WEIGHING THE FINANCIAL AND SUSTAINABLE BENEFITS OF HIGH
PERFORMANCE STRUCTURES IN SEISMICALLY ACTIVE REGIONS

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by

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ABSTRACT

Weighing the Financial and Sustainable Benefits of High Performance Structures in Seismically Active Regions

Alia Talina Barajas

This thesis investigated the potential advantages and disadvantages of high performance structures by comparing the financial and environmental impacts of a *performance based* four-story office building to one designed to meet minimum code-level requirements.

To generate a comparison, the lateral system of a four-story structure utilizing buckling restrained braced frames was designed to meet code-level requirements per the American Society of Civil Engineers' *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-05) and again to meet the immediate occupancy criteria defined by ASCE 41-06 *Seismic Rehabilitation of Existing Buildings*. The following was then performed:

- Test the structural performance of both buildings using simulated code-level and maximum considered earthquakes
- Develop construction costs of both structures using RSMeans *Square Foot Cost* and *Construction Cost Data*
- Determine the financial benefit associated with the upgraded structure by subjecting both structures to a suite of earthquakes
- Calculate the carbon footprint generated during each building's construction.

The final project costs for the code level and immediate occupancy structures were \$27.43 million and \$27.93 million respectively, resulting in an upgrade cost of \$500,000 or roughly 1.8% of the overall project cost. The upgrade cost was then input in FEMA's Benefit-Cost Analysis, where it found the upgrade cost resulted in an annual savings ranging from \$43,000 to \$98,000 over the building's 50-year life cycle.

The carbon footprints were generated using BuildingScope, which relies on volumetric quantities of construction materials. The final models resulted in a carbon footprint of 7890 CO₂ eq and 7940 CO₂ eq for the code level and immediate occupancy structures respectively, showing favor for the structure utilizing fewer materials.

Although the additional materials used in the immediate occupancy structure resulted in a slightly larger carbon footprint, the added capacity will decrease damages, resulting in an overall reduction of energy generated during the building's life cycle.

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LIST OF NOMENCLATURE

BCA	Benefit-Cost Analysis
BCR	Benefit-Cost Ratio
BRBF	Buckling-Restrained Braced Frame
BSE-1	Basic Safety Earthquake –1
BSE-2	Basic Safety Earthquake – 2
DCR	Demand-to-Capacity Ratio
DFA	Damage Frequency Assessment
FEMA	Federal Emergency Management Agency
GHG	Greenhouse Gas
IBC	International Building Code
IO	Immediate Occupancy
LFRS	Lateral Force Resisting System
LS	Life-Safety
NEHRP	National Earthquake Hazards Reduction Program
PBD	Performance-Based Design
PGA	Peak Ground Acceleration
UBC	Uniform Building Code
USGS	United States Geological Survey

1.0 INTRODUCTION

Recent major earthquake have shown the importance of appropriate structural engineering in seismically active regions. While many structures were robustly designed for daily use, many suffered significant damage from large earthquakes resulting in severe economic devastation. These events pose the question, would it be more beneficial to design structures that surpassed the code level requirements?

The purpose of this thesis is to develop a financial and environmental comparison between high-performance structures and those designed to meet the minimum standards required by the International Building Code (IBC). The goal of the financial comparison is to determine if higher performance structures will have lower life-cycle costs over a 50-year life span than those requiring major repairs after experiencing an earthquake. The financial assessment was based on the difference in initial construction cost and repair costs, and the number of injuries and deaths resulting from an earthquake. In addition to the monetary assessment, an environmental comparison was made to evaluate each structure's *carbon footprint*. The software used for the financial risk assessment was Benefit-Cost Analysis (BCA) and BuildingScope. BCA is an application developed by the Federal Emergency Management Agency (FEMA) used by planners for financial assessments for a given environmental hazard, BuildingScope is software developed by CleanMetrics and is used to develop the carbon footprint of buildings.

2.0 BACKGROUND

The idea for this thesis was inspired by former California Polytechnic State University graduate student, David Carmona's thesis, "Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design." Mr. Carmona's thesis investigated the financial benefits of high performance moment frame structures by comparing two versions of one building, one designed for code level performance (*life-safety* or LS) and the other for higher performance (*immediate occupancy* or IO) (Carmona 2011). The software Mr. Carmona used for the cost and risk analysis was a pre-beta version of Performance Assessment Calculation Tool (PACT), the companion software to Applied Technology Council's (ATC) *Guidelines for Seismic Performance Assessment of Buildings* (ATC-58, 2009). Unfortunately, Mr. Carmona concluded that until ATC releases a final version of PACT, the results were too inconsistent to be considered reliable.

This thesis applied the same concepts used in Mr. Carmona's work to investigate a structure utilizing buckling restrained braced frames (BRBF's) as the lateral force resisting system (LFRS). The results for this type of study can vary greatly depending on the type of system used in the structure, which is why the use of the different LFRS is so crucial. Some systems, such as the special moment frames used in Mr. Carmona's research, are more flexible leaving the building and its contents susceptible to drift related damages, while others (such as BRBF's) are significantly stiffer. If multiple

lateral systems produce similar results, then a generic response can be made either in favor of or against the investment of higher performance structures.

3.0 PROJECT OVERVIEW

This thesis is divided into five parts: the structural design, dynamic analysis, cost analysis, financial risk assessment, and carbon footprint comparison. The structural design and analysis were conducted by developing a preliminary code level design using the American Society of Civil Engineers' *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-05) and then modifying the design to meet the life safety (LS) performance objectives defined by the American Society of Civil Engineer's *Seismic Rehabilitation of Existing Structures* (ASCE 41-06). The second design was developed by upgrading the code level structure to meet the higher performance criteria of an immediate occupancy (IO) performance level. Costs for both structures were developed using RSMeans reference materials in conjunction with contacting companies for specialty items. The financial risk analysis was conducted by applying the final structural costs in FEMA's software Benefit Cost Analysis (BCA) to determine whether the upgrade would be financially justifiable for the given location. The carbon footprints for each structure were developed using CleanMetrics' software BuildingScope which was used to calculate the carbon footprint developed during construction.

3.1 Structural Design

According to ASCE 7-05, the goal of a code level structure is to resist forces so that it can protect the lives of its inhabitants. Because the primary goal of a code level structure is to prevent loss of life but not to limit damage to the structure, many buildings designed for this level may require replacement or extensive repairs after an event. This

thesis investigated the cost effectiveness of a higher performance structure by comparing an office building designed to meet a code level, or LS performance level, to one designed to meet IO performance criteria. Although the two structures were designed to meet specific performance levels, the goal of this thesis is not to recommend an IO performance level as the basis for new design criteria. The goal is simply to investigate a performance level that exceeds code level design requirements.

The structure's performance levels were determined by assessing the damage experienced after being subjected to two earthquakes, a *Basic Safety Earthquake – I* (BSE-1) and *BSE-2*. As defined in American Society of Civil Engineers' *Seismic Rehabilitation of Existing Buildings* (ASCE 41-06), a BSE-1 is an earthquake with a 10% chance of occurrence within a 50-year period, and is used to generate seismic forces in a code level design. A BSE-2, or "maximum considered earthquake," is an earthquake with a 2% chance of occurrence within a 50-year period, and generates forces 1.5 times greater than those generated by a BSE-1. A code level structure should experience significant damage after a BSE-2 while still maintaining enough structural integrity to protect the building inhabitants. A structure designed to meet the higher IO criteria will experience significantly less damage after a BSE-2, and should still maintain enough strength to be considered an LS structure.

The structure selected for this study was the Student Services & Administration Building at California State University, East Bay in Hayward, California (Figure A). The original structure is four-stories with a penthouse, and has a footprint of approximately

23,500 sq. ft. The building is fairly rectangular and uses steel framing to resist gravity loads (building self-weight and weight of inhabitants and building contents). The lateral force resisting system (LFRS) consists of buckling-restrained braced frames (BRBF) in both the east-west and north-south directions (Figure B shows a typical floor plan of the structure). For this thesis, the penthouse was removed and the structure was relocated to San Francisco, California. The penthouse was excluded to allow for a simplification in the design and analysis, and the relocation allowed the conclusions to be compared to Mr. Carmona's study (Section 3.3).

Figure A: CSU East Bay Student Administration & Services Building
Source: Elward Systems Corporation

Figure B: Typical Framing Plan

Source: Author

To ensure the most effective design, the final layout consisted of five different LFRS frame configurations in the north-south direction for the code level design and the higher performance design. Both designs had only one configuration in the east-west direction. The code level braces were designed to meet ASCE 7-05 criteria, while the high performance braces were initially sized using ASCE 7-05 criteria upgraded to meet the demands from the BSE-2 level forces. Once the brace sizes in both structures were determined, the column and beams were sized to meet the brace capacities. This step was

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particularly crucial due to the fact that the brace is the primary element in the lateral system, and is expected to yield first. If the beams and/or columns were to fail before the braces, the structure would fail prematurely while leaving the braces intact. The final brace elevations for both the code level and high performance designs are shown in Figures C, D and E.

Figure C: Lateral System Elevation in the North-South Direction

Source: Author

Figure D: Lateral System Elevation in East-West Direction

Source: Author

The footings for the code level and high performance buildings were designed per standard of practice so that the code level footing designs met demand requirements from BSE-1 forces, and the high performance footing designs met the demand of BSE-2 forces. Although both systems were designed for different performance levels, the most cost effective layout for both systems incorporated square footings with grouted anchors. Grouted anchor capacities were assumed based on a nearby project's geotechnical data, resulting in a 100 kip capacity for a 25 foot grouted anchor (1-3/4 inch diameter). The

high capacity of each footing along with the standard of practice minimum of two anchors per footing resulted in a design that was the same for the two systems. The footing layout is shown in Figure E.

Figure E: LFRS Foundation Plan

Source: Author

3.2 Dynamic Analysis

The *linear dynamic procedure* per ASCE 41-06 was used to evaluate each structure's performance level. The linear dynamic procedure applies a response spectra defined by ASCE 41-06 § 1.6.1.5.1 to predict the demand and associated damage experienced by a structure for a given BSE-1 and BSE-2 earthquake. Both response

spectra are shown below in Figure F, and were determined using the design spectral accelerations at 0.20 (S_{DS}) and 1.0 (S_{D1}) seconds along with an assumed damping of 5%.

Figure F: ASCE 41-06 Response Spectra

Source: Author

The expected damage is determined by comparing the demand-to-capacity ratios (DCR) of the members in the lateral system to modification factors, or m-factors, provided by ASCE 41-06, which account for inelastic behavior. In order to meet a performance level, the DCR must fall within the appropriate m-factor ranges. For example, a structure designed to meet the LS performance level must have DCR's that fall between the IO and LS limits. It should be noted however that ASCE 41-06 does not

have m-factors specifically for BRBF's. Because the braces in a BRBF system are expected to yield due to axial loads, the selected m-factors were for braces in tension.

The m-factor values used in this thesis are shown in Table 1.

	Immediate Occupancy	Life-Safety	Collapse Prevention
Braces	1.25	6.00	8.00

Table 1: ASCE 41 m-factors

Source: ASCE 41-06

3.2.1 Performance Based Design Using ASCE 41-06 Methodology

An initial topic of discussion during this thesis was the choice to design/analyze both structures using ASCE 41-06 versus ASCE 7-05. Code level designs using ASCE 7-05 are based on forces from a BSE-1 earthquake, which is scaled down by a response modification factor, R , to account for the system's ductility. The R -value is inversely proportional to the base shear, therefore higher R -values will return lower base shears. ASCE 41-06 is a performance based design, and uses the displacements the structure experiences from an unscaled base shear as the basis for design. By relying on the actual instead of "idealized" displacements, a performance based approach allows a designer to produce a more robust design.

3.3 Cost Analysis

The cost analysis was conducted by developing costs for both the code level and high performance structures. In order to develop a valid comparison, both buildings were assumed to be identical excluding the lateral system resulting in a cost difference that accounted for the structural upgrades.

The typical construction cost of a building was analyzed and divided into four main elements: substructure, shell, interiors, and services. The structural components of this typical building were extracted and replaced with code level and high performance structural components resulting in two estimates identical in contents except for structural systems. The “typical” building was developed using the 2009 editions of RSMeans *Square Foot Costs*. The *Building Construction Cost Data* was employed to develop the specific structural cost.

Square Foot Cost contains unit costs of common building elements that are found in residential, commercial, and industrial buildings such as furniture, wall/floor finishes, and electrical systems. The costs are given in units specific to that element (e.g., elevators are priced per elevator and windows are priced per square footage of wall area) which must be converted to square foot costs. Since some items, such as wiring and exterior/interior finishes were not finalized at the time of costing, RSMeans typical values for offices were assumed to determine a rough estimate of the final building cost.

Construction Cost Data is essentially a catalog of material and labor prices based on the national average. Item costs are listed in per unit quantities; therefore the prices for a building are dependent on the amount of each item present in the structure. For example if one assumes a building has 10 psf of steel per square foot of floor area and the unit cost according to RSMeans is \$2000 per ton, the cost of steel is \$20,000 per sq. ft. The total construction cost of the project is then magnified to account for the contractor (general contractor, overhead, profit) and design fees to determine the project costs.

Once the project costs are developed, the costs are then multiplied by a city index factor to account for complexity based on the building's location.

For this thesis, *Square Foot Cost* was used to determine “typical building” costs and *Construction Cost Data* was used to determine the cost of structural steel, concrete, and labor. To account for connection costs and miscellaneous metals, the amount of steel was increased by 35% (10% for connections and 25% for miscellaneous metals). The remaining items (braces and the rods in the grouted anchors) were not listed in RSMeans and were priced per consultation with vendors. The brace costs were provided by Star Seismic, and were given as an average cost of \$2,800 per brace for the code level braces, and \$4,300 per brace for the high performance braces. The costs for the grouted anchors were provided by Williams Form Engineering, who gave an estimate of approximately \$18 per foot of anchor. Both costs included delivery and were doubled to account for installation costs.

Once the individual elements in both structures were priced, the subtotals were increased by 7% and 25% to account for design and construction project cost respectively. That total was then multiplied by a city index factor of 1.24 to account for the structure's location in San Francisco, California. Table 2 and Figure G show a tabular and graphical summary respectively for the two structures, and the detailed calculations can be found in Appendix 6.3 along with extrapolated costs for both the code level and high performance structures in different areas of the US.

Type	Item	Code Level (\$)	High Performance (\$)
Typical Building Structural	Building Contents	\$15,300,000	\$15,300,000
	Steel	\$3,380,000	\$3,510,000
	Conc. on Deck	\$810,000	\$810,000
	Footings	\$890,000	\$920,000
	BRB'S	\$400,000	\$620,000
	Subtotal	\$20,780,000	\$21,160,000
Typical Building	Construction	\$5,200,000	\$5,290,000
	Design	\$1,450,000	\$1,480,000
	Project Cost	\$27,430,000	\$27,930,000

Table 2: Construction Cost Summary
Source: Author

Figure G: Cost Summary
Source: Author

The structural costs of both structures were approximately 20% of the overall building costs. The figures follow the trend shown in Mr. Carmona's thesis that the upgrade costs have a minimal impact on the upfront project costs (roughly 2% increase).

3.4 Financial Risk Assessment

The financial risk assessment was conducted using the Hazus based software Benefit-Cost Analysis (BCA), an application developed by the Federal Emergency Management Agency (FEMA). BCA was developed to determine the cost-effectiveness of a potential mitigation for a given natural disaster, and is equipped to analyze several hazards through six different modules: earthquake, flood, hurricane, tornado safe room, wildfire, and damage frequency assessment. In each module the user inserts details specific to the structure (building type, location, soil type, etc.) and the application will return a value known as the benefit-cost ratio (BCR). BCR's greater than 1.0 are considered financially justifiable whereas BCR's less than 1.0 are not considered feasible.

Since this thesis investigates the performance of structures in seismic regions, the earthquake module was the primary focus during this study. The earthquake module is divided into two sub-modules, structural and nonstructural. The structural module is used to determine the potential risk associated with upgrading a building's framing, whereas the nonstructural module determines the risk associated with upgrading specific nonstructural components in a structure. The risk for both cases is associated with the level of damage a structure experiences, and the resulting cost of damages, loss of

business income, and casualties. Because the goal of this thesis was to compare two structures, the earthquake structural module was the focal point of the research.

Since BCA is traditionally used to determine the cost effectiveness of potential hazard mitigations, the code level and high performance structures were treated as pre and post mitigation structures, and the differential cost was treated as the mitigation cost (Figure H).

COST ESTIMATION INFO	
Project Useful Life (years) *	<input type="text" value="50"/>
Do you have a detailed Scope of work ? *	☒ Yes ☐ No
Do you have a detailed estimate for the entire project ? *	☒ Yes ☐ No
(If not complete the summary of cost estimation data entries below)	
Mitigation Project Cost *	<input type="text" value="\$500,000"/>
Annual Project Maintenance Cost	<input type="text" value="\$"/>
Summary Of Cost Estimation	
Check the box to enter a lump sum amount if you already have an estimate for the category. To develop an itemized estimate, click the category to link to items.	
☐ Pre-Construction Costs	<input type="text"/>
☐ Construction Costs	<input type="text"/>
Does the estimate for Construction Costs include General Contractor costs and markups?	☒ Yes ☐ No
Construction Type:	☐ New ☐ Repair
☐ Construction Markups	<input type="text"/>
☐ Annual Project Maintenance Costs	<input type="text"/>
Number of Years of Maintenance	<input type="text" value="50"/>
Present Worth of Annual Maintenance Costs	<input type="text" value="\$"/>
Does estimate reflect current prices?	☒ Yes ☐ No
Cost Basis Year:	<input type="text" value="YYYY"/>
Construction Start Year:	<input type="text" value="YYYY"/>
Construction End Year:	<input type="text" value="YYYY"/>
Project Escalation	<input type="text" value="\$"/> <input type="button" value="Escalate"/>
Final Mitigation Project Cost *	<input type="text" value="\$500,000"/>

Figure H: BCA Cost Input

Source: Author

The information that was critical to estimating the level of damage experienced by each structure is found under BCA's "vulnerability" tab. The input in this tab defines the pre and post mitigation structural designs, and is used by BCA to access a database of Hazus' fragility curves based on the structure's lateral system, story height, design code

level per UBC 1997 (Hanus-MH MR3, 2003). Once defined, the fragility curves are used to predict the level of damage both structures will experience. The level of damage is correlated to the structure's elastic period (T_e), design strength (C_s), and *structural* and *nonstructural drift ratios* (STR and NSD respectively). The elastic period, design strength, and structural drift ratios determined per the designs were used for input data and nonstructural drift ratios were selected per Dr. Miranda's research (Miranda 1999). Another critical input is the degradation factor (κ), relates the damping to earthquake magnitude. FEMA conducted several studies regarding the degradation factor and was able to determine values for each lateral system represented in BCA, which are shown in Figure I. In order to determine a fair assessment of the building's performance, sensitivity testing used three κ values. The three κ values selected, 0.70, 0.50, and 0.30 account for each building's performance during a short (magnitude 6 or less), medium (magnitude 6-7), and long (magnitude 7+) earthquake.

Building Type		High-Code Design			Moderate-Code Design			Low-Code Design			Pre-Code Design		
No.	Label	Short	Moderate	Long	Short	Moderate	Long	Short	Moderate	Long	Short	Moderate	Long
1	W1	1.00	0.80	0.50	0.90	0.60	0.30	0.70	0.40	0.20	0.50	0.30	0.10
2	W2	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
3	S1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
4	S1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
5	S1H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
6	S2L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
7	S2M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
8	S2H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
9	S3	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
10	S4L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
11	S4M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
12	S4H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
13	S5L	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
14	S5M	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
15	S5H	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
16	C1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
17	C1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
18	C1H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
19	C2L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
20	C2M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
21	C2H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
22	C3L	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
23	C3M	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
24	C3H	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
25	PC1	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
26	PC2L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
27	PC2M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
28	PC2H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
29	RM1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
30	RM1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
31	RM2L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
32	RM2M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
33	RM2H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
34	URML	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
35	URMM	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
36	MH	0.80	0.40	0.20	0.80	0.40	0.20	0.80	0.40	0.20	0.60	0.30	0.10

Figure I: Degradation Factors for Short, Moderate, and Long Earthquakes
Source: Hazus-MH Technical Manual, Table 5.18

Figure J shows the values entered in BCA for the basis of the assessment, and Figure K shows a breakdown of the results for each building. After testing both the code level and the high performance structure with the same earthquakes, the results swayed in favor of the high performance structure with an annual savings of approximately \$43,000, \$64,000, and \$98,000 for the short, medium, and long frequency return period earthquakes respectively over the building's 50-year life cycle. Considering that the upgrade cost was roughly \$500,000, the high performance structure would pay itself off

in 6-25 years (depending on the earthquake magnitude), well below the 50-year life cycle, further proving that high performance structures are worth the investment in areas of high seismicity. It should be noted that additional studies were conducted with varying kappa values, and the BCA starts to sway in favor of the code level structure for earthquakes weaker than the BSE-1 earthquake.

Seismic Data

Location Economic Values Vulnerability Analysis

*** All fields must contain a value to generate a BCR.**

Select building type for loading initial capacity parameters BEFORE retrofit

Model Building Type: S2 - Steel Braced Frame

Number Of Stories: 4

Design Level: High Code

Load Initial Capacity Parameters

Select building type for loading initial capacity parameters AFTER retrofit

Model Building Type: S2 - Steel Braced Frame

Number Of Stories: 4

Design Level: High Code

Load Initial Capacity Parameters

Capacity parameters

Elastic Period (Te): 0.6800 (sec)

Design Strength (Cs): 0.1430 (LRFD)

Elastic Damping: 5 (%)

Degradation Factor (Kappa): 0.3

Drift-sensitive Damage Thresholds (Drift Ratio):

Complete Structural Damage (STR): 0.010

Complete Nonstructural Damage (NSD): 0.022

Acceleration-sensitive Damage Thresholds:

Complete Nonstructural Damage (NSA): 2.400 (g)

Location of Acceleration-sensitive Components: Uniformly Distributed

Capacity parameters

Elastic Period (Te): 0.5300 (sec)

Design Strength (Cs): 0.2150 (LRFD)

Elastic Damping: 5 (%)

Degradation Factor (Kappa): 0.3

Drift-sensitive Damage Thresholds (Drift Ratio):

Complete Structural Damage (STR): 0.008

Complete Nonstructural Damage (NSD): 0.018

Acceleration-sensitive Damage Thresholds:

Complete Nonstructural Damage (NSA): 2.400 (g)

Location of Acceleration-sensitive Components: Uniformly Distributed

NSD Details NSA Details Show All Input Parameters

Figure J: Pre and Post Mitigation Entry
Source: Author using Benefit-Cost Analysis

Location	Economic Values	Vulnerability	Analysis
Analyze			
Results (All losses are in dollars)			
	As-is		As-retrofit
Average Annual Loss - STR	56,488 (Dollars)		53,828 (Dollars)
Average Annual Loss - NSD	156,266 (Dollars)		142,802 (Dollars)
Average Annual Loss - NSA	50,438 (Dollars)		51,308 (Dollars)
Average Annual Loss - Casualty	933,148 (Dollars)		854,359 (Dollars)
Average Annual Loss - Relocation	89,120 (Dollars)		85,145 (Dollars)
Average Annual Loss - Loss of Rental Income	00 (Dollars)		00 (Dollars)
Average Annual Loss - Loss of Business Income	4,436 (Dollars)		4,210 (Dollars)
Total Average Annual Loss	1,289,897 (Dollars)		1,191,651 (Dollars)
Details			

Figure K: BCA Analysis Output

Source: Author

3.4.1 BCA Data Verification

As part of the development of this thesis methodology, a sensitivity analysis was conducted using BCA to validate the input data and subsequent results.

BCA extracts damage cost data using Hazus' database of *fragility curves*, or curves that are used to predict the probability of reaching given levels of damage. Figure L shows a sample of fragility curve used in Hazus. For an arbitrary displacement of 5 inches, the fragility curves show that there is approximately a 5% chance the building will experience extensive damage. If the displacement increases to 10 inches, the probability of reaching extensive damage increases to approximately a 50% chance.

Figure L: Sample Fragility Curves for Different Damage States

Source: Hazus MR3 Technical Manual, Figure 5.1

Fragility curves are used in conjunction with the building's structural (STR) and nonstructural drift ratios (NSD) to determine the probability of reaching each building's damage states. The damage state probabilities are averaged and multiplied with the specified building replacement values to calculate the repair cost. Additional sensitivity tests were conducted by adjusting BCA's input, but special attention was paid to the nonstructural components through the NSD's.

BCA's output was assessed using three scenarios for each building's NSD's:

(1) identical drifts for pre and post retrofit, (2) larger drifts in the post retrofit scenario, and (3) larger drifts in the pre retrofit scenario. The results for the investigation are shown in Table 3 along with the predicted outcomes.

Scenario	Prediction	Actual Result
1) $NSD_{Pre} = NSD_{Post}$ (2%, 2%)	$BCR > 1$	3.26 – Justifiable mitigation
2) $NSD_{Pre} < NSD_{Post}$ (1%, 2%)	$BCR > 1$	6.69 – Justifiable mitigation
3) $NSD_{Pre} > NSD_{Post}$ (2%, 1%)	$BCR < 1$	0.69 – Mitigation wasteful

Table 3: Sensitivity Analysis Summary

Source: Author

The NSD's of 1% and 2% were arbitrarily chosen so as to display noticeable differences in the produced BCR's. The final results were three BCR's that followed the expected pattern for the experiment. The first scenario ($NSD_{Pre} = NSD_{Post}$) was expected to return a BCR larger than 1, due to the fact that a higher performance structure is significantly stiffer (additional protection for the majority of nonstructural components). Therefore even though both sets of nonstructural components can withstand the same amount of drift, more force will be required on the high performance structure to produce that drift.

The second scenario investigated a similar, but more extreme scenario than the first. The proposed high performance structure in this case was not only stiffer, but it also had a higher allowable capacity for drift than the code level system (likely a case where the nonstructural system would be upgraded in addition to the structural system). This additional tolerance along with the lateral system's increased capacity was expected to yield a BCR significantly larger than 1, and also a value larger than in the first case

because there were added benefits to both the structural and nonstructural components.

Table 3 verified this expectation.

The final scenario showed an opposite scenario where the stiff structure had a lower allowable drift than the life safety structure. The returned BCR was expected to return a value less than or equal to 1 due to the fact that the entire building's damage was highly dependent on the increased capacity of the structure. For this case, BCA returned a ratio of 0.69 meaning that both building's experienced significant damage, and that the upgrade cost of the structure did not repay itself for the specified 50-year life cycle.

Several other tests in addition to the above three cases were run using BCA, but all yielded results that were reasonably predictable and proved to be consistent with the predictions. Due to the consistency in the software's output, BCA's values proved to be an acceptable form of damage cost comparison for the code level and high performance structures.

3.5 Carbon Footprint Analysis

A carbon footprint is defined as the amount of greenhouse gas (GHG) emissions released during a given event. There has been increasing evidence showing a correlation between GHG's and global warming, and as a result carbon analyses have become an item of interest in the construction industry due to the amount of GHG's released during the construction and operation of buildings. A construction related carbon footprint depends on its *embodied energy*, the types of materials used in a project, the amounts of those materials, and the energy required to deliver the materials to the site and later erect

it. Because a code level and high performance structure are expected to have different material quantities, a carbon footprint analysis was conducted to compare their individual effects on the environment.

The carbon footprint analysis was conducted through the use of the application BuildingScope, provided courtesy of CleanMetrics. The software is a web-based application that allows the user to develop the carbon footprint through its five modules: Construction, Operation, Land Use, Waste, and Carbon Storage. Because the original intent of this study was to determine the environmental impacts due to the increased materials in the higher performance structure, this thesis only implemented the construction module to calculate each structure's carbon footprint.

The construction module allows the user to develop an estimate of the greenhouse gas emissions released during the construction phase of a building. In order to develop the values, the user develops a digital model of the building, which is defined by the volumetric quantities of all materials specific to that structure. Once the structure is defined, BuildingScope uses CleanMetrics' internal database (CarbonScopeData) to determine the amount of carbon released by each material and the required energy to bring it to site. Figures M and N show sample input and output generated by BuildingScope.

Add item to building construction model:

Category: Concrete

Item: Concrete, slab, 3500 psi/24.5 Mpa

Quantity: 532940 Kg

Start Year: 0 (<= building service period)

Transport Segments (select up to 5 transport modes and set distances):

Semi-trailer truck	0	km	Calculate
Semi-trailer truck	0	km	Calculate
Semi-trailer truck	0	km	Calculate
Semi-trailer truck	0	km	Calculate
Semi-trailer truck	0	km	Calculate

☐ Enable Automatic Waste & Carbon Storage Analysis

Service Life Time: 50 years

Initial Material Waste: 2 %

Final Material Waste: 100 %

Figure M: BuildingScope Construction Model Sample Input
Source: Author

Figure N: BuildingScope Construction Model Sample Output
Source: Author

Although BuildingScope's models are produced using volumetric quantities of materials, there were a few limitations within the software. BuildingScope has a preloaded list of items to select from; therefore any materials present on site that are not

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defined in the program must be approximated. Because of this limitation, items such as the steel deck, partitions, and electrical that are typically present in a finished project were estimated using similar materials.

Table 4 shows the results generated by BuildingScope in metric tons CO₂ eq. (read as “metric tons of carbon equivalent gas”). The additional weight of materials in the high performance structure resulted in a higher carbon footprint, but the increase was almost negligible. The increase in carbon from the code level to the high performance structure was roughly 50 metric tons CO₂ eq., which was less than 1% of the overall footprint. According to the Environmental Protection Agency, the average passenger vehicle in the United States produces 5.1 metric tons CO₂ eq. annually, therefore the increase due to the additional materials equates to roughly 10 cars per year.

Carbon	Code Level	High Performance	Increase
Construction	7890	7940	50 (less than 1%)

Table 4: Construction and Operational Carbon Footprints

Source: Author

Because BuildingScope showed that the increased materials in the higher performance structure had little impact on the results, this area is worth further investigation. The embodied energy generated from a construction project should be directly related to the amount of materials present; therefore the higher performance structure was expected to have a higher carbon footprint than what is shown above. The possible error in the results could be due to the estimation abilities of BuildingScope,

therefore it is recommended that any future research in this field be conducted using more than one application to increase accuracy.

While any increase in a carbon footprint is perceived as negative, the added benefits due to the higher performance structure's increased capacity must be taken into account. If the two buildings suffer damage due to a significant earthquake the construction necessary for reparations will affect each structure's global warming potential. For example, if a code level and higher performance building experienced a BSE-2 level earthquake, the high performance structure would suffer minor damage while the code level structure might require replacement of the lateral system. The construction necessary to repair both buildings would result in a slight increase in the high performance building's carbon footprint, but it could likely double the code level structure's carbon footprint. Even though there is a slight increase initially, selecting the high performance structure is the environmentally friendly option when looking at each building's life cycle.

4.0 LITERATURE REVIEW

The basic goal of this thesis was to compare two types of structures: one designed to meet code level requirements and one designed to surpass code level requirements. The comparison was based on cost effectiveness and environmental impacts (carbon footprint), and research was conducted to gain the necessary background to conduct the studies.

The structural design and analysis of the code level and high performance structures in this thesis used the linear dynamic procedure described in the American Society of Civil Engineer's *Seismic Rehabilitation of Existing Buildings* (ASCE 41-06). In order to correctly implement the analysis, Matthew Williams' thesis *Performance Based Analysis of Steel Buildings* and ASCE 41-06 were both used as references.

Matthew Williams' thesis, *Performance Based Analysis of Steel Buildings* investigated the four different analysis procedures listed in ASCE 41-06. The goal of his work was to compare the results generated by the four different analysis procedures when applied to the same design to determine the level of accuracy associated with each one. Mr. Williams determined that the nonlinear dynamic and nonlinear static procedures were the most accurate, whereas the linear static and dynamic were the least accurate and tend to generate somewhat conservative results compared to their nonlinear counterparts.

This paper was used as a reference for the different analysis methods, and used in the selection process of the linear dynamic procedure for this thesis. Along with being used in the initial selection of the linear dynamic procedure, Mr. Williams' work was

constantly referenced to ensure the correct implementation of the linear dynamic procedure during the structural analysis.

The American Society of Civil Engineers' *Seismic Rehabilitation of Existing Buildings* outlines the four analysis procedures (linear static, linear dynamic, nonlinear static, and nonlinear dynamic) and is the current standard for performance based design. Originally based on FEMA 356, ASCE 41-06 provides a separate and more stringent methodology for developing structural designs and assessing structural performance through the use of un-scaled seismic forces to determine a building's true response.

This standard was constantly used during the design and analysis of this thesis. Chapters 1 and 3 were used when developing the correct response spectra and later when determining the brace response to rate the structure's performance criteria. Along with providing the basis for the design and analysis, ASCE 41-06 was used to develop the background for understanding the BSE-1 and BSE-2 earthquakes and concepts surrounding the life-safety and immediate occupancy performance methodology.

Consideration of Building Performance in Sustainable Design: A Structural Engineer's Role, and *Quantifying the Life Cycle Benefits of Performance Based Design* were both used as references during the comparison stages of this thesis.

In *Consideration of Building Performance in Sustainable Design: A Structural Engineer's Role*, Erik Kneer and Lindsey MacLise introduce the concept of merging sustainable and performance-based design (PBD). The article is primarily an informative

piece; therefore it does not present any results. The focus is to direct future engineering so that it incorporates sustainable practices (2008).

Part of the goal in this thesis was to prove that the cost of upgrading structures will be offset by the amount of money saved on future reparations. If a structure is able to be sustainable as well as meet higher performance criteria, the initial construction costs will be significantly reduced due to the decrease in structural materials without sacrificing building life.

David Carmona's thesis, *Quantifying the Life Cycle Benefits of Performance Based Design in Sustainable Design* provided the groundwork for this thesis. Mr. Carmona began the initial study comparing life-safety to immediate occupancy design criteria for a moment frame structure, through which he was able to prove the higher performance was financially justifiable. Unfortunately, the latter part of his work, relied on PACT, an application released in its pre-beta stage which he determined was too unreliable use as the basis for his financial risk assessment (2010).

The significance of Mr. Carmona's research was two-fold: his work served as an outline for this thesis while also fueling the research Mr. Kneer and Ms. MacLise conducted in their paper. The basic concepts used in Mr. Carmona's thesis were the basis for this study, and as such his work was used as a guide throughout this thesis. The values generated in the structural design, analysis, and cost analysis were compared with Mr. Carmona's to ensure legitimacy.

The final article that was of great significance during this research was the *Hazus-MH MR3 Technical Manual*, which was used extensively through the financial risk assessment.

The *Hazus-MH MR3 Technical Manual* was developed for Hazus users learning to use the software. The manual describes the advanced use of Hazus ranging from the formation of ground motion data to the estimation of damage due to earthquake debris.

Since BCA was based on Hazus, the basic principles Hazus was based on were essential in understanding BCA. The technical manual was used primarily to understand the input required in BCA's structural earthquake module specifically relating to the fragility curve data. Since the costs are all based off of the fragility curve information, this step was crucial to avoid a "garbage-in-gospel-out" scenario. The technical manual also provided information on the origins of the degradation factor, and the values provided in Table 5.18 were used to conduct the analyses on the short, moderate, and long earthquakes.

5.0 CONCLUSION

Due to the increased public awareness of earthquakes we must ask ourselves, “Is the possibility of a significant seismic event worth the additional cost to produce a more stable structure?” This thesis answered this question by investigating the potential economic benefits associated with a structure designed to exceed the minimum design requirements per the American Society of Civil Engineers’ *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-05). In addition to looking at the potential financial return, this paper explored the correlation between a structure’s disaster resilience and its long-term environmental impact due to the additional material present at construction. The overall conclusion is that in seismically active regions there is a life cycle cost benefit in designing a structure that incorporates BRBF’s as the lateral system.

In order to conduct this study, a structure utilizing buckling restrained braced frames (BRBF’s) was designed to meet life safety (code level) and immediate occupancy (high performance) design criteria. Both performance levels were verified using ASCE 41-06’s linear dynamic procedure and were compared by investigating the cost and embodied energy of each structure. Excluding the elements in the lateral system, both buildings were exactly the same meaning that the differences in cost and embodied energy were directly correlated to the increase in materials.

The initial step in the comparison, the cost analysis, was conducted using RSMeans *Square Foot Cost* and *Construction Cost Data*. Although there was a significant increase in brace capacity from the code level to high performance structure,

the additional cost to upgrade was approximately \$500,000, only a 2% increase of the original \$27 million building cost.

In order to determine the value and associated risk with that \$500,000 upgrade, a financial risk assessment using FEMA's application, Benefit-Cost Analysis (BCA), was implemented. Three assessments were conducted to determine the potential risk for short, moderate, and long earthquakes. The benefit-cost ratios returned by BCA for the earthquakes were 1.18, 1.77, and 2.71, which correlate to an annual savings of \$43,000, \$64,000, and \$98,000 over the building's 50-year life cycle respectively. BCA's results showed that not only was there an added benefit to the additional capacity of the high performance building, but that the higher performance building gained value as the earthquake magnitude increased due to the reduced structural and nonstructural damages.

Due to the rising concern regarding carbon emissions and sustainability in the construction industry, a carbon footprint analysis of both buildings was run in order to determine the environmental impacts associated with the higher performance structure. The increase in materials for the higher performance structure resulted in an increase of approximately 50 metric tons of carbon dioxide emissions, or the equivalent to 10 cars over the span of one year. This increase was less than 1% of the total carbon footprint generated by the code level structure. Although there was a slight increase in the higher performance structure's carbon footprint, the increased capacity makes it the environmentally friendly option because it will experience less damage during a given earthquake allowing it to bypass repair a significant amount of earthquake related repair.

While higher performance structures require a small premium initially, the improved performance will provide numerous benefits for the owner. Increased structural capacity will minimize the amount of damage resulting from an earthquake allowing a business owner to bypass lengthy repairs and unnecessary downtime. In addition to avoiding construction related costs, a high performance structure will also reduce a building's negative environmental impact by avoiding the embodied energy that would have been produced by extra construction. Because of these long-term benefits resulting from increased performance, it is recommended that seismically vulnerable buildings be constructed to meet higher performance objectives than the minimum ones required by ASCE 7-05.

5.1 Next Steps

Due to the potential sensitivity of this research with respect to a structure's lateral force resisting system (LFRS), further studies should be conducted on different types of LFRS's. One system that is of particular interest is the special concentric braced frame (SCBF). The buckling restrained braced frames (BRBF) used in this study are highly efficient systems, and did not have a large impact on the structural costs. Using something more traditional such as an SCBF, would potentially allow for a greater price difference between the high performance and code level structures and could yield more drastic results.

Other types of structures that should also be investigated are those relying on the use of concrete for the structural systems (concrete shear walls or moment frames). The

reason for this is because unlike steel, the capacity of a concrete shear wall is directly related to the volumetric amount present (i.e., a 6-inch shear wall will be weaker than a 12-inch shear wall), as well as the amount of rebar required for that section. The higher demands from the BSE-2 earthquakes may have a noticeable impact on the system's design and would have the potential to provide results that may prove the code level structure to be more cost effective. Along with affecting the cost effectiveness, because concrete is such a carbon intensive material, it could also heavily sway the results in a carbon footprint analysis in favor of the structure utilizing less material.

In addition to investigating the above-mentioned systems, more research should be conducted in the area of carbon footprinting. Sustainability studies are becoming increasingly popular; however some of the tools that are readily available serve only as crude estimates and produce significantly different results. Some applications such as Athena Institute's EcoCalculator are relatively well known in industry; however those models at the time of this study were based on square footage and ignored volumetric quantities. This limitation rendered that spreadsheet inappropriate for this study since both the code level and high performance structures shared the same square footage. Even BuildingScope, which relied on volumetric quantities of materials, provided only a rough estimate of each structure's carbon footprint. Certain materials such as the steel deck, cladding, and partitions were not available in CleanMetrics' database, and had to be estimated using similar materials.

Another area relating to this topic that could be researched is in the development of a carbon database and/or a uniform method to develop a carbon footprint. At the moment, most carbon applications are treated as a “black box” because there simply is not enough public information pertaining to carbon based calculations. Cost is a unifying issue because everyone has an understanding of it. Anyone can calculate the cost of an item, and immediately see how spending those amounts of money will immediately affect them. Carbon gas emissions have a very obvious impact on the environment but very few people have a tangible relationship with the effects. If there was a uniform way of calculating a carbon footprint and showing the immediate and long term financial impacts it could have, more individuals be it industry professionals or clientele, would be able to generate an interest in the topic which could impact design methodologies not just in areas of high seismicity, but globally.

6.0 APPENDIX

6.1 Structural Designs

The buildings' designs were developed using the standard design procedures set aside in ASCE 7-05 and IBC 2006. Forces acting on the members were calculated by combining hand calculations in conjunction with RISA2D and the structural analysis was conducted in ETABS. All hand calculations were transferred to a spreadsheet developed during the course of this thesis. The spreadsheet's functions range from the determination of load distribution of story forces (Figure O) to the programmed linear dynamic procedure and performance level determination.

NORTH-SOUTH DIRECTION							
Level	h_x	w_x	k	$w_x h_x^k$	C_{vx}	V_{NS}	F_x
ROOF	58.5 ft	1245 K	1.00 s	72833	0.361	755 K	273 K
4th FLR	43.5 ft	1510 K	1.00 s	65685	0.325	755 K	246 K
3rd FLR	29.5 ft	1470 K	1.00 s	43365	0.215	755 K	162 K
2nd FLR	15.5 ft	1285 K	1.00 s	19918	0.099	755 K	75 K
Total		5510	$\square$	201800	1.00		755 K

Equations per ASCE 7-05 Section 12.8.3:

w = Weight of floor level (kips)

h = Height from base to floor level (ft)

k = 1 for $T < 0.5$ s, 2 for $T > 2.5$ s, Linearly interpolated for all other values

$$C_{vx} = w_x h_x^k / \sum w_i h_i^k$$

$$F_x = C_{vx} V$$

Figure O: Equivalent Lateral Force Procedure Via Excel.

Source: Author

The linear dynamic portion of the spreadsheet used ETABS output to calculate the demand-to-capacity ratios (DCR) and plot the system performance relative to the corresponding m-factors. Figure P shows a sample of the output required from ETABS.

The table comes from ETABS's member forces, and consists of the axial load each brace in the computer model experiences at each story level for a given response spectra.

RESPONSE SPECTRUM IN X-DIRECTION (BSE2)									
Story	Brace	Load	Loc	P	V2	V3	T	M2	M3
ROOF	D1	BSE2X	0	199374.29	0	0	0	0	0
ROOF	D1	BSE2X	115.256	199374.29	0	0	0	0	0
ROOF	D1	BSE2X	230.512	199374.29	0	0	0	0	0
4TH FLR	D1	BSE2X	0	360745.18	0	0	0	0	0
4TH FLR	D1	BSE2X	110.635	360745.18	0	0	0	0	0
4TH FLR	D1	BSE2X	221.269	360745.18	0	0	0	0	0
3RD FLR	D1	BSE2X	0	462962.37	0	0	0	0	0
3RD FLR	D1	BSE2X	110.635	462962.37	0	0	0	0	0
3RD FLR	D1	BSE2X	221.269	462962.37	0	0	0	0	0
2ND FLR	D1	BSE2X	0	538910.18	0	0	0	0	0
2ND FLR	D1	BSE2X	117.614	538910.18	0	0	0	0	0
2ND FLR	D1	BSE2X	235.228	538910.18	0	0	0	0	0
ROOF	D2	BSE2X	0	199374.29	0	0	0	0	0
ROOF	D2	BSE2X	115.256	199374.29	0	0	0	0	0
ROOF	D2	BSE2X	230.512	199374.29	0	0	0	0	0
4TH FLR	D2	BSE2X	0	360745.18	0	0	0	0	0
4TH FLR	D2	BSE2X	110.635	360745.18	0	0	0	0	0
4TH FLR	D2	BSE2X	221.269	360745.18	0	0	0	0	0
3RD FLR	D2	BSE2X	0	462962.37	0	0	0	0	0
3RD FLR	D2	BSE2X	110.635	462962.37	0	0	0	0	0
3RD FLR	D2	BSE2X	221.269	462962.37	0	0	0	0	0
2ND FLR	D2	BSE2X	0	538910.18	0	0	0	0	0
2ND FLR	D2	BSE2X	117.614	538910.18	0	0	0	0	0
2ND FLR	D2	BSE2X	235.228	538910.18	0	0	0	0	0
ROOF	D5	BSE2X	0	106314.09	0	0	0	0	0
ROOF	D5	BSE2X	115.256	106314.09	0	0	0	0	0
ROOF	D5	BSE2X	230.512	106314.09	0	0	0	0	0
4TH FLR	D5	BSE2X	0	186356.77	0	0	0	0	0
4TH FLR	D5	BSE2X	110.635	186356.77	0	0	0	0	0
4TH FLR	D5	BSE2X	221.269	186356.77	0	0	0	0	0
3RD FLR	D5	BSE2X	0	243296.46	0	0	0	0	0
3RD FLR	D5	BSE2X	110.635	243296.46	0	0	0	0	0
3RD FLR	D5	BSE2X	221.269	243296.46	0	0	0	0	0
2ND FLR	D5	BSE2X	0	283997.6	0	0	0	0	0
2ND FLR	D5	BSE2X	117.614	283997.6	0	0	0	0	0
2ND FLR	D5	BSE2X	235.228	283997.6	0	0	0	0	0
ROOF	D6	BSE2X	0	106314.09	0	0	0	0	0
ROOF	D6	BSE2X	115.256	106314.09	0	0	0	0	0
ROOF	D6	BSE2X	230.512	106314.09	0	0	0	0	0

Figure P: Sample ETABS Input for Spreadsheet.

Source: Author

Once pasted in Excel, the spreadsheet (Figure Q) locates up the axial demand for each brace, and calculates the DCR. Once the DCR's are calculated, each cell will

change colors according to brace's performance category (green for immediate occupancy, yellow for life safety, and red for collapse prevention). Those DCR's are then plotted in a bar chart format shown in Figure R to give a visual representation of the brace with the highest DCR at each level, and the average DCR for each floor level.

DCR - RESPONSE SPECTRUM IN X-DIRECTION (BSE1)									
GRID	B				C				
LEVEL	5-6	6-7	6-7	8-9	5-6	6-7	6-7	8-9	
ROOF	2.23	2.45	2.46	2.03	2.19	2.41	2.42	1.97	
4TH FLR	2.72	3.20	3.21	2.53	2.68	3.16	3.17	2.46	
3RD FLR	2.53	3.02	3.03	2.36	2.49	2.98	2.99	2.30	
2ND FLR	2.27	2.71	2.72	2.15	2.24	2.68	2.69	2.11	

DCR - RESPONSE SPECTRUM IN Y-DIRECTION (BSE1)									
GRID	B				C				
LEVEL	5-6	6-7	6-7	8-9	5-6	6-7	6-7	8-9	
ROOF	0.37	0.28	0.28	0.45	0.32	0.33	0.33	0.41	
4TH FLR	0.41	0.36	0.35	0.49	0.35	0.39	0.39	0.44	
3RD FLR	0.37	0.34	0.33	0.43	0.33	0.38	0.38	0.40	
2ND FLR	0.31	0.29	0.28	0.35	0.28	0.33	0.34	0.33	

	IO
	LS
	CP

Figure Q: Linear Dynamic Procedure using Excel
Source: Author

Figure R: Performance Level Determination per Excel

Source: Author

6.2 Computer Modeling

ETABS Nonlinear Version 9.7.1 was used for the computer modeling and analysis in this thesis. The following assumptions were made in both the LS and IO computer models:

- Elements other than the lateral force system were ignored,
- Diaphragms were modeled as rigid,
- Column bases were modeled as pinned,
- Braces were modeled as perfectly pinned elements.

Figure S: ETABS Model Used in Analysis
Source: Author

6.3 Buckling Restrained Braced Frames

Buckling restrained braced frames are a newer type of lateral system that is gaining popularity in high performance use due to their efficiency. A special concentric brace system uses HSS tube sections as the braces, which leaves the compressive brace susceptible to buckling. The moment a brace buckles, it loses its ability to sustain load therefore rendering the lateral system useless. The braces in a BRBF system consist of a steel plate(s) or cruciform encased in shell, and are bonded to grout. This configuration

prevents the encased steel from buckling; resulting in a compressive brace that theoretically has the same axial capacity as the tensile brace. Figure T shows a sample cross section of a generic BRBF.

Figure T: Section of Buckling-Restrained Brace
Source: Author

6.4 RSMeans Cost Analysis Development

As stated in section 3.3, the individual costs of the building elements were determined per RSMeans *Square Foot Costs* and *Construction Cost Data*. Both manuals provide unit costs for each item based on the national average, which were then converted to costs per square foot. The structural quantities were based on the final designs for each building whereas the quantities of the building contents were assumed using the office templates provided in RSMeans. Table 5 shows a detailed chart of the costs per square foot of every element used in the costing.

		LS BUILDING			IO BUILDING		
	UNIT	UNIT COST	COST/S.F.	% SUBTOTAL	UNIT COST	COST/S.F.	% SUBTOTAL
A. SUBSTRUCTURE							
S.O.G. 4"	S.F. SLAB	\$2.76	\$0.69	4.3%	\$2.76	\$0.69	4.3%
LAT FOOTINGS	C.Y.	\$400.00	\$0.72		\$400.00	\$0.90	
GRAV FOOTINGS	C.Y.	\$400.00	\$0.94		\$400.00	\$0.94	
GB EW	C.Y.	\$400.00	\$0.13		\$400.00	\$0.15	
GB NS	C.Y.	\$400.00	\$0.11		\$400.00	\$0.11	
ANCHORS - ROD	L.F.	\$18.00	\$0.13		\$18.00	\$0.13	
ANCHORS - GROUT	C.F.	\$95.00	\$4.97		\$95.00	\$4.97	
B. SHELL							
SUPERSTRUCTURE							
METAL DECK W/ CONC	S.F. FLR	\$6.91	\$7.01	22.1%	\$6.91	\$7.01	23.4%
GRAVITY BMS	TON	\$4,000.00	\$11.96		\$4,000.00	\$11.96	
GRAVITY COLS	TON	\$4,000.00	\$4.06		\$4,000.00	\$4.06	
LAT BEAMS NS	L.F.	\$147.00	\$0.75		\$151.00	\$0.77	
LAT BEAMS EW	L.F.	\$131.00	\$1.01		\$151.00	\$1.16	
LAT COLS (TOP FLRS)	L.F.	\$171.00	\$0.74		\$299.00	\$1.30	
LAT COLS (BOT FLRS)	L.F.	\$273.00	\$1.20		\$299.00	\$1.32	
CONNECTIONS	% OF STEEL	10%	\$2.67		10%	\$2.76	
MISC. METALS	% OF STEEL	25%	\$6.68		25%	\$6.89	
BRB'S	EACH	\$5,600.00	\$3.47		\$8,600.00	\$5.33	
EXTERIOR ENCLOSURE							
CURTAIN WALL	S.F. WALL	\$75.50	\$36.18	20.5%	\$75.50	\$36.18	20.1%
EXTERIOR DOORS	EACH	\$4,850.00	\$0.52		\$4,850.00	\$0.52	
ROOFING							
COVERINGS	S.F. ROOF	\$6.33	\$1.68	0.9%	\$6.33	\$1.68	0.9%

		LS BUILDING			IO BUILDING		
C. INTERIORS							
PARTITIONS	S.F. PARTITION	\$9.43	\$7.07	18.7%	\$9.43	\$7.07	18.3%
INTERIOR DOORS	EACH	\$875.00	\$8.75		\$875.00	\$8.75	
FITTINGS	S.F. FLR	\$1.10	\$1.10		\$1.10	\$1.10	
STAIR CONST.	FLIGHT	\$15,800.00	\$1.35		\$15,800.00	\$1.35	
WALL FINISHES	S.F. SURFACE	\$1.41	\$1.06		\$1.41	\$1.06	
FLOOR FINISHES	S.F. FLOOR	\$7.62	\$7.62		\$7.62	\$7.62	
CEILING FINISHES	S.F. CEILING	\$6.38	\$6.47		\$6.38	\$6.47	
D. SERVICES							
CONVEYING							
ELEVATORS/LIFTS	EACH	\$292,600.00	\$12.50	7.0%	\$292,600.00	\$12.50	6.9%
PLUMBING							
FIXTURES	EACH	\$3,775.00	\$3.78	2.6%	\$3,775.00	\$3.78	2.6%
DOMESTIC WATER DIST	S.F. FLOOR	\$0.42	\$0.42		\$0.42	\$0.42	
RAIN WATER DRAIN	S.F. ROOF	\$1.84	\$0.49		\$1.84	\$0.49	
HVAC							
TERMINAL & PACKAGE	S.F. FLOOR	\$15.50	\$15.50	8.7%	\$15.50	\$15.50	8.5%
FIRE PROTECTION							
SPRINKLERS	S.F. FLOOR	\$2.96	\$2.96	2.3%	\$2.96	\$2.96	2.2%
STANDPIPES	S.F. FLOOR	\$1.07	\$1.07		\$1.07	\$1.07	
ELECTRICAL							
ELECT SERV./DIST	S.F. FLOOR	\$4.55	4.55	13.0%	\$4.55	4.55	12.7%
WIRING	S.F. FLOOR	\$11.20	\$11.20		\$11.20	\$11.20	
COMM & SEC	S.F. FLOOR	\$6.42	\$6.42		\$6.42	\$6.42	
OTHER	S.F. FLOOR	\$1.02	\$1.02		\$1.02	\$1.02	
SUBTOTAL		\$178.94	100%		\$182.15	100.0%	
CONTR. FEES		25%	\$44.74		\$45.54		
ARCH. FEES		7%	\$12.53		\$12.75		
TOTAL BUILDING COST		\$292.89	per sq. ft		\$298.14	per sq. ft	

Table 5: RSMeans Costing
Source: Author

To compare the project cost for both structures in other regions, city factors from different states were applied. The upgrade costs consistently fell below 2% of the overall building costs, consistently showing favor toward the higher performance structure.

Location	City Index	Code Level	High Perf	Increase
San Francisco, CA	1.24	\$27,430,000	\$27,930,000	\$500,000 (1.82%)
Birmingham, AL	0.87	\$20,650,000	\$21,030,000	\$380,000 (1.84%)
Honolulu, HI	1.17	\$25,540,000	\$26,010,000	\$470,000 (1.84%)
Columbus OH	0.83	\$20,000,000	\$20,370,000	\$370,000 (1.85%)

Table 6: Project Costs Across United States

Source: RSMeans, Location Factors Table

6.5 Benefit-Cost Analysis

Benefit-Cost Analysis (BCA) was used to determine the financial risk associated with the higher performance structure by using Hazus' database of fragility curves to predict the damage experienced during an earthquake. BCA does this by determining the financial losses associated with structural and nonstructural damages, along with casualties, relocation, and loss of business income. These costs are totaled and compared to the amount of money invested in the upgrade.

Figure U shows a sample window for the BCA Vulnerability Tab. This window contains the most pertinent information regarding the structure's structural integrity. The building type, number of stories, and code level are the basis for the fragility curve database and the capacity parameters allow the software to determine damages the structure will actually experience. BCA has the ability to load its own capacity parameters, however the values are for structures with a 12'-0" story height and should be modified accordingly. The elastic period, design strength, structural, and

nonstructural damages should be entered according to what the structural design permits, but the degradation factor, kappa allows for flexibility in determining the structure's response to various earthquakes.

Seismic Data

Location
Economic Values
Vulnerability
Analysis

*** All fields must contain a value to generate a BCR.**

Select building type for loading initial capacity parameters BEFORE retrofit

Model Building Type
S2 - Steel Braced Frame

Number Of Stories
4

Design Level
High Code

Load Initial Capacity Parameters

Capacity parameters

Elastic Period (Te)
0.6800 (sec)

Design Strength (Cs)
0.1430 (LRFD)

Elastic Damping
5 (%)

Degradation Factor (Kappa)
0.3

Drift-sensitive Damage Thresholds (Drift Ratio):

Complete Structural Damage (STR)
0.010

Complete Nonstructural Damage (NSD)
0.022

Acceleration-sensitive Damage Thresholds:

Complete Nonstructural Damage (NSA)
2.400 (g)

Location of Acceleration-sensitive Components
Uniformly Distributed

Figure U: BCA Vulnerability Input

Source: Author

Location	Economic Values	Vulnerability	Analysis
<div>Analyze</div>			
Results (All losses are in dollars)			
	As-is		As-retrofit
Average Annual Loss - STR	56,488 (Dollars)		53,828 (Dollars)
Average Annual Loss - NSD	156,266 (Dollars)		142,802 (Dollars)
Average Annual Loss - NSA	50,438 (Dollars)		51,308 (Dollars)
Average Annual Loss - Casualty	933,148 (Dollars)		854,359 (Dollars)
Average Annual Loss - Relocation	89,120 (Dollars)		85,145 (Dollars)
Average Annual Loss - Loss of Rental Income	00 (Dollars)		00 (Dollars)
Average Annual Loss - Loss of Business Income	4,436 (Dollars)		4,210 (Dollars)
Total Average Annual Loss	1,289,897 (Dollars)		1,191,651 (Dollars)

Figure V: BCA Calculated Losses

Source: Author

SUMMARY OF BENEFITS	
<div>Expected Annual Damages Before Mitigation</div> <div>Annual \$ 1,289,897</div> <div>Present Value \$ 17,801,541</div>	
<div>Expected Annual Damages After Mitigation</div> <div>Annual \$ 1,191,651</div> <div>Present Value \$ 16,445,673</div>	
<div>Expected Avoided Damages After Mitigation (BENEFITS)</div> <div>Annual \$ 98,246</div> <div>Present Value \$ 1,355,868</div>	
MITIGATION BENEFITS	\$ 1,355,868
MITIGATION COSTS	\$ 500,000
BENEFITS MINUS COSTS	\$ 855,868
BENEFIT-COST RATIO	2.71

Figure W: BCA Summary of Benefits

Source: Author

6.6 BuildingScope

Table 7 shows the material calculations used to generate the input for BuildingScope's construction module. All of the material quantities are consistent with what was used in the cost analysis, and were converted to kg units prior to being used in BuildingScope.

BUILDINGSCOPE VOLUMETRIC CALCULATIONS - CODE LEVEL

BUILDING INFORMATION

PERIM.	767	ft
AREA	93,664	sq. ft
HEIGHT	58.5	ft
AREA _{WALLS}	44,879	sq. ft

CONCRETE

ITEM	UNIT	V, C.F.	W, LBS	METRIC	UNIT	NOTES
FTGS	475	12,825	1,923,750	874,035	kg	ENTERED AS VOLUME, C.Y.
S.O.G	4	7,820	1,173,000	532,940	kg	ENTERED AS SLAB THICKNESS, IN.
FLOOR SLABS	4	31,677	4,751,510	2,158,796	kg	ENTERED AS SLAB THICKNESS, IN.
WALL FTG	528	2,813	421,942	191,705	kg	ENTERED AS CROSS SECTIONAL AREA OF WALL FOOTING, SQ. IN.

GROUT

ITEM	UNIT	V, C.F.	W, LBS	METRIC	UNIT	NOTES
ANCH. GROUT		84	12,037	5,469	kg	ENTERED AS VOLUME, C.F.
BRB GROUT	1,499,243	867.62	124,330	56,488	kg	ENTERED AS VOLUME, IN ³

METALS

ITEM	UNIT	A	W, LBS	METRIC	UNIT	NOTES
GRAV. STEEL	375		750,000	340,754	kg	ENTERED AS WEIGHT, TONS
STEEL DECK	3	95,030	285,091	129,528	kg	ENTERED AS WEIGHT, PSF
LAT. BEAMS	62		27,760	33,803	kg	ENTERED AS WEIGHT, PLF
LAT. BEAMS	62		44,640			ENTERED AS WEIGHT, PLF
LAT. COLS	68		27,608	31,120	kg	ENTERED AS WEIGHT, PLF
LAT. COLS	99		40,887			ENTERED AS WEIGHT, PLF
BRB STEEL	284,159		80,577	36,609	kg	ENTERED AS VOLUME, IN ³
ROD	61		29,932	13,599	kg	ENTERED AS VOLUME, C.F.

MISC. CONSTRUCTION MATERIALS

ITEM	UNIT	A	W, LBS	METRIC	UNIT	NOTES
ROOFING	1	93,664	93,664	42,555	kg	ENTERED AS PSF
EXT. WALLS	100%	44,879		4,169	m^2	ENTERED AS PERCENTAGE OF WALL AREA
CARPET	3	93,664	280,992.61	127,666	kg	ENTERED AS PSF
PART. - LG	3.75	93,664	351,241	159,582	kg	ENTERED AS WEIGHT, PSF COLD FORM STEEL
PART. - GWB	11.25	93,664	1,053,722	478,747	kg	ENTERED AS A WEIGHT, PSF GWB
PAINT	10	17,952	2,798	1,271	kg	ENTERED AS SPECIFIC GRAV OF PAINT
ELECT. WIRES	1.554	70,248	9,097.14	8,266	kg	ENTERED AS WEIGHT, PLF
HVAC DUCTS	1	95,030	95,030.20	43,176	kg	ENTERED AS WEIGHT, PSF
POLYSTYRENE	2	95,030	31,676.73	14,392	kg	ENTERED AS THICKNESS, INCHES
PLUMBING	2	93,664	187,328	85,111	kg	ENTERED AS WEIGHT, PSF

Table 7: BuildingScope Material Weight Calculations

Source: Author

7.0 GLOSSARY

Basic Safety Earthquake-1

An earthquake with 10% probability of being exceeded within a 50 year period. Per ASCE 7-05 and IBC 2006, BSE-1 earthquakes have a reoccurrence period of 500 years.

Basic Safety Earthquake-2

Also known as a “maximum considered earthquake” (MCE), an earthquake with 2% probability of being exceeded within a 50 year period. Per ASCE 7-05 and IBC 2006, BSE-2 earthquakes have a reoccurrence period of 2500 years and are 1.5 times larger than BSE-1 earthquakes.

Carbon Footprint

The amount of carbon dioxide released into the atmosphere by a single endeavor.

Collapse Prevention

Buildings designed to this level may experience extensive damage to both structural and nonstructural components. Repairs may be required before reoccupancy, and may be considered economically impractical (ASCE 41-06, 2007).

Embodied Energy

The energy consumed in the production of materials, transportation to site, and their construction.

Fragility Curve

A curve that defines the probabilities of damage at various levels of ground acceleration.

Immediate Occupancy

Minimal or no damage to structural components, and minor damage to nonstructural components (ASCE 41-06, 2007).

Life-Safety

Extensive structural damage to both structural and nonstructural components. May require repairs before reoccupancy (ASCE 41-06, 2007).

Linear Dynamic Procedure

Linear model based on loading using a response spectrum analysis or linear time history analysis. LDP is considered more accurate than LSP, but is allowed only for some structures without irregularities. Considered more accurate than LSP.

Linear Static Procedure

Linear model where triangular loading of base shear is applied to building to determine seismic response. LSP is typically only performed on structures without irregularities. Least accurate of the four analysis procedures per ASCE 41-06.

Nonstructural Drift Ratio

The amount of drift required to cause damage to the nonstructural components in a building.

Performance Based Design

An attempt to design buildings that have a predictable and reliable performance in earthquakes (FEMA 349, 2000).

Response Spectrum Analysis

Procedure for computing the statistical maximum response of a structure to an earthquake.

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