Consideration of Building Performance in Sustainable Design: A Structural Engineer's Role

Erik Kneer, PE, LEED AP; Lindsey Maclise, PE, LEED AP; Co-Chairs
SEAONC Sustainable Design Committee
San Francisco, CA

Abstract

The role of structural engineering in sustainable design is widely perceived as being limited to material specifications and structural efficiency. However, as innovation in structural design continues, performance-based design (PBD) and building life-cycle assessment (LCA) present more opportunities for structural engineers to contribute to the sustainable design team. With these tools, design professionals now have the ability to determine whether placing high-performance architectural and mechanical systems in a building with a code-based structural system offers the greatest value to our clients, or whether such a design fails to protect the investment of capital and resources for a building in a high-risk hazard area.

This document summarizes the synergies between PBD and the sustainable design process. It will outline the developing procedures and design tools available to the structural practitioner as they integrate PBD into their green building projects. Lastly, it will discuss PBD within the context of the USGBC's current and future LEED rating system, and present case studies for examples of implementation.

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Introduction

Structural engineers form an integral part of the sustainable design process. Their role can include the judicious use of materials, resourceful use and application of structural systems, and provisions for future adaptability and deconstruction of buildings. Collaboration with other design professionals is critical to the structural engineer's successful role on a project. Understanding lighting, stacking, thermal mass, and cooling/heat gain strategies enables the structural engineer to anticipate and respond to these issues in the building structure.

Structural engineers have the opportunity to play an even larger role in regions of high natural hazard risk. Protecting the high-performance architectural and mechanical systems is essential for a sustainable building that is likely to experience a high-consequence natural hazard over its lifetime. Such hazards include earthquakes, hurricanes, tornados, fires and floods. The risk of seismic events will be the primary focus of this paper. However, the strategies presented can be applied as a model for other natural hazards.

The intent of this paper is to focus on the role that building performance plays in minimizing the environmental impact of buildings located in areas of risk, and advocate the continued leadership of structural engineers in developing tools and strategies for use in sustainable design.

Building Performance Behavior and Consequences

The SEAOC blue book states that its purpose is "primarily to safeguard against major structural failures and loss of life, not to limit damage or maintain function." [SEAOC Blue Book, 1999]. Therefore, designing a sustainable building with a code-based lateral system does not ensure the protection of the high-performance M/E/P and architectural systems that are often expected to payoff their operation over the life-cycle of the building. This has significant consequences for sustainable structures in areas at risk from natural hazards.

In California, the natural hazard of most concern is earthquakes. Using observed damage from earthquakes, engineers are able to better predict damage scenarios for buildings based on the structural system. Damage, as defined in this paper, references damage to structural, non-structural, and building contents. When damage occurs, a building and its contents must be repaired or replaced. The repair effort uses resources in the form of labor, raw materials, and business resources that are suspended or redirected. If the damage is extensive, such that repair is not cost effective, then the building may be demolished and its components disposed of in a landfill or recycled.

During a seismic event, damage to a building is generally the result of excessive floor accelerations and inter-story drifts. As the following sections will show, non-structural components and building contents comprise the majority of the building's initial and post-earthquake recovery cost.

In 2003, Taghavi and Miranda performed a study of component cost distribution in offices, hotels, and hospitals. [Provide footnote] The variation between nonstructural components and building content was found to be related to the building use. In general, structures that contain large amounts of equipment, such as laboratories or hospitals, had a greater portion of their construction cost devoted to contents rather than to non-structural components. The chart below represents the result of the study.

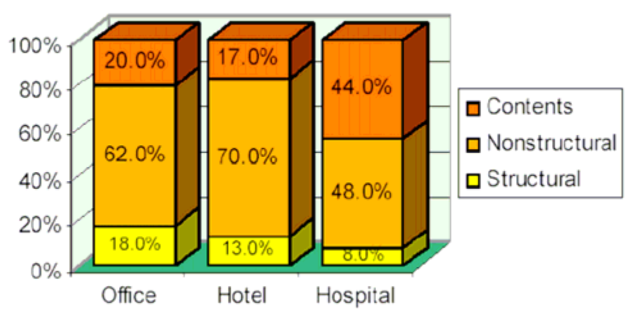

Figure 1: Taghavi and Miranda Study: Distribution of Building Cost by Building Type

Additionally, it was determined that mechanical systems account for between 20-30% of the construction cost, while electrical systems generally comprise 10%. Although, nonstructural components and building contents comprise the majority of the buildings' cost, the intent of the building codes is to provide "life safety", and does not preclude significant damage to these secondary components.

For example, ASCE 7-05 limits inter-story drift in buildings to between 0.01-0.025 of the story height depending on the selected structural system. Recently full-scale tests were conducted in Japan that cyclically loaded three interior partition configurations with increasing amplitude. The study investigated both the extent of damage and the cost of repair associated with varying levels of drift. Partition configurations containing door openings experienced the most damage at the lowest drift. At a drift of 0.01, resulting in shear distortion of the door of 0.006, the door could no longer open, and the partition was severely cracked. In general, solid partitions performed relatively well, being able to accommodate drifts of 0.015 before crushing. The study attributes the good performance of these partitions to their careful detailing. In Japan it is common to leave the vertical studs unscrewed from the floor runners allowing the gypsum to slide over the runners at the onset of loading. The study suggests that typical detailing in the US does not provide this type of sliding mechanism, therefore it was estimated that US partitions would likely incur damage at drifts of 0.005. In all of the partitions tested, the cost to repair damage exceeded the initial cost of the partition at drift levels of 0.02. Therefore, based on the code required inter-story drift limit of 0.01-0.025, this study shows that extensive damage to the non-structural elements may result during a major seismic event, resulting in extensive damage.

The damage resulting from a major seismic event can have significant financial impact. In a study entitled "When the Big One Strikes Again," engineers evaluated the consequences of likely building damage and losses if a repeat of the 1906 San Francisco earthquake were to occur in 2006 [Kircher et al 2006]. The study looked at a M7.9 on the San Andreas Fault over a 19-county region of the Bay Area including an estimated 3 million buildings amounting to 7.75 billion square feet and $1.5 trillion dollars of capitol invested in buildings and building contents. It was forecast that 7,000 to 10,000 commercial and 160,000 to 250,000 residential buildings would suffer damage severe enough to force evacuation. The study estimates that it would cost $111 billion dollars to repair or replace damaged components. Of this $111 billion dollars, $75 billion is related to non-structural components, while $17 billion is contained within building contents, and $20 billion within the structural system. These costs do not include loss of infrastructure or potential loss from fire or other post-earthquake outbreaks. It should be noted that the predicted ground motions are equivalent to the current California Building Code (CBC) Design Basis Earthquake (DBE) for regions within 15km from the fault. In addition, only 3.5% of the total at risk square footage is comprised of unreinforced masonry, non-ductile concrete frames, or soft-story wood structures, which emphasizes the degree to which Code-designed buildings are seismically vulnerable.

To put these figures in the context of damage from past events, the 1989 Loma Prieta earthquake was estimated to have cause in excess of $7 billion based on the total cost of the buildings damaged and approximately 34,000 buildings were damaged. The 1994 Northridge and 1995 Kobe earthquake losses were estimated at $20 billion and $80 billion respectively. In a proper comparison, these numbers should be factored up by approximately 1.5 to estimate current value.

There are additional negative financial impacts resulting from seismic damage. The recovery efforts have additional physical and time components. For example, repair of the building as well as an interruption of business operations can be costly. The losses from downtime of the business can contribute significantly to the overall repair costs. In the Kircher study of the repeat 1906 event, the additional costs due to loss of building function (i.e. business interruption) was $11 billion dollars. Furthermore, the owner may lose some or all long-term cost advantages of initial sustainable design decisions, such as the installation of high efficiency M/E/P systems or solar panels.

The losses cited above show how possible financial impact of a highly damaging event can far outweigh the initial upfront costs for many clients. In a typical building the structural system accounts for approximately 10%-20% of the construction cost. Therefore, a 10% increase in cost of the structural system equates to only a 1%-2% increase in the overall cost of the building, but may provide substantially better building performance. A structural system that provides enhanced performance will result in a reduction of floor accelerations and/or inter-story drifts. Advanced structural systems, such as base-isolation, damped frames, or self-restoring frames are some options available to structural engineers. In addition to limiting damage and conserving initial construction cost, the initial embodied energy of the structure is preserved and the usable life of the building may be extended.

Building performance targets after an earthquake are divided up into the categories of Operational, Immediate Occupancy, Life Safety, and Collapse Prevention. For a building to achieve Operational performance after an earthquake the building must have little or no damage to structural and non-structural elements and business is uninterrupted. Immediate Occupancy performance allows for minor non-structural damage and repairable structural damage after an event, however there is continued use of the building. Life Safety performance is defined as heavy non-structural and structural damage that must be repaired before the building can be used, and occupant casualties must be avoided. Collapse Prevention means that the building is heavily damaged and repair is not possible, however occupants are able to escape the building. The SEAOC Blue Book provides basic requirements for seismic design which can be defined within these building performance categories [SEAOC Blue Book, 1999]. Structures designed in accordance with the Blue Book should provide the following basic performance levels:

- Have the ability to resist a minor earthquake without damage, Operational building performance.
- Have the ability to resist a moderate earthquake without structural damage and with only minor non-structural damage, Immediate Occupancy building performance.
- Have the ability to resist a major earthquake (MCE) without collapse but possibly with structural and non-structural damage, Collapse Prevention building performance.

When a higher level of performance is required, the performance-based design is achieved by “targeting” a performance objective of a building for a certain level of earthquake. For example an owner may request minimal damage (i.e. Immediate Occupancy) after a more frequent event, but allow for major damage (i.e. Collapse Prevention) after a major event.

Affect of Building Performance on Embodied Energy and Global Warming Potential

To further understand the environmental importance of considering building seismic performance, it is necessary to understand the concept of embodied energy. The embodied energy associated with a building consists of all the elements that were used to create the building. This starts from mining of the minerals to produce steel, to the harvesting of trees for lumber, to the quarrying of aggregates for concrete. Embodied energy includes the transport and processing of these materials in each step until they reach the construction site, and theoretically should include the energy expended during construction and within the construction waste materials.

The embodied energy of structural components makes up about a quarter of the embodied energy of all elements installed at the time of construction. Even though structural components generally comprise a small proportion of the total building cost, they contribute to a larger proportion of the total embodied energy of the building. This percentage is due to the energy intensive processes required to manufacture concrete and steel, in addition to possible high transport distances for particular materials.

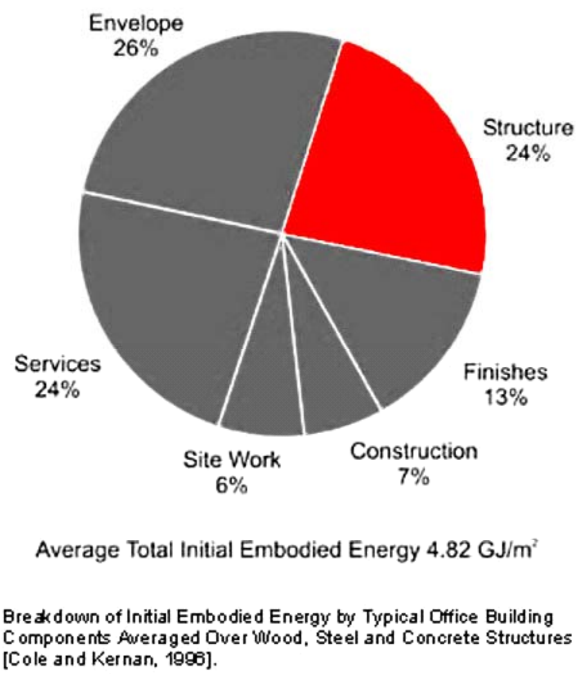

Figure 2: Breakdown of Building Embodied Energy for a Typical Office Building [Cole and Kernan, 1996]

Material	MJ/kg [Embodied Energy per unit of Mass]
Aggregate	0.1
Straw bale	0.24
Concrete block	0.94
Precast Concrete	2
Concrete	1.3
Lumber	2.5
Brick	2.5
Plywood	10.4
Steel (new)	32
Steel (recycled)	8.9
Cellulose Insulation	3.3
Gypsum Wallboard	6.1
Linoleum	116
Carpet	148
Aluminum	227

Table 1: Embodied Energy for Typical Building Materials

As shown in Table 1, architectural components of the building, such as gypsum board and carpet, have high embodied energy values, per unit of mass, when compared to structural materials. Although the listed environmental impacts represent current and typical values, structural engineers can reduce the embodied energy and global warming potential of commonly used materials through reduction, thoughtful selection, and reuse.

It is important to note that embodied energy is not the only quantity that contributes to environmental impacts. Carbon-containing gases, such as carbon dioxide (CO_2) and methane (CH_4) are found to be the largest contributors, by volume or toxicity, to global warming. These emissions are commonly weighted into a “carbon equivalent” metric, seen as “CO_2e.” The charts below show the embodied energy and green house gas emissions based on building area for commonly used structural materials.

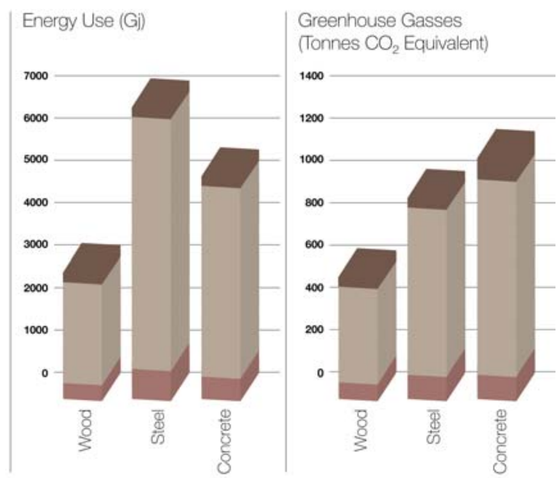

Figure 3: Athena Comparison of Greenhouse Gas Emissions and Energy Use for three 4600 m^2 Buildings [Athena Project]

Every structural material has different embodied environmental inputs and outputs. The three most popular -- steel, concrete, and wood – vary in their impacts. Steel has the highest embodied energy per ton, while concrete is highest in CO_2 emissions due to calcination of cement in addition to the energy use. Wood has much less embodied energy and CO_2 associated with it, but deforestation has a significant indirect affect on global warming [Webster, 2001]. More significantly, if the lower inherent durability of a wood structure, as compared to a concrete or steel structure, causes it to be replaced, then the embodied energy and carbon are nearly equalized. [Athena Institute] All three materials have advantages and disadvantages for use in sustainable design. When selecting materials, it is important to examine specific project requirements including site context, material source, availability, transportation, fabrication, and an appropriate application of the material based upon its intended use.

Each material needs to be judged for its qualities within this framework, and then a maximum amount of effort should be taken to reduce the negative environmental impacts. For example, if steel is chosen for its ductility in a high-seismic region, then one could investigate reusing locally salvaged steel and design the long span elements for deconstruction allowing for use in future steel structures. Likewise, if concrete is chosen for its durability in a region near salt water, or allowance for low floor-to-floor heights, then a maximum amount of cement replacement and recycled aggregate should be employed. [Brand 1995] The following case study demonstrates a typical embodied energy analysis for structural materials.

Case Study: The Council for Information Technology Research in the Interest of Society (CITRIS) Building [Mehta, 2008]

This building, located on the University of California, Berkeley campus utilized High Volume Fly Ash [HVFA] as a replacement for Portland cement. The CITRIS building, designed by Forell/Elsesser Engineers, is comprised of two buildings that are seismically separated. One building is concrete construction with shear wall lateral system. A concrete system was selected to maximize floor-to-floor heights and long spans while meeting stringent vibration criteria for laboratory spaces. Through the replacement of Portland cement, the building was able to reduce its carbon footprint and embodied energy significantly. The building utilized a 55% fly ash and slag replacement mixture for most of its structural elements. Through the use of HVFA the building was able to achieve higher compressive strengths at 56 days, and was estimated to save 1300 tons of CO_2.

Besides reducing environmentally harmful impacts within the structural materials themselves, the structural system has the potential to play an even larger role. The structure has the critical role of protecting the non-structural systems from damage. Combined these systems comprise more than 80% of the total embodied energy. Low-probability, high-consequence events such as earthquakes pose a particular threat to shortening the life span of the elements that comprise the embodied energy of the building.

The proportion of embodied energy and carbon should be understood in context of total building energy use and carbon output. Building energy reduction strategies tend to focus on operational energy. Operational energy is defined as the energy that a building consumes while in use and is typically measured as an annualized cost. This includes electricity, water and refuse. The total environmental impact of a building over its life span, both embodied and operational, is commonly referred to as Cradle to Grave.

Building Life Span

The ratio between operational and embodied energy is highly dependent on the assumed life-span of the structure. It is commonly stated that a building's embodied energy only comprises 8-20% of the total energy consumption; however, the life-span this is based on is around 66 years. [Athena Institute]. Of the total building energy 3-5% is for structural components alone [ISE, Nov 1999].

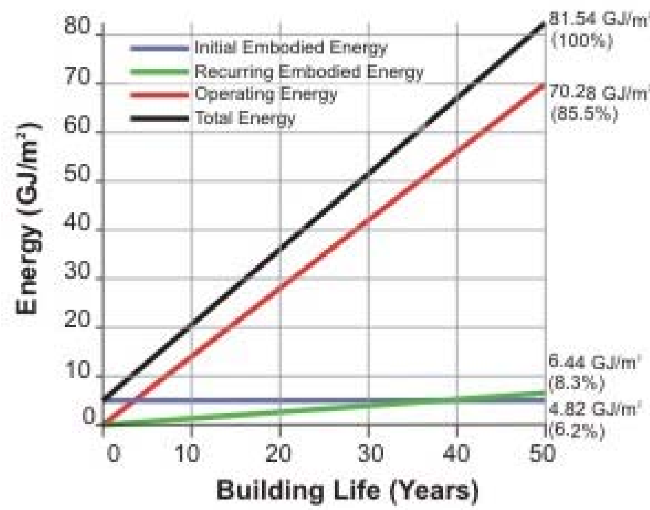

Figure 4: Components of Energy Use During 50-Year Life-cycle of Typical Office Building with Underground Parking, Averaged Over Wood, Steel and Concrete Structures in Vancouver and Toronto [Cole and Kernan, 1996].

Published life-span estimates range between 35-200 years [Brand, 1995]. The quality of construction and durability of building materials are a primary factor in extending building life. However, because quality and material choice is often tied to initial cost, the owner and not the designer may make these decisions. Estimates on building life-span that exceed 100 years are generally limited to institutional buildings where the owners have social, political, or other incentives to build long-lasting structures. On the other hand, shorter life spans can be expected for some commercial or warehouse type buildings, such as tilt-ups, where the developers focus primarily on housing goods or services as quickly and economically as possible [Webster, 2008]. In a seismic area, there is an increased probability that the building life may be shortened. In these regions it is important that the appropriate building life-span is selected based on the building's designed structural performance when assessing total energy consumption.

With a greater emphasis on performance-based design (PBD) for sustainability, and future building reuse, this life span can and should be extended. Benefits from designing for increased structural performance are two-fold: the initial embodied energy is preserved by extending building life, and the need for new materials is minimized.

Life-Cycle Assessment

The Life-Cycle Assessment (LCA) methodology is based on the scientific principles of conservation of energy and mass. Energy conservation represents a resource reduction on the input side while CO_2 represents a harmful emission on the output side. Other harmful environmental impacts affecting resource demand due to required input are deforestation, non-renewable resource depletion, such as fossil fuels and most aggregates, water use, and land exhaustion. Impacts due to outputs include harmful emissions to air, water, and soil that are found to be toxic to wildlife, humans, and the balance of eco-systems. These include particulates, volatile organic compounds (VOCs), dioxins, and solid waste.

A LCA involves compiling an inventory from extraction of raw materials to create the product to its final disposal, or reuse as an input to a different product. For building components this can include mining or harvesting, processing, transportation, and energy sources for each of these processes as well. It is easy to see how detailed and complex these processes can be. Defining the boundaries and scope of the assessment is critical to understanding the meaning of its results. One limitation of LCA is that it does not account for changes in impacts over time [Trusty 2008]. Thus, LCA for building materials is usually limited from extraction to delivery of the materials at the construction site, or Cradle to Gate. In truly considering a building over its life, one would also need to include impacts related to maintenance, replacement, and operation of its components. Nevertheless, LCA is a powerful tool for the designer who is interested in evaluating the cost and energy impact design decisions will have over the life of a building. (Refer to Appendix A for a more detailed description of some of the tools available for LCA).

Using Performance Based Design (PBD) to Improve Sustainability of Buildings

A broad sense of PBD is any systematic approach that aims to achieve performance targets that differ from the single life-safety performance threshold of the building code. A basic procedure can be as simple as evaluating a structural system against variances to the prescriptive code requirements. A more complex methodology could involve completing a full probabilistic analysis of the hazards to which the building is subjected coupled with modeling system behavior through advanced analysis to determine damage of the structural assemblies.

PBD looks at the environmental demands on the building and designs it to perform desirably in these events. There are several pathways for using performance-based design methodologies to decrease the environmental impact of a building as outlined below.

(1) Use PBD to justify additional up-front structure costs in order to achieve a higher performance level and reduce overall life-cycle costs
(2) Use PBD to decrease structural materials without decreasing building life. LCA is not necessary to prove the decrease in environmental impacts, as this can be ascertained qualitatively
(3) Use PBD to extend life-cycle of existing building

There exist strategies to extend the life of a building other than PBD, such as designing for durability, flexibility, deconstruction, and even aesthetics. Their merit may be evident in the qualities of buildings we tend to preserve and reuse, such as the many spacious, column free brick warehouses turned into lofts, office space, and retail. However, the benefits of these methods are more difficult to quantify. This section will examine the various PBD methodologies available to designers, and how they can be utilized on sustainable design projects.

Using PBD to Extend the Life of the Building and Protect its Contents

To achieve higher performance by reducing or limiting damage requires establishing design criteria distinct from the mandatory building code. Performance considerations of a structural system can have different criteria, depending on the function and objectives set out for the building. Acceptable performance can be defined as reducing the damage to the building shell and contents such that the building can be occupied and operated soon after a seismic event. For another type of building and set of objectives, a measure of acceptable performance may be simply limiting the damage to discreet locations in the building, or reducing downtime to within a pre-determined duration. Evaluating and choosing a structural system for either scenario involves a process of evaluating and balancing considerations in a probabilistic risk and cost analysis. This includes performance metrics (accelerations, drift, damage, etc.), different seismic levels, initial first cost, cost of repair or re-engagement of the building system.

In order to mitigate these negative impacts in an earthquake hazard environment, careful selection of the structural systems must be determined in relation to the site characteristics, architectural constraints, local practices, and material availability. Typical structural systems such as braced frames and shear walls result in stiff structures with low drift and high accelerations. Other systems such as moment frames result in more flexible structures with high drifts and lower accelerations. Energy dissipating systems such as base isolation and viscous dampers can reduce both accelerations and drifts.

Since the earliest versions of the methodology, there have been four basic steps to performance-based design. Initially, the performance objectives for the building must be assessed according to the owner's requirements, followed by the development of a preliminary design for the building. These steps are followed by assessing the performance and finally, evaluating the building to see if it meets the performance criteria [ATC-58, 2003]. As with most engineering procedures this is an iterative process. Therefore if the building does not meet the performance objectives a new design must be developed, assessed, and evaluated.

The following case study shows how implementation of a PBD methodology resulted in significant savings of initial material costs, as well as protection of non-structural elements, without use of costly, high-tech devices.

Case Study: California Academy of Sciences

[Field, et al., 2007]

The California Academy of Sciences directed Arup, the project structural engineer, to produce a Code-level design for a museum/research building in Golden Gate Park, San Francisco, CA. Recognizing the importance of the building and its contents, the high probability of a seismic event occurring in the San Francisco Bay Area, and the limitations of the CBC to predict a building's performance beyond life safety, Arup performed an assessment of the code-designed building from a performance-based design perspective. This assessment assisted the Academy in establishing performance objectives for the building's structural and non-structural elements. PBD was then used to evaluate modifications to the code-based design that would reduce material and construction cost while maintaining equal or better performance.

The Academy is a concrete shear wall structure, and due to its material and unusual contents it has a very high seismic mass. Hence the code-based design resulted in large uplift forces and numerous ground anchors. The modified design approach considered the interaction of the structure with its surrounding soil, and allowed the structure to rock under high seismic demand. Rocking at the foundation leads to a more flexible system, thus reducing the seismic forces/accelerations over those in the Code design. However, a rocking foundation system also increases the overall building displacement and drift, which must be taken into account for the non-structural components design.

Nonlinear time history (NLTH) analyses were conducted to measure the performance of the initial Code-level design and to assess the global effects of soil-structure interaction. The model accounted for geometric and material non-linearity of reinforced concrete shear wall, slabs, beams and columns. Vertical non-linear spring elements were also modeled to allow for uplift of the walls. Results from 8 time history acceleration records, of which two were with near-fault effects, were averaged for comparison against limits set by the design criteria with regard to displacement and base shear. Figure 5 shows the roof displacements in each direction for the NLTH models averaged and compared to displacements from the fixed base model (in parentheses).

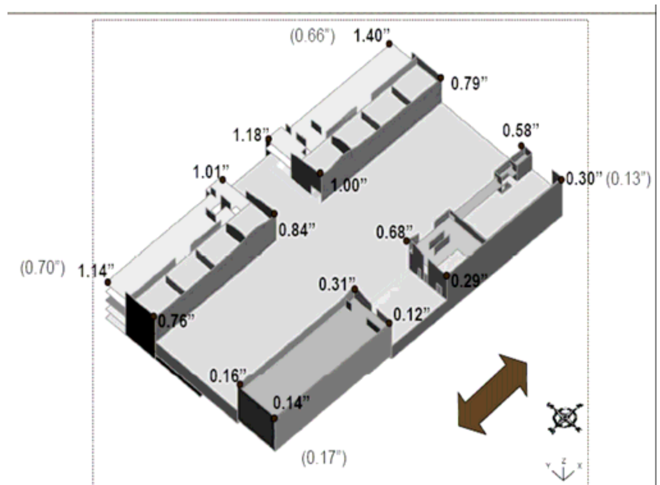

Figure 5: Max E-W DBE Roof Displacements (in.)

The performance-based design guidelines of the 1999 SEAOC Blue Book (BB) were used. The analyses indicated the performance-based structural design would behave favorably in a major seismic event, above and beyond the life-safety level prescribed by the UBC.

According to the NLTH analysis, the maximum drift ratios of the system with and without foundation rocking were 0.009 and 0.003 respectively. Both limits are lower than the BB limit of 0.011 and the CBC generic limit of 0.025. In the longitudinal and transverse directions of the building the rocking model exhibited a 10% and 20% reduction in the peak base shear from the fixed base model respectively.

The NLTH analyzes identified areas of potential concern and possible cost savings that may not have been as quantifiable using a conventional Code-level approach. For example, the analysis indicated that beams connecting the ends of shear walls to adjacent perpendicular walls may have significant flexural yielding if foundation rocking is considered. Therefore, special detailing was provided to address this concern. The main benefit of PBD to this project came from the elimination of 300 fifty-foot-long pressure grouted soil anchors by allowing foundation rocking. This resulted in a construction cost saving of $1.5 million, as well as a reduction in the use of new materials and a decrease in the building's total embodied energy.

Performance of Non-Structural Elements

Non-structural elements for this project included items such as collections, dioramas, tanks, waterproofing, cladding, skylights, and utilities. While the code intent is to provide some damage control by limiting inter-story drifts, a higher level of performance for non-structural systems and elements can be achieved by systematically designing and analyzing them to accommodate drift and structural accelerations based on the previously defined targets.

A linear dynamic analysis model with a fixed-base was studied to assess difference in demands on non-structural components versus code-based demands. The following table compares the accelerations that would be required by the empirical code formula to design the anchorage of non-structural elements, versus the accelerations determined by linear dynamic analysis. Note that the site-specific spectra accelerations have been divided by R_p = 3.0 for direct comparison with the code design accelerations (which have also been reduced by R_p).

	EMPIRICAL CODE FORMULA (Rp = 3.0)	LINEAR DYNAMIC ANALYSIS (Rp = 3.0)
Level	97UBC anchorage acceleration (g) *	Elastic (unreduced) site-specific response spectra (DBE5% with plateau) (g)
Roof	0.65	3.91/3 = 1.30
L3	0.55	2.98/3 = 0.99
L2	0.45	2.31/3 = 0.77
L1	0.36	1.92/3 = 0.64
B1	0.34	1.55/3 = 0.52
B2	0.34	0.65/3 = 0.22

Table 2: Comparison of Displacements for Linear Dynamic Analysis vs. Code Analysis for the California Academy of Sciences

The drift and acceleration results from these analyses provided the engineer with the proper recommendations for the design of non-structural components. Building drift was accommodated through proper separation of joints and connections and designing for inelastic deformations consistent with the selected performance objective. The calculated building accelerations were used in assessing the elastic and inelastic behavior of the non-structural elements as determined in shake table testing or data.

Recommendations were different for various components. Elements such as utilities and falling hazards were advised to meet the Safety Critical Objective, whereas tanks and other life-supporting components received recommendation to be designed per Essential Facility (I=1.5). Displacement-controlled groups such as roof waterproofing, cladding and curtain wall glazing, skylights, and ceilings were recommended for design to the expected drifts under the advanced analysis. Other groups such as the collections and dioramas were left for the Academy to decide on objectives based on protection from future damage.

Establishing performance-based targets and subsequent design parameters should help to protect a significant amount of non-structural damage in the Academy.

Current Methodology of Performance Based Design

The previous case study and such documents as FEMA 445 implemented early versions of non-prescriptive, advanced analysis methodology based on the basic principles of performance-based design. Recent advancement of PBD through the ATC-58 project provides engineers with detailed "performance-based seismic design guidelines" to assess damage of structural and non-structural elements. (Refer to Appendix A for a detailed description of some of the tools available for PBD).

This methodology considers casualties, injuries, direct economic losses including repair and possible replacement of the building, downtime including time spent evaluating and repairing the building, induced physical damage (i.e. damage due to fires, floods, hazardous waste etc.), and indirect losses caused by the inability of suppliers to provide services which are required for normal building operation [Hazus, 2002]. Prior to ACT-58 these parameters were typically qualified by drift and acceleration limits.

To quantify the above stated parameters when assessing the design of the structure, it is necessary to consider principles of probability because of the random nature of natural hazards. Performance-based design methodology does this by utilizing loss functions. A loss function plots the expected loss that is being examined, versus the probability of nonexceedance. Fragility curves are the primary means of evaluating a building's expected loss functions. Fragility curves plot the probability that a component of the structure will meet or exceed a certain damage state as a function of an engineering demand parameter, as illustrated in Figure 6. Common earthquake demand parameters include spectral accelerations, story drifts, and story accelerations.

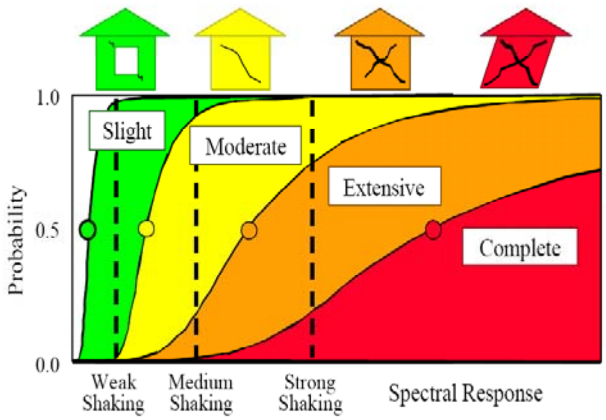

Figure 6: Damage Parameters

In order to describe a component's damage as a function of an engineering demand parameter it is generally necessary to utilize more than one fragility curve [Hazus, 2003]. This is accomplished by defining different fragility functions associated with discrete damage states for the component in question. Slight damage of a component may result in no repair, moderate damage may mean significant repair, and extensive damage could require complete replacement [ATC-58, 2003]. For example, a certain amount of cracking in a concrete wall after an event is generally acceptable and may be ignored depending on the preferences of the owner. However, repairs will be required if an excessive amount of the concrete cover has spalled, and more costly repairs, potentially including complete or partial replacement, will be required if the reinforcement has buckled or fractured. Often, loss is quantified in terms of annual expected loss. The annualized loss provides an average expected loss over the course of a year for a structure when considering all possible events that may impact it. Once the loss curves or annualized losses have been determined for a given structure they should be compared to the initial design objective.

Part of the challenge to the designer is to convey the meaning of these losses to the building owner. However, by presenting the risk in terms building owners are familiar with (dollars, downtime, etc.), the designer can provide their client with enough information to make an educated decision on the best course of action. If the client understands the risks associated with the post-earthquake performance of their buildings, and is interested in the long-term returns of sustainable design, it is likely that extending the life of the building by reducing the risk of damage will be perceived as a worthwhile investment.

Case Study: VA Seattle Hospital

In the late 90's a Presidential Executive Order required all federally owned or leased buildings to have a minimum level of seismic safety. Due to the mandate, the US Department of Veterans Affairs (VA) required their portfolio of hospitals to be evaluated. In 1999 Degenkolb Engineers began their seismic hazard evaluation of the VA Seattle hospital.

The main hospital is approximately 275,000 square feet. The building was a 4-story steel concentric braced frame building, located in close proximity to several other buildings on the campus. The evaluation determined that the braced frames were expected to incur heavy damage during the Maximum Considered Event (MCE) with a short period spectral acceleration, S_s, of 1.6g. Specifically, many of the braces had a high slenderness ratio (kl/r>140) and non-ductile connections that were unable to develop yielding in the brace member. It was determined that a seismic rehabilitation would be required to upgrade the building performance to an Immediate Occupancy performance level.

It was essential that the retrofit scheme be as non-invasive as possible to the hospital's continued operation because of the critical nature of the facility. Consequently, the designers chose to use the existing braced frame configurations, and replace the existing hollow structural steel tube braces with new buckling restrained braces (BRB's). The use of BRB's provided predictable inelastic behavior for the structure, while reducing the demands on the existing brace connections and column splices. At the time of design, BRB's were not recognized by the IBC, which required Degenkolb to develop a specification, testing procedure and acceptance criteria in conjunction with the BRB manufacturer, CoreBrace. After further analysis, it was determined that over 85% of the existing steel gusset plates could be re-used without modification. Additionally, a non-linear static pushover analysis was performed to further reduce the impact of the retrofit, resulting in a reduction in BRB sizes of 25% when compared to the initial linear static analysis.

Figure 7: Installation of (N) BRBF's at VA Seattle through upper-story window

The completed retrofit of the building achieved the building owners' performance objective of Immediate Occupancy. Additionally, the higher level of analysis and thoughtful reuse of existing structural components resulted in a total construction cost of less than $20 psf, minimal disruption of building operations, and reduction in material use. This example illustrates how performance based design can be used to preserve a significant portion of a deficient structure's material resources. Additionally, advanced analysis was used to achieve a high level of performance with a minimal amount of new material. This example demonstrates how we as structural engineers, using appropriate performance based tools and strategies, can protect our clients' capital and resources invested in their existing building portfolios.

Figure 8: Replacement of (E) TS's with (N) BRBF's at VA Seattle

Green Building Codes and Standards

The growing awareness of sustainable design and green building over the past 10 years has generated a demand for structured guidelines that building owners and design professionals can reference. There are several competing standards available on today's market. However, the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system has established itself as the de facto national standard for green building. First introduced in 1998, LEED is an incentive based quantitative green building rating system that is enforced through a third-party review process. The building standard awards points through several sustainable design categories: Materials and Resources (MR), Energy and Atmosphere (EA), Sustainable Sites (SS), Water Efficiency (WE), Indoor Environmental Quality (EQ), and Innovation and Design (ID). In the current standard, LEED Version 2.2, structural issues are generally only accounted for in the Materials and Resources (MR) and Innovation and Design (ID) categories. The engineer serves primarily a supporting role on the remainder of the credits. For the purpose of this paper we will be focusing on earning points in the ID category. For more information on the sustainability impact that structural engineers can have throughout LEED, please refer to this committee's earlier paper entitled "Structural Engineering Strategies Towards Sustainable Design" which is available for download on the SEAONC Sustainable Design Committee's website.

In the current standard, there is no discussion of disaster resilience or natural hazard mitigation over the life-cycle of the building, and the format leaves little room for its implementation outside of the Innovation in Design credits. According to USGBC's documented LEED ID approved points LEED ID credits have been achieved where savings in embodied energy can be demonstrated. Previously a LEED ID credit was awarded to "non-conventional" cable suspension systems that demonstrated the least amount of embodied energy compared to parallel chord truss, tied-arch, and other conventional roof systems. Similarly, an ID credit in MR category was issued for conducting an environmental life-cycle analysis of building materials during the design development phase, then adjusting material use to improve performance. In addition to prolonging the life of new buildings, LEED v2.2 provides credits for re-use of building materials, and ID credits, which have been issued in Site Selection (SS) and Materials and Resources (MR) categories for the preservation of historic buildings. In the context of LEED v2.2, performance-based design can also be used to justify minimal disruption to existing structures while achieving the desired performance characteristics.

However, as of this writing, there is no precedent for receiving an ID credit for PBD. Nevertheless, we feel that there is strong justification for improved life-cycle building performance in areas of high risk to be considered for an innovation credit. As demonstrated in the California Academy of Science's case study, a building designed based on the desired performance, can greatly reduce the anticipated post-earthquake damage to both structural and non-structural elements. Structural engineers should consider such an approach to achieve the LEED ID credit.

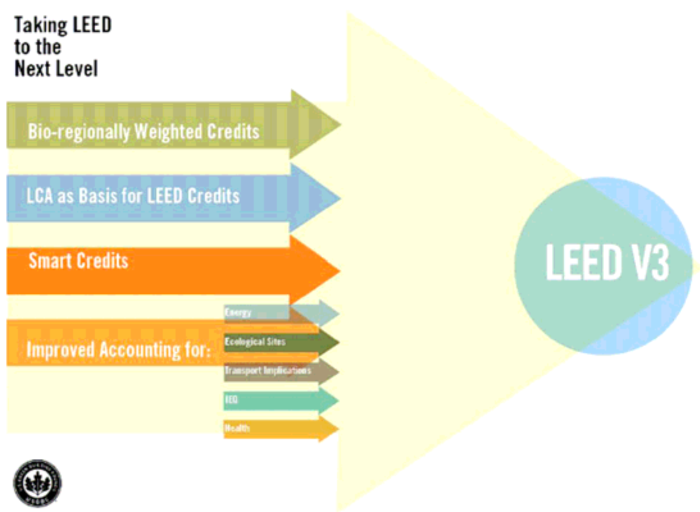

Figure 9: Upcoming LEED Changes

The USGBC continues to refine the LEED standard to meet the changing demands of the green building industry. The new LEED 2009, or LEED V3, system represents a significant change to the standard and that presents new opportunities for structural engineers to contribute to the green building design process. Figure 9 highlights the changes upcoming in LEED 2009 [Fredrizzi]. The new standard has focused on making LCA a basis for the credits and their point allocation. The point system has been normalized to 100 points, and values of existing credits were adjusted to better reflect their equivalent impact on the environment. There are also life-cycle compliance paths for a number of the credits including those in the Material Resources category. Most significantly, the USGBC has introduced regionalization into LEED 2009 as a series of bonus points in the Innovation & Design section of each rating system. Six credits existing in each rating system will be identified as regional credits similar to current exemplary performance points. These Regional Bonus Credits will be identified by the USGBC Chapters and Regional Councils for each "environmental zone". [USGBC, 2008] Designers will then be able to choose up to 4 of the 6 pre-qualified regional credits. The first draft of LEED 2009 was made available for public comment in mid-2008. Portions of the new rating system will be introduced for balloting at GreenBuild 2008, a national sustainable design conference held in November. We believe this presents a unique opportunity for the topic of disaster resilience and life-cycle building performance to be incorporated in the LEED standard in areas at risk of natural hazards, and encourage structural designers to contact their local USGBC advisory committee to discuss the development of the Regional Credits. By considering the material cost associated with replacing building contents under varying degrees of hazards, structural engineers may utilize PBD to demonstrate a quantifiable material waste reduction in the event of a natural hazard through improved structural and non-structural performance.

The California Green Building Standards Code (CGBSC)

While LEED is not currently required at the state level, many local jurisdictions are requiring various minimum green building standards. The City of San Francisco is currently focusing on large-scale new construction. The city proposes to require LEED certification by 2008 and LEED Gold by 2012 for all commercial and industrial buildings greater than 5,000 square feet. The City of Palo Alto requires LEED Silver for all new City owned buildings and is proposing similar requirements for all new non-residential buildings. The City of Albany requires various levels of LEED or GreenPoints certification for all new building projects. The list of counties and local jurisdictions across California that require minimum green building standards is growing every day.

Seeking to provide a consistent statewide baseline for green building, California began developing the Green Building Standards Code (CGBSC), and a draft for public comment was published in December of 2007. It is essentially an update and expansion of Title 24. The CGBSC being developed for the 2007 code cycle shall primarily be voluntary, though some local jurisdictions may select to make them mandatory. However, it is intended that most of the standard be made mandatory for the 2010 CBC.

Section 709 of the CGBSC is titled "Life-Cycle Assessment", however the only recommendation is that the designer "select material assemblies based on life-cycle assessment of their embodied energy and/or green house gas emission potentials". The CGBSC does explicitly recommend enhanced durability and reduced maintenance, and focuses on the ability to reuse the building's materials at its end-of-life through life-cycle assessment of the building. However, there is no mention in the standard of building performance during a seismic event or any other natural hazard. Particularly since this document is currently under development, it is our recommendation that structural engineers take a proactive role and participate in advocating the consideration of life-cycle building performance in sustainable buildings in California.

Conclusion

There is a natural synergy between the long-term perspectives of sustainability and performance-based design. We believe that owners who are interested in the gains of sustainable design over the life of their building must consider their performance when subjected to natural hazards. Engineers in California have the opportunity to continue their leadership in performance based design, and offer their clients services to protect the material and resource investments in their new and existing structures. It is important to educate owners and clients about building performance, and what they can expect to achieve in terms they can easily understand.

Sustainable design has made great progress in the last 10 years since it first began receiving favor in the public domain. However, buildings located in areas of natural hazard risk, must consider life-cycle performance to properly protect their sustainable systems.

There is still a lot of work ahead before sustainable structural design becomes a mainstay in today's industry. Very little legislation or documentation exists that promotes this type of design and more research needs to be done to present compelling case studies. A comparison using probabilistic seismic hazard analysis to study\ "typical" building performance vs. elevated performance levels over the life-cycle of a structure would help to illustrate the potential gains of PBD. The SEAONC Sustainable Design Committee intends to continue acting as an advocate for PBD in green building through further research, code development, and education of engineers, architects, and building owners.

As structural engineers, we have the opportunity to become an instrument of change in the industry. The tools available today allow us to extend the building life-cycle and mitigate negative impacts on the environment due to excess material or damage to both structural and non-structural components. Coupled with encouraging the responsible use of our natural resources, and considering total building performance over its life-cycle, we can proactively collaborate and participate in the "best practices" of structural and sustainable design.

Appendix A: Software Tools

Tools Available for Life-Cycle Assessment

Tools for Life-Cycle Assessment vary in their applicability to structures and stage in design. There are process-based tools that require creating the product inventory from scratch, and building LCA tools, which create secondary databases of common building components. Building LCA tools include Athena Impact Estimator, Athena EcoCalculator, and Building for Environmental and Economic Sustainability (BEES) software.

The Athena suite is most applicable to engineers as it allows one to create an inventory of structural components during the early design phase. The Athena institute has recognized that it is impossible to account for every possible element in the building, and has provided for an inventory of the components that contribute the most to environmental impacts. The EcoCalculator can be downloaded for free from www.atheansmi.ca while the Impact Estimator must be purchased.

BEES differs from Athena software in that it offers branded building products for comparison, such as insulation and finishes. One useful aspect of BEES is that is has an array of cement replacement percentages for concrete elements. However, these percentages are predefined and cannot be adjusted by the user. BEES can be downloaded for free from the Building and Fire Research Laboratory, www.bfrl.nist.gov.

BEES and both Athena tools are intended for comparing impacts of differing products or scheme designs within the same tool. Due to the varying format of the tools, results produced from one system should not be compared to the other. Even when comparing results from the same tool, the known differences of a particular building from the assumptions made in the software should be considered if using the results to inform a design decision.

Tools Available for Performance-Based Design

The following tools are available to structural engineers for the use in PBD to quantify damage in terms of cost and bring figures to building owners that will justify higher performance structures. There are several tools available for turning component fragility functions into building loss functions capable of being processed into meaningful project data. Two tools available are FEMA's Hazards U.S. (HAZUS) and ATC's Performance Assessment Calculation Tool (PACT).

HAZUS is a free program created for use as a risk assessment tool on a large scale for analyzing potential losses from earthquakes, hurricanes, and floods. It is best suited for government agencies that are interested in developing plans for disaster mitigation, or large private organizations that operate many buildings in which losses will be distributed across in the event of a disaster. Hazus was utilized in generating the loss estimated in the previous study "When the Big One Strikes Again". For more information visit www.hazus.org [Hazus, 2003].

PACT is free software that utilizes the ATC 58 methodology, and is currently available in a draft form. The ATC 58 methodology was created for use in analyzing a single building's risk due to earthquakes. Due to its focus on individual buildings PACT is applicable for considering casualties, direct economic losses, and downtime [ATC-PACT, 2007].

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