structure Calculations

For residential structures, we took the model that was created by Dr. Guzman, and applied it to an average residential structure for Puerto Rico. For these calculations, we assumed an average square footage of twelve hundred. The cost of construction, C_0, was then found by multiplying the square footage by the cost of construction per square foot. We applied inflation calculations to the value of \$51 per square foot proposed by Dr. Guzman to obtain a value of \$59.38 dollars per square foot. C_0 was then found to be \$71,252. After applying the damage indexes in Table B.1 to the Equation (B.7) for R_f, we obtained the values shown in Table B.7.

Table B.7 – R_f for Residential Buildings

Damage Index	**R_f**
0.4265	0.000423397
0.3949	0.000297196
0.3598	0.000200592
0.3539	0.000187765
0.1823	2.74748E-05
0.1626	2.2035E-05
0.1494	1.90067E-05
0.1146	1.28717E-05

If we plug in our area of twelve hundred square feet into Equation (B.8), we obtain a value of approximately 12.88 for λ. After looking at Table B.3, we determined that the N_D value for residential structures was 6.29, using the 90% fractile. When calculating C_U, we used eighteen dollars for C_1, as discussed by Dr. Guzman. Table B.6 produced a value of 1.09 for C_2, while a moderate value of 0.85 was used for C_3. For Puerto Rico, Dr. Guzman's study suggested using a value of 0.91 for C_L. Finally, an inflation value of $(1.052)^3$, or 1.164, was applied to C_T. After multiplying these five numbers together, a value of $17.67 was obtained for C_U.

Once all of the values for the constants were calculated, we were ready to calculate the four cost values for the eight different damage indices. These thirty-two cost values are shown in Table B.8.

Table B.8 – Residential Structure Cost Variables Values

Damage Index	C_U	C_C	C_H	C_E
0.4265	$32516.32	$7165.2	$14794.08	$4879.41
0.3949	$66123.16	$6634.32	$10384.43	$4183.15
0.3598	$60245.92	$6044.64	$7008.94	$3472.57
0.3539	$59258.01	$5945.52	$6560.76	$3359.62
0.1823	$30524.82	$3062.64	$960.00	$891.46
0.1626	$27226.20	$2731.68	$769.93	$709.20
0.1494	$25015.95	$2509.92	$664.12	$598.72
0.1146	$19188.94	$1925.28	$449.75	$352.28

The numbers corresponding to the same damage index were added together to get the values shown in Table B.9 for C_D.

Table B.9 – C_D Values for Residential Structures

Damage Index	C_D (US Dollars)
0.4265	$60728.27
0.3949	$88385.77
0.3598	$77582.48
0.3539	$75899.83
0.1823	$35684.69
0.1626	$31650.72
0.1494	$28982.32
0.1146	$22060.97

Finally we substituted these damage costs into Equation (B.13) and obtained the following inequality:

$$\$16{,}004.18 > \$9{,}253.93$$

This showed us that on average, a residential structure in Puerto Rico should be retrofitted because the mathematical statement is true. This statement means that there would be $16,004.18 in damage to an unretrofitted structure, while there is only $9,253.93 in costs, including the retrofitting cost, to a structure which has undergone retrofitting.

B.3 School Building Calculations

We also applied Dr. Guzman's model to schools in Puerto Rico. For these calculations, we used a square footage of 2242 sq. ft. The cost of construction remained $59.38 dollars per square foot. Therefore, C_0 for schools was found to be $133,123. The values for R_f were the same as shown in Table B.7. When we plugged in our area of 2242 square feet into Equation (B.8), we obtained a value of approximately 18.20 for λ. After looking at Table B.3, we determined that the N_D value for schools was 7.29, using the 90% fractile. A value of $17.67 was still used for C_U.

The cost of life value that was used for schools was more complicated to come up with than it was for the residential structures. The 123,930 students worth a value of $441,000 each, and the 5,543 teachers worth $337,500 had to be weighted against the total population of 129,473 in vulnerable schools. After doing this, a value of $436,570 was obtained for the average cost of life in schools.

The cost values were then recalculated for and are shown in Table B.10.

Table B.10 – School Structure Cost Variable Values

Damage Index	C_U	C_C	C_H	C_E
0.4265	$60751.33	$14194.24	$35443.76	$0.00
0.3949	$123540.11	$13142.57	$24879.08	$0.00
0.3598	$112559.47	$11974.41	$16792.08	$0.00
0.3539	$110713.72	$11778.05	$15718.33	$0.00
0.1823	$57030.55	$6067.08	$2300.00	$0.00
0.1626	$50867.62	$5411.45	$1844.61	$0.00
0.1494	$46738.14	$4972.14	$1591.10	$0.00
0.1146	$35851.35	$3813.97	$1077.53	$0.00

The C_E values were all zero because there is no economic loss from a school, since it is a non-profit organization. The numbers corresponding to the same damage index were added together to get the values shown in Table B.11 for C_D.

Table B.11 – C_D Values for Schools

Damage Index	**C_D (US Dollars)**
0.4265	$99176.39
0.3949	$153691.04
0.3598	$136013.63
0.3539	$133237.47
0.1823	$64669.99
0.1626	$57540.11
0.1494	$52798.03
0.1146	$40401.96

Finally we substituted our numbers into Equation (B.13) again and obtained the following inequality:

$$\$29,150.09 > \$17,168.51$$

This showed us that the schools should be retrofitted because the mathematical statement is true.

Key Terms

Aramid – The generic name for an aromatic polymide polymer derived from petroleum, produced under the trade name of Kevlar in the US, Arapree in Europe and Technora in Japan

Bent – A planar framework designed to resist both vertical and horizontal forces in the plane of the frame

Braced Frame – Any framework braced against lateral forces, often used to describe a frame braced by trussing

Cantilever – A projecting structure, such as a beam, supported at only one end

Couple – Two forces of the same magnitude separated by a distance

Critical Damping – The amount of damping that will result in a return from initial deformation to the neutral position without reversal

Dead loads – Permanent loads due to gravity, including the weight of the structure itself

Diaphragm – A surface element used to resist forces in its own plane by spanning or cantilevering

Dual Bracing System – Combination of a moment-resisting space frame and shear walls or braced frames, with the combined systems designed to share the lateral loads

Elastic – Used to describe two aspects of stress-strain behavior.

1 – A constant stress-strain proportionality, or constant modulus of elasticity, as represented by a straight line of the stress-strain graph

2 – The limit within which all the strain is recoverable; no permanent deformation

Factored Loads – A percentage of the actual service load, usually an increase, used for strength design

Fault – The subterranean effect that produces an earthquake; usually slippage, cracking, sudden release, etc.

Lateral Force Resistive System – The combination of elements of the building construction that contributes directly to the general bracing of the building against lateral forces

Live loads – Any load component that is not permanent, including those due to wind, seismic effects, temperature changes, or shrinkage

Loads – The forces, or combination of forces, exerted on a structure

Load Path – The means by which applied forces flow through a structure and are resolved by its supports.

Member – One of the distinct elements of a structure

Moment – Bending resulting from equal and opposite couples acting in the same longitudinal plane

Multiple Load Paths – Refers to structures with redundancy in the form of backup load resistant paths that can take over when the initial load path elements fail

Occupancy Importance Factor – Term used in the basic equation for seismic force. Expresses potential for increased concern for certain occupancies

Overturn – The toppling, or turning over, effect of lateral loads

Redundancy – Refers to the existence of multiple load paths

Reinforced Concrete – Concrete with steel bars embedded in such a way that the tension forces needed for moment equilibrium can be developed in the bars after the concrete cracks

Retrofit – Refers to the task of bringing and existing object into conformance with recent, typically more stringent, standards

Rigid Frame – Framed structure in which the joints between the members are made to transmit moments between the ends of the members

Safety Factor – The ratio of the resisting capacity of a structure to the actual demand on the structure

Seismic – Pertaining to ground shock

Seismic Gap – An area that compared to the surrounding areas, has had little seismic activity

Separation Joint – Connection between adjacent parts of a building that allows for some controlled movement of the separate joints

Service Loads – The total load combination that the structure is expected to experience in use

Shear – A condition in or deformation of an elastic body caused by forces that tend to produce an opposite but parallel sliding motion of the body's planes

Shear Wall – A vertical diaphragm, used to brace the building against horizontal forces due to wind or seismic shock

Soft Story – In a multistory structure, refers to a story level whose lateral stiffness is significantly less than that of its adjacent stories

Torsion – Moment effect involving twisting or rotation in a plane perpendicular to the major axis of an element. Lateral loads produce torsion on a building when they tend to twist about its vertical axis. This occurs when the centroid of the load does not coincide with the center of stiffness of the vertical elements of the lateral load-resisting structural system

Uplift – Net upward force effect due to wind, to overturning moment, or to upward seismic acceleration

Weak Story – In a multistory structure, a story level whose lateral strength is significantly less than that of the adjacent stories

References

Aguilar, J., Juarez, H., Ortega, R., and Iglesias, J. (1989). The Mexico Earthquake of Sept. 19, 1985- Statistics of Damage and of Retrofitting Techniques in Reinforced Concrete Buildings Affected by the 1985 Earthquake. Earthquake Spectra-The Professional Journal of the Earthquake Engineering Research Institute, 5(1), 145-151.

Ambrose, J. & Vergun, D. (1999). Design for Earthquakes. New York: John Wiley & Sons, Inc.

Arthur, W. B. (1981). The Economics of Risks to Life. The American Economic Review, 71(1), 54-64.

Army Corps of Engineers (1996). Engineering Reconnaissance Report for the Catastrophic Earthquake Plan.

Augusti, G., and Ciampoli, M. (2000). Heritage Buildings and Seismic Vulnerability. Progress in Structural Engineering Materials, 2(2), 225-237.

Bayles, Michael D. (1978). The Price of Life. Ethics, 89(1), 20-34.

Benedetti, D., Benzoni, G., and Parisi, M.A. (1988). Seismic Vulnerability and Risk Evaluation for Old Urban Nuclei. Earthquake Engineering and Structural Dynamics, 16, 183-201.

Bolt, Bruce A. (1993). Earthquakes. NewYork: W. H. Freeman and Company.

Breyer, D. E., Fridley, K. J., & Cobeen, K. E. (1999) Design of Wood Structures: ASD. (4th ed.). New York: McGraw-Hill.

Brumbaugh, David S. (1999). Earthquakes: Science and Society. Upper Saddle River: Prentice Hall.

Central Intelligence Agency (2000). The World Factbook. Accessed through the World Wide Web on January 22, 2001 from: http://www.odci.gov/cia/publications/factbook/geos/rq.html#Econ

CSA Engineering, Inc. (2001). Tuned-Mass Dampers for Vibration Control. Accessed: February 16, 2001 http://www.csaengineering.com/tmd.html.

Daza, Luis Guillermo (1996). Methodology to Evaluate Existing Reinforced Concrete Frames Under Earthquake Loads. University of Puerto Rico, Mayagüez.

Denning, James. (1993, February). Seismic Retrofitting: Spending to Save. Civil Engineering. 48-51.

DiJulio, R. (1989) Static Lateral-Force Procedures. In F. Naeim (Ed.), The Seismic Design Handbook. (pp. 119-141). New York: Van Norstrand Reinhold

Emmons, P.H., Thomas, J., Vasyburd, A.M. (1998, January). Muscle Made With Carbon Fiber. Civil Engineering. 60-61.

Flores, Albert (1980). Ethical Problems in Engineering. Troy, NY: Center for the Study of Human Dimension of Science and Technology at Rensselaer Polytechnic Institute.

Freytes, Jose Molinelli (2000, November 30—last update). Earthquake History of Puerto Rico. Puerto Rico Civil Defense. Accessed: January 17, 2001 http://neic.usgs.gov/neis/states/puerto_rico/puerto_rico_history.html

Guzman, Alberto Luis (1998). Cost-performance Criteria For Seismic Retrofitting. University of Puerto Rico, Mayagüez.

Hamilton, H.R., & Dolan, C.W. (2000) Durability of FRP Reinforcements for Concrete Progress in Structural Engineering and Materials, 2(2), 139-145.

International Conference of Building Officials (1997). Uniform Building Code. Whittier, California. Volume 2.

International Code Council (2000). International Building Code. Whittier, California.

Lavelle, Marianne (1988, October 10). Placing a Price on Human Life; A Legal Puzzle. The National Law Journal [Online], 1-7. Available: Lexis-Nexis Electronic Database. [2001, January 24].

Lomnitz, Cinna (1994). Fundamentals of Earthquake Prediction. New York: John Wiley & Sons, Inc.

Mogi, Kiyoo (1985). Earthquake Prediction. New York: Academic Press.

Morlan, Kent (2000). Jury Verdicts and Settlements. Tulsa: Morelaw.com Inc. Accessed through the World Wide Web on February 4, 2001 from: http://www.morelaw.com/verdicts/index.asp

Mostaghel, N., Hejazi, M., Khodaverdian, M. (1986). Response of Structures Supported on Resilient-Friction Base Isolator (R-FBI). 3rd U.S. National Conference on Earthquake Engineering: Charlton, South Carolina, 3, 1993-2003.

Multidisciplinary Center for Earthquake Engineering Research (2000, December 28). Guide to International Seismic Codes. MCEER. Accessed: February 17, 2001 http://mceer.buffalo.edu/infoService/bibs/intcodes.asp

Nateghi-A. F. (1995). Retrofitting of Earthquake-Damaged Steel Buildings. Engineering Structures, 17(10), 749-755.

National Earthquake Information Center (2001). Geological Hazards. USGS. Accessed: January 21, 2001 http://neic.usgs.gov/neis/eqlists/eqstats.html

National Geophysical Data Center (2001a). Results of Earthquake Intensity Data Search. Accessed:February 17, 2001 http://www.ngdc.noaa.gov:8800/seg/plsql/eqi.results

National Geophysical Data Center (2001b). NGDC Natural Hazard Slides. Accessed: March 23, 2001 from http://nndc.noaa.gov/cgi-bin/wt/nndcp/ShowDatasets?bt_SDE_USER.COLLECTION_AND_SET.COLLECTION_ID=&st_SDE_USER.COLLECTION_AND_SET.COLLECTION_ID=&EQ_SDE_USER.COLLECTION_AND_SET.COLLECTION_ID=5&submit_SDE_USER.COLLECTION_AND_SET.COLLECTION_ID=Select+Using+Slide+Set+Collection+ID&query=++&dataset=100024&search_look=0&display_look=1&source_id=3

Neale, K.W. (2000). FRPs for Structural Rehabilitation: A Survey of Recent Progress. Progress in Structural Engineering and Materials, 2(2), 133-138.

Puerto Rico Seismic Network (2001). 2000 Monthly Seismicity. University of Puerto Rico. Accessed: January 17, 2001 http://rmsismo.upr.clu.edu/ingles/PRSN-Seismicity.html#2000

Reinhorn, A.M., Manolis, G.D., and Wen, C.Y. (1986). Control of Structures by Coupling Rubber Isolators and active pulses. 3rd U.S. National Conference on Earthquake Engineering: Charlton, South Carolina, 3, 1899-1909.

Robinson Seismic Limited (2001). Lead Rubber Bearing. Accessed: February 16, 2001 http://www.robinson-seismic.co.nz/products/lrb.html.

Rowan, Williams, Davis and Irwin Inc. (2001). RWDI Damping Systems. Accessed: March 26, 2001 from http://www.rwdi.com/html/archeng/exp/dampingsystems.asp

Seible, F., and Karbhari, V. (1996, August). Advanced Composites Build on Success. Civil Engineering, 44-47.

Shepard, R., and Platt, C.M. (1986). Economic Aspects Involved in Retrofitting a Commercial Building. 3rd U.S. National Conference on Earthquake Engineering: Charlton, South Carolina, 3, 1947-1958.

Social Security Administration (2001). Social Security Online. Accessed through the World Wide Web on April 16, 2001 from: http://www.ssa.gov/.

Takenaka Corporation (2001). Base Isolation System. Accessed: March 26, 2001 from http://www.takenaka.co.jp/takenaka_e/quake_e/menshin/menshin.htm

United States Geological Survey (2001). Earthquake Effects and Experiences. Accessed: March 26, 2001 from http://earthquake.usgs.gov/faq/effects.html

USDOT; U.S. Department of Transportation, Federal Highway Administration. (1991). The Cost of Highway Crashes (Publication No. FHWA-RD-91-055). McLean, Virginia; Research and Development U.S. Government Printing Office.

Zenitaka Corporation (2001). Zenitaka's Base Isolation Structural System. Accessed: March 26, 2001 from http://www.zenitaka.co.jp/tech/mensin.html