QUANTIFYING THE LIFE CYCLE BENEFITS OF PERFORMANCE-BASED
DESIGN IN SUSTAINABLE DESIGN

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TITLE: Quantification of the Life-Cycle Benefits of
Performance-Based Design in Sustainable Design

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ABSTRACT

Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design

David Carmona

For this thesis, a method is developed and tested for use with performance-based design to quantify the sustainable and financial benefits of designing buildings to a structural performance level higher than Life-Safety. This paper starts to answer the question, “which would be a better investment: build structures to a performance level of Immediate Occupancy (IO) with the likelihood of less damage and downtime after an earthquake or continue to build to the building code’s implied minimum performance level of Life-Safety (LS)?”

An ASCE 7-05 designed base model building (six-story, steel moment frame, office located in San Francisco) was designed to meet the minimum requirements of the LS or stricter code requirements of the IO performance objectives, respectively. Performance levels were verified using the ASCE 41-06 linear static procedures and ETABS models.

The overall cost and cost difference for building the two structures were determined using RSMeans reference manuals. The structural upgrade cost from LS to IO is roughly 1.6% of the $33.4 million initial building cost for a total of approximately $500,000.

The financial damage caused to the two buildings due to a series of earthquakes was determined using the ATC-58 Guidelines and the modeling capabilities of its companion software Performance Assessment and Calculation Tool (PACT). Due to PACT’s work-in-progress status and limited quantity of fragility curves representing building components, results are questionable and expected to become more fine-tuned as the software develops and there is an increased availability of fragility curves.

Using the PACT program, the difference in annualized loss between the IO and LS buildings was determined to be roughly $40,000. This is equivalent to a 2009 present cost of $590,000 over a 50-year building lifespan. By designing the building to an IO performance level, the owner potentially saves 18% ($590,000 loss to future seismic damages/ $500,000 cost to upgrade) over the life-span of the building. As buildings begin to incorporate state-of-the-art, more expensive and efficient components, designing higher performing structures to protect these upfront costs will prove more beneficial than repairing the components at a future date. Considering building downtime and loss of life would increase the value of savings and provide an additional incentive to design a structure directly to a higher performance level.
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISC</td>
<td>American Institute of Steel Construction</td>
</tr>
<tr>
<td>ASCE</td>
<td>American Society of Civil Engineers</td>
</tr>
<tr>
<td>ATC</td>
<td>Applied Technology Council</td>
</tr>
<tr>
<td>CBC</td>
<td>California Building Code</td>
</tr>
<tr>
<td>CSI</td>
<td>Computers and Structures, Inc.</td>
</tr>
<tr>
<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
</tr>
<tr>
<td>IBC</td>
<td>International Building Code</td>
</tr>
<tr>
<td>IO</td>
<td>Immediate Occupancy</td>
</tr>
<tr>
<td>LSP</td>
<td>Linear Static Procedure</td>
</tr>
<tr>
<td>LS</td>
<td>Life-Safety</td>
</tr>
<tr>
<td>PBD</td>
<td>Performance-Based Design</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
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</table>
1.0 INTRODUCTION

This thesis uses performance-based design\(^1\) (PBD) to quantify the sustainable and financial benefits of designing buildings to a structural performance level higher than that implied in the International Building Code’s (IBC), Life-Safety (LS).

1.1 Topic of the Thesis

This thesis investigates building performance to determine if it is more sustainable and economical to design a building’s structural system to a higher performance level than LS. For the purpose of this thesis, sustainability is defined as achieving more usage of the structure and its components with the use of fewer resources. Sustainability could be achieved by using less material over the building’s lifespan or increasing the useable life of the components and structure. There is a growing belief that a sustainable building’s structural systems should be designed to protect the non-structural components (i.e. solar panels, partitions, entertainment equipment, computers, etc.) to a higher degree than what is required from current code standards. Most structures are designed to the IBC’s minimum LS performance level requirement. The primary intent of the code is to protect occupants, not to guarantee the integrity of the building or its contents after a seismic event. As a result, significant damage to structural and non-structural components during seismic events can occur.

\(^1\) Italicized words are defined in the Glossary
When designing a sustainable structure, engineers design for the safety of the inhabitants as well as to protect the building's non-structural components. These non-structural components constitute a large financial portion of the building’s construction cost. According to Taghavi and Miranda (Miranda 2003), a typical building’s construction costs are broken into the following rounded percentages: 20%-30% for the mechanical systems; 10% for the electrical systems; and 10%-20% for the structural system. Buildings that contain larger amounts of equipment (content) invest a lower percentage of money towards the structural and nonstructural portions than to the content. Figure A, below, shows the small percentage of total building cost that is allocated to the structural system for three different building types. In sustainable buildings, non-structural “green” components (such as photovoltaic cells and efficient electrical and mechanical systems) can be expected to consume a higher percentage of the construction cost when compared to traditional building’s components due to their higher costs. Since significant cost and building materials are allocated to the non-structural components, a structural engineer should design beyond the LS requirement in order to protect non-structural systems. Through proper protection of the non-structural components, material resources can be saved and less additional monies need be invested in repairing or replacing the non-structural systems. By designing the building to an appropriate PBD level, structural engineers can create a sustainable and cost-effective building.
1.0 Introduction

Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design

1.2 Purpose of the Thesis

The purpose of this thesis is to quantify and compare the cost and risk of damage to high-performance sustainable structures and their contents; this is accomplished by studying levels of performance over the life-cycle of a conventional code-based structure as compared to a high-performance structure.

This thesis provides a cost comparison between designing new construction to the current-IBC performance level of LS or the higher performance level of Immediate Occupancy (IO). The cost comparison will take into account initial structural construction costs (the difference in cost between two identical buildings with one having the structural system of LS and one upgraded to the level of IO) and the cost to repair damage of the structures and contents due to varying earthquakes.

The thesis utilizes, as the basis for comparison between the two buildings, the Applied Technology Council’s ATC-58 Guidelines for Seismic Performance Assessment of Buildings (Guidelines) (50% draft), in addition to the Guidelines’ companion software, Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design
Performance Assessment and Calculation Tool II Alpha (PACT) (also in draft form).

The *Guidelines* and PACT will be used to determine the financial risk to the structures and to make the financial comparison between the two buildings.
2.0 BACKGROUND

The paper, “Consideration of Building Performance in Sustainable Design: A Structural Engineer’s Role,” by Erik Kneer and Lindsey Maclise (2008), sets the foundation for this project. This paper introduces the concept of merging building performance and sustainable design. Kneer and Maclise discuss the importance of protecting the non-structural components by designing structures to higher performance levels. Fewer resources would be needed to repair or replace components which would experience little or no damage during frequent earthquakes. Sustainability would be achieved through the use of less material over the building’s lifespan and an increased longevity of the components and structure. In summary, matching the performance level of the structural system to the non-structural components’ expected lifespan will improve the sustainability of a building.

2.1 History of the Project

Sustainable design is rapidly becoming an integral part of the building industry’s design process. The United States Green Building Council (USGBC) is a nonprofit organization working to promote sustainability in the construction industry. The USGBC’s green building rating system, Leadership in Energy and Environmental Design (LEED), encourages the building industry’s shift toward sustainability. The Structural Engineering Association of Northern California’s (SEAONC) Sustainability Committee is working to assist the USGBC’s LEED program to incorporate PBD into the
development of sustainable buildings. According to Kneer and Maclise (2008), very little legislation or documentation exists promoting sustainable structural design; the inclusion of PBD in the LEED system will create opportunities for sustainable design to become more mainstream. To support the case for PBD, more research and compelling case studies are required to show the benefits of incorporating PBD in green buildings (Kneer and Maclise 2008).

This thesis develops and tests a research methodology to support the Kneer Maclise hypothesis through the concepts advanced in the ATC-58 Guidelines. ATC-58, developed by the Applied Technology Council (ATC), is a long-term project that develops next-generation performance-based seismic design guidelines for new and existing buildings and to this purpose ATC has released the (50%) draft of the Guidelines and the companion software, PACT. PACT, an ATC project funded by the Federal Emergency Management Agency (FEMA), is being developed to estimate direct property losses using the Guidelines. The project and companion software are in a state of development and future changes are expected.

2.2 Performance-Based Design (PBD)

PBD, a building design method, allows a structural engineer to minimize the theoretical extent of damage a building incurs due to increasing seismic activity levels. The damage predicted for a given seismic event determines the building’s performance level, LS or IO. Current building codes allow for a limited use of performance level. The
majority of structures are designed to meet the IBC’s minimum standard of LS performance. Depending on the type of analysis used to determine the building’s performance level, an engineer will work to limit forces on building members (beams, columns), deflections, ductility, connections, etc.

The concepts of PBD were developed in the 1980s. According to Ronald Hamburger (Hamburger, 2004), structural engineers developed simple PBD procedures to reduce financial damage and other losses due to earthquakes following the Loma Prieta earthquake in 1989 and the Northridge earthquake in 1994. As he states, "present performance-based seismic design practice for buildings in the United States is embodied in appendices to the Recommended Lateral Force Requirements and Commentary (SEAOC, 1999) and the FEMA-356 (ASCE, 2002) national rehabilitation guidelines" (Hamburger 2004). These simplistic performance-based appendices have been adopted by building codes in the United States and are implemented today. However, there are known limitations to these current methodologies. FEMA and ATC are working together to address these limitations with the development of next-generation PBD methodologies in the ATC-58 Guidelines.
3.0 DESIGN MODELS USED IN THE THESIS

To support the cost-comparison investigation, two structural models were developed, a LS model and an IO model, and these were subjected to a series of earthquakes. These two performance levels differ in the amount of damage that is acceptable after a seismic event. A building designed to LS will protect the occupants but can experience significant damage. A building designed to IO, while still protecting the occupants, will experience significantly less damage. The LS and IO model buildings share the same basic building design except in the lateral structural system (due to performance objective differences in deflection and member demand requirements). The two models have a common layout. This base model is a five-bay by six-bay six-story steel moment frame building with two basement levels per Figure B (below). Each bay in plan is 30 feet by 30 feet. Lateral loads are resisted by a single pair of moment frames in the east-west orientation and two pairs of moment frames in the north-south orientation. The base model is symmetrical to each relative axis and is concentric in plan. The structure is located in San Francisco, California. This base model is a representative example of a regular, medium-sized office building from which parallels to existing structures can be drawn. It is intended that a variety of structures with varying performance levels will be compared in the future.

The original base model was designed by Matthew Williams, a previous graduate student at California Polytechnic State University, San Luis Obispo, as part of his thesis,
3.0 Design Models used in the Thesis

titled “Performance Based Analysis of Steel Buildings.” The Williams’ base model building was designed using the Equivalent Lateral Force Procedure per section 12.8 of the ASCE 7-05 *Standard Minimum Design Loads for Buildings and Other Structures*. The base model meets the requirements for use with the ATC-58 *Guidelines* with a performance level midway between LS and IO.

For this thesis, the original base model design was taken and either upgraded or downgraded, while maintaining minimum design checks and code requirements, so that two new models would be produced: one model with structural members upgraded to meet the IO performance level and the other model downgraded to meet the LS performance level. Since the original model was designed to LS, only minor changes were possible. To provide the most cost effective structures, these new models produced buildings that would minimally meet their target performance levels. It should be noted that in the Williams’ base model design, beams were controlled by the shear force, so deeper wide flange shapes were used, and are used in the models herein. Due to design requirements and checks (e.g., moment capacity checks in the beams, or panel zone checks in the columns), the entire LS structure could not be downgraded enough to incorporate only the minimum requirements of LS. In any building design, there are some criteria that reach the target performance level and others that force the component to be minimally above the target level. For instance, a few beams were limited by the moment capacity and therefore oversized for other design requirements in the LS model (refer to Appendix Section B.0 Building Designs and Models, for more information on the...
3.0 Design Models used in the Thesis

building and additional checks performed). Additionally, to replicate industry practice, a limited number of column and beam sizes were used (as opposed to making all columns and beams theoretically their most efficient shapes).

With these considerations, the structural solutions for the LS and IO design were determined. Since detailed connection designs (e.g. beam to column, joist to beams, etc.) were not part of the models, an upgrade in member (i.e. beams and columns) sizes marks the major difference between the two designs. This thesis is based on using the same lateral system for both models. Future areas to investigate are the differences between systems and connection designs since they can contribute significant expenses to a project. A sample difference in structural member sizes between the LS and IO buildings can be seen in the figures below (refer to Appendix Section B.0 Building Designs and Models, for more structural elevations and plans). Figure C and Figure D are the elevations of the East-West oriented moment frames. Note the difference in member sizes between the LS and IO buildings.
3.0 Design Models used in the Thesis

Figure B: IO Model and LS Model Floor Plan and Legend
Source: Author, Using AutoCAD
Figure C: East-West LS Elevation  
Source: Author, Using AutoCAD

Figure D: East-West IO Elevation  
Source: Author, Using AutoCAD
4.0 EXPERIMENTAL PROCEDURE

There are three main stages for this thesis: designing to performance level, costing analysis, and determining the financial risk. The buildings’ performance levels were verified using the ASCE 41-06 *Seismic Rehabilitation of Existing Structures* code. Costing of the structures was based on RSMeans reference guides. Determinations of financial risks were based on the ATC-58 *Guidelines* (which frequently direct the user to follow the ASCE 41-06 and 7-05 code for specific portions of the procedure). Figure E below represents a flowchart of the analysis procedure.
4.0 Experimental Procedure

Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design

Figure E: Analysis Procedure
Source: ATC-58, Modified
4.1 Building Performance Levels Analysis Procedures

This thesis addresses two buildings: one designed to the LS performance and the other designed to the IO performance level. ASCE 41-06 *Seismic Rehabilitation of Existing Buildings* provides methods to analyze, determine, and verify the current performance levels of these two structures. As defined earlier (Section 2.2 Performance-Based Design (PBD)), the extent of damage predicted on a structure for a given seismic event determines the building’s performance level. For this thesis, Williams’ original building design, as discussed in Section 3.0 Design Models used in the Thesis, was downgraded or upgraded into two separate structural models which meet the LS and IO performance level requirements of ASCE 41-06’s Linear Static Procedures. In ASCE 41-06, a static load is determined using the building’s seismic weight, response spectrum (based on the building’s period and damping), and modification factors (found in section ASCE 41-06 3.3.1.3). Williams’ original base model was analyzed with, and compared to, the m-factors of the Linear Static Procedures per ASCE 41-06. The ASCE 41-06’s m-factors provide a method to account for nonlinear deformation capability of structural members of a building using a linear elastic analysis procedure. In order for the structure to be classified under the appropriate target performance level (in this case, LS or IO), the linear static procedure requires the demand-to-capacity ratios of the building’s structural members to fall within the required m-factors (which represent demand-capacity ratios). Table 1 below is a summary of the m-factors used in the project.
4.0 Experimental Procedure

Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design

Table 1: ASCE 41-06 m-factors
Source: ASCE 41-06

<table>
<thead>
<tr>
<th></th>
<th>Immediate Occupancy</th>
<th>Life-Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams</td>
<td>2.00</td>
<td>6.00</td>
</tr>
<tr>
<td>Panel Zones</td>
<td>1.50</td>
<td>8.00</td>
</tr>
<tr>
<td>Columns P/P&lt;0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>6.00</td>
</tr>
<tr>
<td>0.2 ≤ P/PCL ≤ 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>3.00</td>
</tr>
</tbody>
</table>

The LS building is designed to meet Life-Safety for a Basic Safety Earthquake-1 (BSE) level earthquake and Collapse Prevention with a BSE-2 level earthquake. The IO building is designed to meet Immediate Occupancy with a BSE-1 level earthquake and Life-Safety with a BSE-2 level earthquake.

4.2 Cost Analysis Procedure

In order to make a financial comparison and risk assessment, the costs of the two buildings were calculated. The two building designs, LS and IO, with the exception of structural elements in the lateral design, are identically configured and contain the same non-structural components. Due to their non-structural component similarity, the cost difference between the buildings is the difference in the price of structural systems. Three cost components that differed between the buildings were investigated; changes to steel moment frames, foundations, and diaphragms. Analysis and cost differences focused upon weight differences of these three elements due to increased demands. The cost of the connections (i.e. bolts, welds, plates) was taken as a 10% of the total structural steel cost per each building. Miscellaneous steel was assumed to add an additional 25% to the
4.0 Experimental Procedure

Steel weight. Sample cost calculations can be found in Appendix E.0 Building Costs Processes.

Overall building costs were determined using the 2009 editions of RSMeans Building Construction Cost Data, RSMeans Assemblies Cost Data, and RSMeans Square Foot Costs reference manuals. These references were used to determine an average cost associated with office buildings in the state of California and modified for the San Francisco area. All costs are developed as construction pricing assuming construction to begin in 2009. Total cost includes material and labor costs as well as project soft cost as defined in Appendix E.0 Building Costs Processes.

To determine a difference in building costs between LS and IO, the base model foundation and diaphragm were checked for increased seismic force and change in weight due to steel frames. The diaphragm and foundation elements of the LS building were found to meet the IO requirements, and therefore were used in the IO building design as well. As a result, the main cost increase is a function of the additional steel required in the IO building members. Appendix Section E.0 Building Costs Processes further describes the costing process.

A graphical summary of the costing between the two building models is provided in Figure F below. Since the nonstructural base of the buildings is consistent, the difference in price between the two buildings is a result of the cost of the upgraded member sizes in the IO building. The LS and IO buildings cost $33.4 million and $33.9 million, respectively. The rounded structural cost is $4,100,000 for LS and $4,600,000.
4.0 Experimental Procedure

for IO (Appendix Section E.0 Building Costs Processes). This structural cost increase from LS to IO is roughly 1.6% of the total building cost of the LS building (approximately $500,000 for the IO model over the LS model). For the LS building, the percentage of structural cost to that of the entire building is 12.2%, and 13.5% for the IO building.

![Building Cost Diagram](source: Author)

**Figure F: Building Cost Breakdown**

**4.3 Ground Motion Procedures**

The ATC-58 *Guidelines* section 5.7.3 *Time-Based Assessment* was used to develop ground motions. As described in these procedures, the seismic hazard curve from United States Geological Survey (USGS) was used to establish spectral demands. PACT analysis’ were performed with eight target values of spectral acceleration specified as a...
4.0 Experimental Procedure

recommended minimum in the Guidelines. The spectral accelerations range from the Guidelines’ minimum of 0.05/T, where T is the building period, to a maximum of two times the spectral acceleration for an annual frequency of exceedance of 0.0004. The accelerations collected from the ATC-58 procedures were used to develop a design response spectrum using the procedures of the ASCE 7-05 section 11.4.5. The two buildings were analyzed to determine drift using the same response spectra, as opposed to using the same forces. For figures and a more in-depth explanation of the procedure, refer to Appendix Section D.0 Development of Ground Motions.

4.4 Financial Risk Analysis Procedure

Financial risk assessment was performed using the ATC-58 Guidelines and the companion PACT software. The ATC-58 Guidelines “describe a basic methodology and recommend procedures to assess the probable earthquake performance of individual buildings based on their unique site, structural, nonstructural and occupancy characteristics.” The Guidelines were used to determine the type of analysis performed in this thesis, to designate the procedures required to get the necessary PACT inputs, and to interpret PACT results.

The ATC-58 Guidelines contain two procedures for risk assessment: non-linear and simplified. This thesis uses the simplified procedures to make the risk assessments. The simplified procedures use linear analysis methods and simplified analysis procedures to determine the forces in the building. The Guidelines notes that the simplified
4.0 Experimental Procedure

procedure analysis and output is less accurate than the more in-depth non-linear procedures. More advanced analysis procedures may provide higher performance with a more economical design. However, since the intent of this thesis is to compare two buildings against each other, as long as both buildings are designed and analyzed consistently, the use of the simplified procedures will produce equivalent results suitable for the comparative process (an “apples to apples” approach).

The simplified procedure of the ATC-58 Guidelines is based on the following building assumptions:

- The building is independent along each horizontal axis,
- The building is regular in plan and elevation,
- Story drifts do not exceed four times the corresponding yield drift,
- The story drifts are less than 4%, and
- The building is less than 15 stories in height.

The two buildings being analyzed meet these requirements.

In the simplified procedure methodology used for this thesis, the PACT software develops 500 “realizations” per intensity levels, to develop a loss curve. Each “realization” represents one possible set of demands the building will experience due to a ground motion scenario (such as floor accelerations, drifts, forces, and deformations). An intensity level is determined from the target spectral accelerations taken from the site specific seismic hazard curve (Figure R, Appendix Section D.0 Development of Ground
The eight intensity levels represent all possible ground motions the structure may see across its lifetime.

The initial input into the PACT software includes the set of floor accelerations, drifts, and dispersion rates (associated with those two demands) the structure experiences due to each of the eight intensity levels. With these initial building demand inputs, PACT develops an additional set of 499 possible demands the structure may experience as a result of each seismic intensity level (these 500 sets of demands, or realizations, represent 500 potential ways the building will react to the applied intensity level ground motion). PACT determines these additional demands by randomly selecting them from an internally created statistical distribution which considers variations in the “earthquake intensity, ground motion characteristics, and the inherent structural modeling uncertainty” (ATC-58 Guidelines, 2009). These variation uncertainties are assessed through statistical simulation methods, including the Monte Carlo method.

Each realization is then used to determine the damage state of all components in the building through the use of the individual component’s fragility curve (force versus damage, refer to the definitions section of this report for a more in-depth discussion of fragility curves.). Since each of the 500 realizations represents a set of floor accelerations and floor drifts, the PACT software can determine the damages caused to each building component on each floor. PACT sums together all component damage to determine the building’s damage state.
4.0 Experimental Procedure

The building’s damage state and a series of consequence functions (which represents the unit cost versus quantity) are used to determine a single value of cost for each of the 500 realization developed per intensity level. The 500 loss values are assembled into a distribution by being “sorted in ascending or descending order to enable the calculation of the probability that the total loss will be less than a specific value for the given intensity of shaking” (ATC-58 Guidelines, 2009). This allows for the creation of a loss curve.

Each loss curve is multiplied by the “annual frequency of shaking [exceedance values] in the interval of earthquake intensity [target spectral accelerations] used to construct the loss curve; and summing the annual frequencies for a given value of the loss” (ATC-58 Guidelines, 2009).

The outputs collected from the PACT software for use in this thesis are the annualized loss. As explained in the Guidelines, “the annualized loss for repair costs represents the premiums that one should be willing to pay for an insurance policy… While it is not actually expected that an earthquake producing the [annualized loss] will occur each year, in theory, if the owner of the building could self-insure, by placing this amount of money in an interest bearing account each year, over a very long period of time, he should be able to pay for any actual earthquake repair costs using the money in this account” (ATC-58 Guidelines, 2009 Section 2-9). The difference between the annualized losses for the LS and IO building is used to determine the annualized repair savings of one structure compared to the other.
Damage to the building elements is completed using fragility curves. Fragility curves predict how much damage a building component receives due to an experienced force, deflection, or acceleration. After populating the building models with fragility curves, the forces caused by earthquakes can be used to determine how much damage the building experiences. Due to the work-in-progress state of the ATC-58 project and the limited database of available fragility curves, there were only a total of sixteen fragility curves available in PACT. Table 2, below, contains the list of available fragility curves included in the PACT software and which of those curves were used in the analysis.

<table>
<thead>
<tr>
<th>PACT Fragility Curve</th>
<th>Applied in Structure? (X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post 1994 RBS Connection with Welded Web</td>
<td>X</td>
</tr>
<tr>
<td>Exterior Wall OSB and Stucco - Type 3a</td>
<td></td>
</tr>
<tr>
<td>Exterior Skin-Glass Curtainwall – Type 1</td>
<td>X</td>
</tr>
<tr>
<td>Exterior Roofing Concrete Tile - Type 2</td>
<td></td>
</tr>
<tr>
<td>Interior Walls GWB on Wood Studs</td>
<td></td>
</tr>
<tr>
<td>Interior Partitions - Type 9a</td>
<td>X</td>
</tr>
<tr>
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</tr>
<tr>
<td>Conveying - Hydraulic Elevator 1</td>
<td>X</td>
</tr>
<tr>
<td>Conveying - Hydraulic Elevator 2</td>
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</tr>
<tr>
<td>Air Handler</td>
<td>X</td>
</tr>
<tr>
<td>Miscellaneous Housewares and Art Objects</td>
<td></td>
</tr>
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<td>Home Entertainment Equipment</td>
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</tr>
<tr>
<td>Desktop Computers</td>
<td>X</td>
</tr>
<tr>
<td>Servers and Network Equipment in a Single Rack</td>
<td>X</td>
</tr>
<tr>
<td>Tall File Cabinet</td>
<td>X</td>
</tr>
<tr>
<td>Unanchored Bookcase</td>
<td>X</td>
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</table>

Table 2: 16 Fragility Curves Available in PACT
Source: Author
There exist a limited number of fragility curves worldwide. Due to the “apples to apples” project approach in this thesis, even the few fragility curves available should predict a realistic comparison of building damage. Damage to high cost sustainable systems was approximated through the placement of numerous non-structural elements such as home entertainment units, servers, cabinets, and bookcases. An additional effort to model a more extensive equipment HVAC system resulted in the placement of the HVAC on the third and sixth floor. The selected fragility curves were placed throughout the building as per Table 3, Figure G, and Figure H, below.

The PACT II Alpha software incorporates the ability to take into account loss of life and building downtime when considering the effects of seismic events. Neither loss of life or downtime was considered in this project.

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<th>Direction</th>
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<tr>
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<td>7380 ft(^2)</td>
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<td>Interior Partitions - Type 9a</td>
<td>720 ft</td>
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<thead>
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<th>Fragility Curve</th>
<th>Per Floor</th>
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<td>x3 (first floor only)</td>
</tr>
<tr>
<td>Air Handler</td>
<td>x2 (3(^{rd}) Floor)</td>
</tr>
<tr>
<td>Home Entertainment Equipment (later removed)</td>
<td>x48 per floor</td>
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<tr>
<td>Desktop Computers</td>
<td>x120 per floor</td>
</tr>
<tr>
<td>Servers and Network Equipment in a Single Rack</td>
<td>x24 per floor</td>
</tr>
<tr>
<td>Tall File Cabinet</td>
<td>x120 per floor</td>
</tr>
<tr>
<td>Unanchored Bookcase</td>
<td>x120 per floor</td>
</tr>
</tbody>
</table>

Table 3: Fragility Placement
Source: Author
As can be seen in the elevation view below (Figure G), two air handlers were placed on both the ground and third floor, while four were placed at the roof level. The building model has been designed to have twelve offices per floor (Figure H). Each office contains 10 desktop computers, cabinets, and bookcases, 2 servers, and 4 entertainment equipment set ups (the entertainment equipment set ups were later removed, as discussed in Section 5.1 Recommendations for PACT). The placement of these items with their associated fragility curve was to approximate a high functioning sustainable office system.

Figure G: Fragility Placement, Elevation
Source: Author
4.0 Experimental Procedure

Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design

Figure H: Fragility Placement, Plan
Source: Author

Typical Room:
10x Computers
10x Cabinets
10x Bookcases
2x Servers
4x Entertainment Equipment

Typical Floor Layout
5.0 FINDINGS

This thesis uses an “apples to apples” approach to analyze and make comparisons between damage sustained by a LS and IO building due to a seismic event. Due to this approach, a financial comparison could be made despite the work-in-progress status of PACT software (which is not yet developed to a point where the annualized loss output can be fully accepted as discussed in Section 5.1 Recommendations for PACT). Potential annual savings in repair costs for the IO versus the LS building were approximately $40,000 a year (PACT provides an annualized loss for each building modeled. This repair cost is the difference in annualized loss between the two models). Using a 50-year building lifespan and the Federal Discount Rate of 7% in the calculations, the annualized savings is equivalent to a present value of $590,000 in 2009 dollars. Comparing this to the increased first cost of $500,000 of the IO over the LS building, this equates to $90,000 in savings over the 50-year span for the IO building. This single reference point supports the premise of the thesis that PBD yields a more sustainable building since a relatively modest increase in current resources reduces the use of future resources to repair damage due to a seismic event. It should be noted that if a lower interest rate is used, there would be a larger savings (and a quicker breakeven point). A 6% interest rate equates to $130,000 in savings over the 50-year span for the IO building. Additional savings are likely if causalities and building downtime are incorporated in future models.

Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design
While the results thus far indicate that a stronger (higher performance) building provides more protection for contents, there is variation regarding the degree to which LS and IO differ in annualized cost. Fragility curves can be either acceleration or drift controlled. If a low period building is tested on the response spectrum (located on the plateau, Figure I), the LS version would experience higher drifts while analytically experiencing the same acceleration as the IO building. This would imply, for the PACT software, that acceleration damage may be the same for the two buildings, but damage due to drifts will determine the difference in damage. The buildings used in this project have long periods that are not on the plateau (constant acceleration region). This means that the shorter period IO building will experience higher accelerations and lower deflection, while the longer period LS building will experience the opposite: lower accelerations and larger deflection. Unlike a shorter period building, a longer period building (like the one used in this project) will have fragilities affected by both acceleration and drifts. This is important because the LS structure will experience lower accelerations and higher drifts when compared to the IO structure. With this situation, the IO structure theoretically might not save repair cost over the LS structure. The results depend on the type and quantity of materials along with their fragilities (which may be more sensitive to accelerations or drifts).
5.1 Recommendations for PACT

The financial portion of this thesis and subsequent conclusions rely heavily on PACT II alpha software. To better understand the program, various building models were inputted and their characteristics, costs, and components were varied to explore the software’s sensitivity to those components. The following section includes observations made during the project.

The programming for the software is assumed to yield valid results (although the program is still in beta testing), so the technical issues found with the PACT II alpha

Figure I: Design Response Spectrum
Source: ASCE 7-05, Modified
5.0 Findings

program have to do with the software interface. The following are the observed technical issues:

- Result outputs are over a gigabyte in size (this leads to files that are inconvenient to transfer via email or flash drive),
- Ordering issues with data input (the input tables are defaulted to arrange information in order of descending building story level, but when the user reselects input to be arranged in ascending order, and then inputs information, the building story level order reverses to descending, while the input remains ascending), and
- Analysis files are defaulted to save as “.bin,” but only “.xml” files can be opened (the PACT software will error when running “.bin” files).

These issues, although minor, complicated the analysis process.

There are a limited number of fragility curves which limit one’s ability to accurately model any buildings. The lack of fragility curves limits many financial risk programs available today. At the moment, the PACT software is very sensitive to the quantity and placement of fragility curves. With the inclusion of more fragility curves, the financial loss results can be expected to change. The PACT team is currently creating additional fragility curves. Those currently incorporated in the software are still preliminary (some curves have unverified data or contain “place holders” for future entries).
Originally the building was populated with fragility curves as shown in Section 4.3 Financial Risk Analysis Procedure. With this layout, the annualized loss collected from the PACT software indicated a significant deviation for the home entertainment equipment, which more than doubled the repair cost and dwarfed any other structural or nonstructural damage (Figure J and Figure K). This cost due to a single type of component is questionable. The program was run again with the home entertainment fragilities removed and annualized losses indicated a considerably more realistic number. This is shown graphically in Figure J and Figure K. Note how the costs associated with the components’ damages are comparable on the bar plots with home entertainment components removed.

The home entertainment component is relatively expensive ($2500 replacement cost) and very sensitive to accelerations (0.2g cause severe damage) when compared to other fragilities. Although this may be an accurate representation of the component, the software damages the component on a significant number of the seismic events and adds up the damage. Probabilistically, these components may need replacement after many seismic events; but in reality, significant seismic events do not occur yearly. It is unreasonable to assume these components need to be replaced annually. Other fragility curves used in the project were tested for sensitivity but did not have as drastic an effect on the annualized loss.
5.0 Findings

Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design

Figure J: IO PACT Results with Entertainment Equipment Included
Source: Author, using PACT

Figure K: IO PACT Results with Entertainment Equipment NOT Included
Source: Author, using PACT
6.0 CONCLUSIONS AND RECOMMENDATIONS

In this thesis, a method is developed and tested to determine the benefits of designing a structure to a performance level higher than the International Building Code’s implied performance level of Life-Safety (LS). An ASCE 7-05 designed base model building (six-story, steel moment frame, office) was downgraded and upgraded to meet the minimum requirements of the LS and stricter code requirements of the Immediate Occupancy (IO) performance objectives, respectively. The performance level was verified using the ASCE 41-06 Seismic Rehabilitation of Existing Buildings.

The overall cost and cost difference between these two buildings were determined using RSMeans reference manuals. The upgrade cost from LS to IO is roughly 1.6% of the $33.44 million building cost for a total of approximately $500,000. Although this can constitute a large sum of money, it is well understood that a higher performance building better protects its contents. Expensive components are better protected by an upgraded structural system in an expensive state-of-the-art green building. Protecting expensive building contents may be a future buyer’s incentive to upgrade to IO building requirements.

The financial damage caused to the two buildings due to a series of earthquakes was determined using the ATC-58 Guidelines and its companion software Performance Assessment and Calculation Tool (PACT). PACT determined the difference in annualized loss between the IO and LS buildings to be roughly $40,000. This is equivalent to a present cost of $590,000 over a 50-year building lifespan. The benefit-to-
cost ratio of designing the modeled structure directly to IO is 1.18 ($590,000 loss to future seismic damages/ $500,000 cost to upgrade). By designing the building to an IO performance level, the owner potentially spends 18% less during the 50-year lifespan for an IO building over a LS building and the initial up-front cost is returned.

Buildings that are sustainably designed are considered to be green buildings, yet, like hybrid cars, they are often based upon a buyer’s ideals rather than on financial investments: some investors will pay additional initial costs if their investment supports their ideals. However, many green building owners are looking for a return on their investment on those “costly” green components. Sustainably and financially, the client will save resources with an upgraded building and will gain a return on their investment over a long period of time. With these results, it is recommended to build directly to IO for this type of building (long period, six-story, steel moment frame building).

Furthermore, it is expected that if the building had additional components (more fragility curves) it would experience higher repair costs and thus save even more money. A high performance green building (which could not be modeled due to lack of fragility curves) or other structures with expensive equipment (i.e. server farms, museums) would benefit greatly if housed within a higher performing building.

### 6.1 Recommendations for Future Research

Possibilities for future research include exploring the financial and sustainable impacts of designing structures to higher performance levels using different building...
types, advanced analysis methods, and/or advanced structural systems (i.e. damped systems and base isolation). Additionally, costing should be explored which takes into account how often components of the building are replaced due to the component’s age (for instance, desktop computers may be replaced every four years due to upgrades in technology).

More research should be focused into developing fragility curves. Prioritizing on the development of fragility curves that represent fixed structural and architectural components (i.e. building skins, lighting options, finishes, ductwork, architectural features, etc. as opposed to desktop computers, filing cabinets, desks, etc.) would best aid in investigations similar to that performed in this thesis. More of these fixed types of components would allow for a better understanding of how an earthquake damages a building, as opposed to damages to the components in a building. Though both types of damages are desired, and the PACT software looks into both damages occurring simultaneously, having enough fragility curves to be able to make these distinctions confidently would be useful for future investigations.

Furthermore, research should go into observing how different combinations of fragility curves affect the financial assessment. The fragility curves used in this project are either deflection or acceleration sensitive. In this thesis, the two buildings fall in different locations off of the response spectrum’s constant acceleration plateau; one building will cause more damage to acceleration fragilities and less damage to deflection fragilities while the other building will do the opposite (i.e. the IO building is stiffer).
two types of fragilities have the potential of balancing each other out. Since only 16
fragility curves are available, not enough “sensitivities” are provided in the building to
capture the damage in the ideal state-of-the-art sustainable buildings (for instance, if
fragilities were available for high efficiency light fixtures, it is most likely they would be
acceleration sensitive since the light fixture is not affected by the displacement of the
building), and since they are expensive components this would mean more cost damage
would occur for the LS building than the less drifting IO building). Additionally,
comparing the numbers of acceleration based fragility curves to drift based fragility
curves should be explored, otherwise, a building can be “stacked” to skew the results (as
discussed in Section 5.0 Findings). If the proportion of acceleration to drift based fragility
curves is skewed, an engineer may present data that misrepresents the advantages or
disadvantages of upgrading a building (if the engineer places a greater ratio of
acceleration-dependent fragilities, an IO building will receive more damage than the LS
building).
APPENDICES

A.0 The Performance-Based Design Process (defined by ATC-58)

"Performance-based design is a process that explicitly considers building performance in the design process. This is in contrast to the typical building design process in which building components and systems are proportioned and detailed to satisfy prescriptive criteria contained within the building code without direct consideration of the building’s performance. In the performance-based design process, the designers and other stakeholders jointly identify the desired building performance characteristics at the outset and these performance goals then guide the many design decisions that must be made” (ATC-58 Guidelines, 2009).
B.0 Building Designs and Models

The buildings’ structural members were determined using standard code checks. Forces acting on the members were determined using ETABS. A sample portion of the calculation spreadsheet used for beam and column design can be found on the following page (Figure J). The performance level of the structure was determined using an additional spreadsheet (Figure K). This spreadsheet compares the capacity of the member, multiplied by its respective “m-factor” (LS or IO), with the member’s experienced load. The spreadsheet is programmed to provide a color code on the beam members to tell the user which performance level the member falls within. In this spreadsheet, members satisfy either pre-IO requirements or IO requirements (the author’s objective was to meet the bare requirements of the target performance and, thus, some members slightly exceed or barely reach the performance requirements)
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### Figure K: Performance Level Sample Excel Spreadsheet

#### Source: Author, using Excel

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<td>$P/P_{CL}$ ≤ 0.2</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Maximum Moment in Beam</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Frame Line 6</td>
<td>A-B</td>
<td>B-C</td>
<td>C-D</td>
<td>D-E</td>
<td>E-F</td>
<td>F-G</td>
<td>Average</td>
</tr>
<tr>
<td>$P/P_{CL}$ ≤ 0.5</td>
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<td></td>
</tr>
<tr>
<td>Moment Capacities</td>
<td>A-B</td>
<td>B-C</td>
<td>C-D</td>
<td>D-E</td>
<td>E-F</td>
<td>F-G</td>
<td>Average</td>
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</table>

#### Normalized to D Moment

<table>
<thead>
<tr>
<th>Frame Line 1</th>
<th>A-B</th>
<th>B-C</th>
<th>C-D</th>
<th>D-E</th>
<th>E-F</th>
<th>F-G</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P/P_{CL}$ ≤ 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame Line 6</td>
<td>A-B</td>
<td>B-C</td>
<td>C-D</td>
<td>D-E</td>
<td>E-F</td>
<td>F-G</td>
<td>Average</td>
</tr>
<tr>
<td>$P/P_{CL}$ ≤ 0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The structural design solutions for the LS and IO buildings can be found below.

As mentioned earlier, the upgrade in structural member sizes marks the major difference between the LS and IO buildings. Figure L and Figure M are the elevations of the external North-South oriented moment frames. Figure N and Figure O are elevations of the internal North-South oriented moment frames.
Figure L: External North-South LS Elevation
Source: Author, Using AutoCAD

Figure M: External North-South IO Elevation
Source: Author, Using AutoCAD
Figure N: Internal North-South LS Elevation
Source: Author, Using AutoCAD

Figure O: Internal North-South IO Elevations
Source: Author, Using AutoCAD

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C.0 ETABS Model Assumptions

The modeling and analysis was performed using the software ETABS Nonlinear Version 9.6.0. ETABS is a structural analysis software released by Computers & Structures, Inc (CSI). The output collected from this program for input into PACT II-alpha was absolute story drifts.

ETABS modeling assumptions include the following:

- All diaphragms rigid,
- Base of model was pinned, and
- Lateral forces were determined based on the superstructure.

Two ETABS models were developed to represent the LS and IO buildings.

Figure P: ETABS Model
Source: Author
D.0 Development of Ground Motions

The ATC-58 *Guidelines* section 5.7.3 *Time-Based Assessment* was used to develop ground motions. As described in these procedures, the seismic hazard curve from USGS was used to establish spectral demands. A logarithmic interpolation was taken to find the seismic hazard curve at the two buildings’ fundamental period (roughly 1.6 seconds and 1.8 seconds for IO and LS, respectively). The fundamental periods were originally attained through the use of ETABS software and comparisons with period approximation methods such as the Rayleigh Ritz method. The USGS-produced basic hazard curves at periods of 1 second and 2 seconds were used as the boundary values for the interpolation (Figure Q is a screenshot of the data collected). PACT analysis’ were performed with eight target values of spectral acceleration ranging from the *Guidelines*’ minimum of $0.05/T$ to a maximum of two times the spectral acceleration for an annual frequency of exceedance, 0.0004. A spectral acceleration represents the approximate acceleration experienced by the building. Figure R (on the following page) represents the hazard curve and target accelerations developed using these procedures. These two maximum and minimum values are labeled on the chart.

The accelerations collected from the ATC-58 procedures were used to develop a design response spectrum using the procedures of the ASCE 7-05 section 11.4.5. The two buildings were analyzed to collect drift using the same response spectra, as opposed to the same forces. Figure S is the response spectrum developed using the accelerations and
exceedance values of the ATC-58 procedure. Figure T (on the following page) is the standardized ASCE 7-05 developed design response spectrums.

Figure Q: Screenshot of USGS Data
Source: USGS

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Figure R: Seismic Hazard Curve
Source: Author, Using MATLAB

Figure S: Hazard Spectrums through Eight Targets
Source: Author, Using MATLAB
The set of figures above represent some of the key graphs developed during ground motion preparation procedures. Additionally, Table 4 (below) includes the eight target spectral accelerations, $S_a$, and their corresponding exceedance rates, $e$, developed and used for this thesis.

<table>
<thead>
<tr>
<th>Target</th>
<th>Exceedance</th>
<th>LS $S_a$ [g]</th>
<th>IO $S_a$ [g]</th>
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</thead>
<tbody>
<tr>
<td>Target 1</td>
<td>0.01419</td>
<td>0.1339</td>
<td>0.1673</td>
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<tr>
<td>Target 2</td>
<td>0.00391</td>
<td>0.2383</td>
<td>0.2672</td>
</tr>
<tr>
<td>Target 3</td>
<td>0.00150</td>
<td>0.3492</td>
<td>0.3756</td>
</tr>
<tr>
<td>Target 4</td>
<td>0.00057</td>
<td>0.4962</td>
<td>0.5631</td>
</tr>
<tr>
<td>Target 5</td>
<td>0.00032</td>
<td>0.5665</td>
<td>0.6881</td>
</tr>
<tr>
<td>Target 6</td>
<td>0.00013</td>
<td>0.7541</td>
<td>0.8756</td>
</tr>
<tr>
<td>Target 7</td>
<td>0.00008</td>
<td>0.8200</td>
<td>0.9381</td>
</tr>
<tr>
<td>Target 8</td>
<td>0.00004</td>
<td>0.8859</td>
<td>1.0631</td>
</tr>
</tbody>
</table>

**Table 4: Spectral Accelerations with Corresponding Exceedance Rates**

Source: Author

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E.0 Building Costs Processes

As mentioned in the body of the report, three structural costs were investigated to determine the difference in building cost for the two buildings. These were based on the following differences in weights: the steel frames; potential fortifications to foundations due to the increased steel frame weight, and the added steel in the diaphragms. The cost of steel associated with the connections is represented as a percentage of the total structural steel per each building.

To calculate the difference in steel frame weight, the weight in pounds was determined for each building by developing an individual element weight and then summing these elements. The total tonnage was determined for each building and 10% of that weight was added to account for connections, and 25% for miscellaneous steel (including miscellaneous foundation steel).

Changes in foundation design are based on increases in axial loads due to increased building weight and overturning forces. Foundations sizes were determined using tables from the Concrete Reinforcing Steel Institute (CRSI 1992). These tables allow a designer to use a pre-determined footing when the concrete capacity, soil capacity, and loading on the footing are known. The larger IO seismic loading was not enough to increase the footing size.

The main difference in loading between the LS and IO building is the difference in weight due to the difference in steel frames. The weight variation was not enough to
require different foundations for each building. It is likely that the building basement configuration contributed to this small foundation change. Future investigation may want to consider a slab on grade configuration to capture foundation differences.

Increased diaphragm loads due to increased lateral forces did not trigger a change in the composite deck design. The composite deck used in the LS building was checked and found sufficient for use in the IO building.

Building costs were determined using the RSMeans Building Construction Costs reference manuals (2009 Editions). RSMeans collects cost information on various types of construction projects across the nation. These generic costs were modified to reflect geographic location and specific building configurations. Average national costs were adjusted by RSMeans-provided multipliers to account for the building’s specific geographic location.

A second modifier reflects specific configuration constraints. The basis of RSMeans is that the default-configured layout and building type provided in the reference manual can be modified to match the desired building by the provided adjustment multipliers/additions. Modifications were required for square footage and perimeter of the building. Project costs are based on construction being completed in 2009. Soft cost were based on RSMeans standards and include: Contract Fees (General Requirements 10%, Overhead 5%, Profit 10%) and Architect Fees (6%).

Provided below is a sample breakdown of the types of numbers and assumptions made during the costing analysis. Note that the references were used to determine an
average cost associated for office buildings in California. Project costs are based on construction being completed in 2009.

Sources:
RSMeans Square Foot Costs 2009 (Square)
RSMeans Assemblies Cost Data 2009 (Assemblies)
RSMeans Building Construction Cost Data 2009 (Construction)

RSMeans Base Model (Square):
8 Story Office Building with 12’ Story Height and 80,000 ft\(^2\) Floor Area

**Building Information:**
- **Type:** 6-Story Steel Moment Frame, 2 Basement Levels, Office
- **Location:** San Francisco, California
- **City Index:** Metals: 1.065 (multiplier) (Construction), General: 1.24 (multiplier) (Square)
- **Typical Story Height:** 12.5 ft
- **Perimeter:** 660 ft
- **Area:** Per Floor: 27000 ft\(^2\), Total: 162000 ft\(^2\)
- **Steel Weight:** LS: 910 tons, IO: 1025 tons

The required adjustments include: square footage, story height, perimeter, structural components, and geographic location.
## Adjustments to RSMeans Base Model

<table>
<thead>
<tr>
<th></th>
<th>RSMeans Model</th>
<th>Base Model</th>
<th>Adjustment</th>
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<tbody>
<tr>
<td><strong>Square Foot (ft²)</strong></td>
<td>200000-150000</td>
<td>162000</td>
<td>$154.98*</td>
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<tr>
<td><strong>Perimeter (ft)</strong></td>
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<td>660</td>
<td>+$3.50</td>
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<tr>
<td><strong>Structural</strong></td>
<td></td>
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<td>-$22.48</td>
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<tr>
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</tr>
<tr>
<td>Structural**</td>
<td>Removed from RSMeans Model</td>
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<tr>
<td></td>
<td></td>
<td>LS</td>
<td>+$25.13</td>
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<td>IO</td>
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<tr>
<td><strong>Basement</strong></td>
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<td>2 Floors</td>
<td>$1,965,600</td>
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<tr>
<td><strong>Totals</strong></td>
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</tr>
<tr>
<td>LS</td>
<td></td>
<td></td>
<td>$33,356,340</td>
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<tr>
<td>IO</td>
<td></td>
<td></td>
<td>$33,869,880</td>
</tr>
</tbody>
</table>

* RSMeans model base cost per square foot
**Add the LS or IO to the base, but not both. This value takes into account the difference in steel costs between the two structures (including the 10% and 25% steel increase for connections and misc, respectively). This value already includes materials multiplier (do not apply city multiplier).

Table 5: Adjustments to RSMeans Base Model
Source: Author
The nonstructural building base is consistent in cost between the two structures.

The difference in price between the two buildings is a result of the structural systems being used, specifically the heavier steel beams and columns in the IO model.
F.0 Additional PACT Considerations

The ATC-58 Guidelines recommends the use of their pseudo lateral force method for simplified analysis when developing drifts. After drifts were collected, they were to be modified by the Guidelines’ corresponding modification procedures to account for inelastic action and higher mode effects (ATC-58 Section 6.3). Instead, a design response spectrum was developed (Section D.0 Development of Ground Motions) and a modal analysis was performed using ETABS to develop the drift values. These modal analysis drift values were used as input into PACT.

Additional requirements for the performance assessment, as aside from ETABS drift values, are median story accelerations and dispersion rates. Median floor acceleration values were determined using the Guidelines’ Section 6.3 and dispersion values were collected from Table 6-3 in the Guidelines’ Section 6.3. To use these tables, the force causing the building to yield must be known. This yield force was determined using the non-linear static procedures of the ASCE-41-06.

PACT II-alpha allows the user to select “seeds” associated with the random seed generator in order to use a consistent set of probabilities. By using a selected “seed,” the same earthquake probabilities were used to generate PACT results for both the LS and IO buildings.
Glossary

The following list defines phrases, names, and words used frequently throughout this report:

**Acceleration:**
The rate of change of velocity per second.

**Annualized Loss:**
According to the ATC-58 *Guidelines*,

> “the annualized loss for repair costs represents the premiums that one should be willing to pay for an insurance policy. […] While it is not actually expected that an earthquake producing the [annualized loss] will occur each year, in theory, if the owner of the building could self-insure, by placing this amount of money in an interest bearing account each year, over a very long period of time, he should be able to pay for any actual earthquake repair costs using the money in this account.”

**Deflection:**
The change in distance of a component from the component’s starting position.

**Federal Discount Rate:**
The rate the Federal Government assigns for the value of money in any cash flow related project.

**Fragility Curves and Damage States:**
The degree of damage a building component receives is categorized into different Damage States (DS). A component falls under a certain DS when the damaged component requires the same type and degree of repairs accounted for in that DS. For instance, DS 1 might account for re-plastering cracks that formed on a wall while DS 3 may account for complete replacement of the wall after if it is un-repairable. By categorizing components damages into DS, the user can easily associate a cost to damage.

Through repeated testing and recordings of how components experience damage as a result of an applied demand (i.e. acceleration or drift), a user can generate a fragility curve. A fragility curve correlates demand to the probability of reaching a certain DS. In
Figure U below, the drift-controlled component can be proportioned into three different DS based on the level of drift the component experiences.

For example, if the drift-controlled component experiences a story drift of 5% (or 0.05), as demonstrated in Figure V, there is a 55% probability of reaching the most severe DS 3, a 21% probability of reaching DS 2, an 18% probability of reaching the easily repairable DS 1, and 6% probability of receiving no damage. As the drift the component experiences increases, the component has a higher probability of entering more damaging DS. At lower story drift levels, the component has a higher probability of reaching lower DS.
After determining how the component is being proportioned into DS, it is possible to predict a cost. Using the example above and assigning a cost of $10 to DS 1, $30 to DS2, and $100 DS 3, the predicted cost of repair (Cr) associated with this drift-controlled component would be:

\[ Cr = 55\% \times $100 + 21\% \times $30 + 18\% \times $10 = $63.10 \]

The predicted cost of repair for this component would be $63.10. This process would be repeated for all the other components in the structure with the appropriate demand.

Since the objective of this report is to simulate the range of all possible earthquakes, this process is repeated for each realization (500 realizations were used for each intensity level) and the data is manipulated as described in Section 4.4 Financial Risk Analysis Procedure.
Immediate Occupancy:
According to Naeim, Bhatia, and Lobo (2009):

*Immediate Occupancy: [(a) structurally]: Limited structural damage with the basic vertical and lateral force resisting system retaining most of their pre-earthquake characteristics and capacities. . . [ (b) Non-structurally]: Non-structural elements are generally in place but may not be functional. No back-up systems for failure of external utilities are provided.*

Life-Safety:
According to Naeim, Bhatia, and Lobo (2009):

*Life-Safety: [(a) structurally]: Significant damage with some margin against total or partial collapse. Injuries may occur with the risk of life-threatening injury being low. Repair may not be economically feasible. . . [ (b) Non-structurally]: Considerable damage to non-structural components and systems but no collapse of heavy items. Secondary hazards such as breaks in high-pressure, toxic or fire suppression piping should not be present.*

Non-Structural Component:
ATC-58 Guidelines (2009) defines a non-structural component as "a building component that is not part of the structural system."

Performance:
ATC-58 Guidelines (2009) defines performance as "the consequences of a building’s response to earthquake shaking expressed in terms of the probable number of casualties, downtime and direct economic loss."

Performance-Based Design (PBD) or Performance-Based-Seismic Design:
According to Naeim, Bhatia, and Lobo (2009):

Performance-based design is an attempt to predict building [behavior] with predictable seismic performance. Therefore, performance objectives such as life-safety, collapse prevention, or immediate occupancy are used to define the state of the building following a design earthquake.

Performance Levels:
According to Naeim, Bhatia, and Lobo (2009):

*Life-Safety: [(a) structurally]: Significant damage with some margin against total or partial collapse. Injuries may occur with the risk of life-threatening injury being low. Repair may not be economically feasible. . . [ (b) Non-structurally]: 

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Considerable damage to non-structural components and systems but no collapse of heavy items. Secondary hazards such as breaks in high-pressure, toxic or fire suppression piping should not be present.

Immediate Occupancy: [(a) structurally]: Limited structural damage with the basic vertical and lateral force resisting system retaining most of their pre-earthquake characteristics and capacities. . . . [(b) Non-structurally]: Non-structural elements are generally in place but may not be functional. No back-up systems for failure of external utilities are provided.

Repair Cost:
The cost to restore a building to the building's pre-earthquake state.

Structural Component:
ATC-58 Guidelines (2009) defines a structural component as "a building component that is part of the intended vertical or lateral force resisting system, or that provides measurable resistance to earthquake-induced building deformations."

Sustainability:
Sustainability is defined as achieving more with the use of less resources.

Time-Based Assessment:
ATC-58 Guidelines (2009) defines time-based assessment as "an assessment of probable building performance over a specified period of time, considering all earthquake scenarios that could occur during that period of time, and the probability of occurrence of each."
WORKS REFERENCED


Quantifying the Life Cycle Benefits of Performance-Based Design in Sustainable Design
WORKS CONSULTED


