APPLICATIONS OF PERFORMANCE-BASED ENGINEERING TO RISK MANAGEMENT DECISIONS

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ABSTRACT

Performance-based engineering procedures (PBE) promises significant related improvement in the capability to manage seismic risks effectively and efficiently from a business perspective. This paper first previews the document *FEMA 440: Performance and Risk Assessment for Buildings in Extreme Events* that proposes to use risk as the fundamental characterization of building performance. The three basic risk parameters are deaths and serious injuries, economic losses due to direct damages, indirect economic and societal losses attributable to loss of use of a facility due to damage. Once these basic parameters are quantified they can be reformulated to address the specific needs of various stakeholder decision makers. This is illustrative with several practical application examples.

Keywords: Performance-based engineering, risk analysis, risk management,

INTRODUCTION

This paper summarizes portions of a document currently being prepared as one product of the ATC 58 to develop next-generation performance-based seismic design guidelines (Hamburger, 2004). *FEMA 440: Performance and Risk Assessment for Buildings in Extreme Events* will present the results of project efforts to date to determine effective ways to characterize and communicate concepts of building performance to both design professionals and the numerous stakeholders and decision makers whose lives and financial interests are dependent on the performance of buildings that may be subject to earthquakes, fires, blasts and other extreme hazards. The primary objectives are to:

- establish a basic characterization of performance of buildings in extreme events that is technically sound and comprehensive from an engineering perspective.
- illustrate how this basic characterization can be adapted to the multiple specific needs of individual decision makers.

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The following sections address each of these objectives. The basic concepts apply to many extreme hazards, but they are illustrated with seismic shaking. Examples of actual applications to buildings are also included.

THE USE OF RISK TO CHARACTERIZE PERFORMANCE

Building performance is defined effectively for a given building, at a given location, in terms of three basic risk parameters. Each of these is an aggregation, or integration, of potential losses over the life of the building from the hazard of interest. The basic risk parameters are these aggregations for:

- deaths and serious injuries.
- economic losses due to direct damage.
- economic and societal losses that indirectly occur as a result the loss of use of a damaged building or facility (downtime).

These can be expressed in a number of different forms (e.g. annualized loss, net present value of expected losses, annual probability of exceeding a certain loss). Note that conversion from one format to another is a relatively simple numerical transformation. Thus each basic risk parameter has a unique value regardless of the form of expression. The median values of the basic risk parameters also have an associated reliability as a measure of uncertainty.

This characterization of performance derives directly from the Pacific Earthquake Engineering Research Center Framing equation (Moehle, 2003) as illustrated in Figure 1.

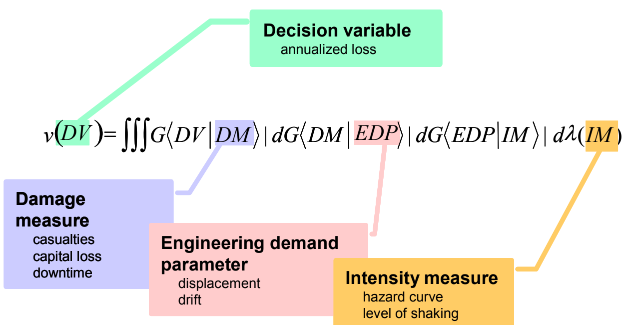

Figure 1. PEER framing equation and example parameters for seismic shaking

The basic risk parameters are the decision variables for the three categories of losses (deaths, dollars, downtime). Figure 1 includes example parameters for engineering demand and intensity measure for seismic shaking; however, the basic concept can be applied to other extreme hazards using appropriate alternative parameters. (Deierlein, 2003 and Whittaker, 2003).

PRACTICAL ADAPTATION FOR STAKEHOLDER DECISIONS

The implementation the performance-based design using the basic risk parameters is illustrated in Figure 2. While the characterization of performance with the basic risk parameters is technically sound and practical from an engineering perspective, the results of the performance assessment are not useful directly to all stakeholders. As shown in Figure 2 the results are reformulated to address the specific decision making needs of various stakeholders. Some of these are summarized in the following

Minimum performance standards (code compliance)

One of the important goals of the ATC 58 project is to develop performance based design procedures that can be used in codes and standards. Traditionally, codes have not stated the performance they are intending to achieve with their prescriptive provisions, except through broad, highly qualitative statements that their intent is to protect the public safety. The basic risk parameters that can be derived from the performance assessment can either be used to demonstrate that a design meets the performance criteria, or alternatively, can be used to improve the statements of performance criteria currently contained in the codes. For example, the primary purpose of seismic provisions in present prescriptive codes is to provide for a minimum level of public safety. The casualties risk parameter that is an output from the performance assessment methodology provides a quantifiable measure of safety for a building design. With this tool in place, codes could specify a maximum allowable life safety risk. This could be in the form, of not greater than a 10% chance of single life loss, given a 500-year event, or in the alternative but similar form, less than a 0.0002 chance per year of single life loss. Similarly, codes could require maximum levels of risk associated with capital losses or downtime depending on the importance or function of a facility (e.g. public buildings, hospitals). This format would be a much more useful and transparent code basis.

Conventional performance objectives

Similar to the code application described above, the performance levels of current performance-based design procedures such as *FEMA 356* (BSSC, 2000) and *ATC 40* (ATC, 1996) could be indexed easily using the basic risk parameters a performance assessment. The performance assessment could also be used to de-aggregate losses, if desired. This allows the estimation of losses associated with a specified seismic hazard level (e,g, casualties expected for a 500 year event). De-aggregation to deterministic events is also possible.

Specialized Decision Variables

Individual stakeholders will have interest in particular information on the risk implications of design decisions that will be most useful to their decision processes. Corporate risk managers, for example, may be most interested in project down time, as the loss of use of a facility for an extended period could affects not only short term profits but long term market share and viability. Lenders will typically be interested in downtime as well, because if a borrower is unable to use a building for an extended period of time, or obtain rents from tenants, they may be unable to service their loan. Insurers will typically be interested in likely repair costs, but may also be interested in downtime as they may underwrite lost income from operations due to damage. Building officials will typically be more interested in risk to life. The basic risk parameters can be easily re-formatted to provide such information. For example,

- What is the chance of a death or serious injury due to an earthquake in my building in the next 20 years?
- Can I be 90% sure that an earthquake will not put me out of business with a capital loss of over a million dollars in the next 50 years?
- Is there greater than a 10% chance that our hospital will be unable to accept new patients for more than a week after an earthquake in the next 50 years?
- Is there greater than a 10% chance that fire stations in a city will be unable to service the fire department following a major earthquake?
- What is the likely repair cost for my building in the event of a large earthquake?

The use of performance-based engineering to characterize losses in terms of risk enables the engineer, facility owner, building tenant, city planner, and others, to answer important questions such as these in economic terms. For example:

Should the owner retrofit a facility to reduce earthquake losses?

The engineer formulates the basic risk parameters in dollars for the existing facility then discounts them to a net present value. The engineer then conceptually develops a retrofit design to address the deficiencies of the facility and estimates the associated cost. Using the retrofit design the engineer can then repeat the calculation of losses for the retrofitted facility, again expressed in present value. These should be less than the losses for the un-retrofitted case. The difference represents the economic benefit of the retrofit. If the benefit exceeds the retrofit cost, the retrofit is a good investment. Many decision makers will divide the benefit (net present value of loss reduction) by the cost to obtain a cost benefit ratio or return on investment measure. Then an optimal level of retrofit could be determined by repeating this exercise until a maximum cost/benefit ratio is obtained.

For a new facility, is it preferable to use shear walls or unbonded braces as the lateral-force-resisting system?

The engineer performs a conceptual design and cost estimate for both options, then determines the net present value of the basic risk parameters for each option. If the cost premium for the more expensive alternative is less than benefit in terms of reduced expected losses, the additional cost is economically justified.

For an industrial production facility, is it advisable to design for performance greater than required by the building code?

The engineer formulates a design and cost to meet the minimum requirements of the code as a baseline and estimates the basic risk parameters. One or more alternative designs can be prepared to improve expected performance beyond the baseline. The additional costs of these alternatives compared to the baseline costs is are an investment in seismic risk management. The reduction in the present value of basic risk parameters (from code design to upgraded criteria) represents the return on the investment.

Should an owner invest in a design for higher performance or transfer (or accept) the risk?

An economic analysis can identify the optimal investment in risk reduction through improved performance. Beyond some level the incremental return on investment drops. An owner may choose to supplement the design with risk transfer through insurance or simply accept it. By understanding the excess risk and the probabilistic distribution of that risk over a range of hazard levels, the owner is in a better position to develop a risk transfer and management plan that more precisely meets his tolerance and capacity needs.

Where does investing in seismic risk management fit into an owner's overall business plan?

Once the engineer determines the risks and rate of return on investments in risk reduction, risk transfer, or other seismic risk management strategies, the owner can make a comparison with other business investments (e.g. equipment, research, personnel). An owner typically has finite resources with which to invest; he must therefore make decisions that select the best investments from among competing demands on capital.

Should a community upgrade existing low-income housing with retrofit design or phase it out with newly designed replacement facilities?

Many towns and communities face great economic and social challenges in providing decent housing for the less privileged. Current code provisions, including those addressing seismic issues, are most often an impediment because of cost implications. The proposed characterization of performance and related analysis techniques might show that significant new or retrofit construction cost savings could be realized (compared to compliance with a prescriptive code) while still meeting sufficient levels of life safety.

How can home owners or builders using the non-engineered contruction provisions of the code efficiently improve seismic performance?

It is not very likely that the analysis procedures envisioned for this project will be used directly to design many single family homes. Most homes are now built by contractors complying with prescriptive directions in a special section of the code for non-engineered construction. Nonetheless, the proposed performance characterization and related analysis procedures enable the investigation and documentation of risks associated with these provisions in general. They can also be used to evaluate the effectiveness and efficiency of changes or alternatives. Eventually, the non-engineered provisions might include optional upgrades that can be prioritized and correlated to local seismicity. This would give home owners, buyers, and builders more options than they currently have.

There are significant uncertainties associated with seismic risks including estimating ground motion hazard, structural capacity, and losses. The preceding discussions represent these parameters simplistically as expected values. In reality, they are central (median or mean) values associated with individual probabilistic distributions. The risk-based approach to seismic performance characterization enables the tracking of uncertainty directly. For example, using the expected (central) values of the performance parameters the chance that the predicted losses from earthquakes are exceeded is 50%. They are equally likely to be less than the expected values. If an owner wishes to increase reliability to a higher level the probabilistic framework enables an upward adjustment of losses for a higher degree of confidence (e.g. 90%) that they will not be exceeded.

This is another important advantage of these procedures. Since codes are primarily concerned with life safety, they are naturally intended to be conservative. It would be publicly unacceptable, for example, to design a building based precisely on median values of hazard and capacity, if the result was that one-half of buildings would perform well, protecting their occupants, and one-half would not. When owners make decisions about enhancing performance however, to protect their capital and business operations, rather than conservative estimates of performance outcomes, they want to understand the median expected losses and the variance about that median. In this way, they can define a design based on their own risk tolerance and compare investments in risk management and reduction with other known business risks.

EXAMPLE APPLICATIONS

The proposed basic approach to seismic performance characterization and analysis has been used in a very rudimentary form in the past few years. The following are some examples of recent practical applications. In reviewing the examples, one should keep in mind that the procedures that were used, although conceptually similar to those envisioned for the future, are very simplistic. For example, damage is estimated strictly from a global perspective without investigating component behavior directly. The basic inelastic analysis procedure are nonlinear static as opposed to the more detailed response history anayses. Also, each application had to be developed and implemented from scratch without the benefit of guidelines or special purpose analysis tools. As a result, there are large uncertainties associated with the results. The future techniques will improve the accuracy of the results significantly and provide practitioners with consensus based guidance on reliable procedures.

Selection of an appropriate structural system for a critical facility

The University of California at Berkeley is building a new state-of-the art laboratory building to replace an existing building. The $200 million facility will serve the needs of important bioscience research for the next thirty to fifty years that are funded at a current annual rate of $40 million. The design engineer proposed the use of unbonded braces, a new structural system with enhanced performance characteristics, with the goal of protecting the University's investment and future research capabilities. However, as a public institution, receiving government funding, the University had to justify use of the new system, which was a more expensive alternative than a more conventional system would still meet the minimum requirements of the State of California Building Code, such as concentric braced steel frames. Figure 2 presents an architectural rendering of the building together with information on the development cost, projected value of building contents and of the economic loss to the University projected for each year that the building is out of service.

Item	Cost
Capital	$160 million
Contents	$50 million
Business Interruption	$40 million annually

Figure 2: Example Building at the University of California at Berkeley

The engineers developed designs for both the proposed unbonded brace frame system and a conventional braced frame system. The unbonded brace design was estimated to be approximately $1.2 million more expensive than the conventionally braced system. Using, presently available tools, that are rely heavily on the judgment of the analyst as to economic losses and structural damage, an economic analysis was performed for each system to quantify the potential loss of capital, contents and research revenue using the basic procedures outlined in the previous sections. As illustrated in Figure 3, the evaluation suggested that the unbonded brace system would reduce annual losses due to earthquakes by $139K. Using a discount rate of 5%, the net present value of this reduction over the life of the building was calculated as $2.5M or more than twice the extra cost (see Figure 4). The equivalent return on investment using the unbonded braces in place of the conventionally braced frame was estimated at approximately 11%. As shown in Figure 5, the analysis suggested that the investment would theoretically pay for itself in approximately 15 years, far less than the 50 year projected lifetime.

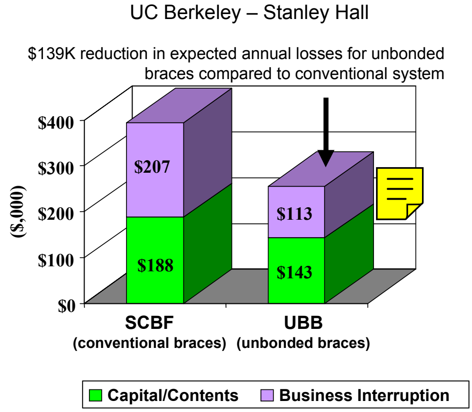

Figure3: Reduction in expected annual earthquake losses attributable to the use of unbonded braces in place of conventional braces

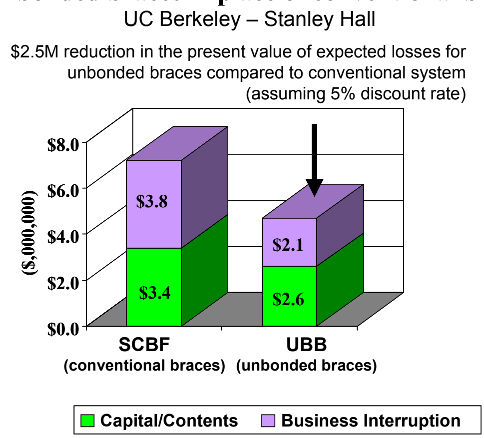

Figure 4: Reduction in the net present value of expected earthquake losses attributable to the use of unbonded braces in place of conventional braces

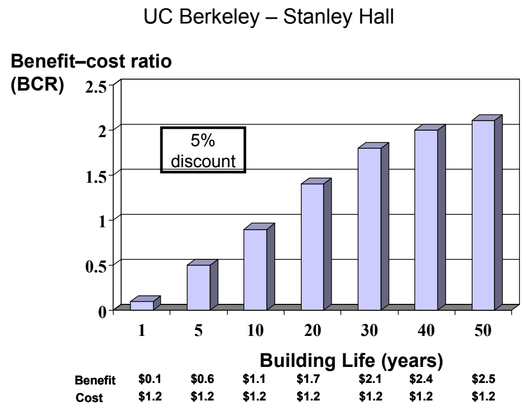

Figure 5: Ratio of benefits to costs for use of unbonded braces in place of conventional braces

Recognizing the uncertainties involved, the basic parameters were varied to explore the sensitivity of the results to the basic assumptions. The analysis did not include direct consideration of some potential losses that are difficult to quantify. These include the loss of research faculty that might move to other institutions while repairs are made to the building, the losses associated with on-going experiments, and the sizable effect of the loss of the facility on the economy of the local community. The analysis, coupled with these qualitatively expressed considerations, provided sufficient evidence to support the investment in the enhanced system.

Enhanced performance objectives

San Leandro is a city on the San Francisco Bay, about eight kilometers from the Hayward Fault. Recently a national chain of automobile dealerships proposed to build a new sales and repair facility in the city. The projected cost of the building is $5 million with an inventory value of $2 million and projected gross annual revenue of nearly $4 million. The owner's lender required earthquake insurance in order to finance the project because of the proximity of the site to a major earthquake fault. The best quote on earthquake insurance the owner could find was $150,000 per year. The owner had both a long-term interest in reducing future potential losses, and a desire to reduce the amount of earthquake insurance the bank would require.

Using tools available today, an analysis was performed to estimate potential losses in a design level earthquake. The analysis suggested that for a large earthquake on the nearby fault, repair costs would approach about 40% of the replacement cost of the building. Most lenders require that this expected loss be less than 20% to remove insurance requirements. The design engineer developed an enhanced structural design that would reduce the expected losses. The design added structural elements and increased the size of others. The total expected cost of the enhancements were estimated to be $200,000.

Reanalyzing the building with the proposed enhancements, the expected losses dropped to 16%. Furthermore, the expected reduction in capital, contents and business interruption losses on an annualized basis over the projected building life showed an overall return on investment of nearly 14%. This alone convinced the owner to implement the enhanced design. However, the greater value came when the owner presented the lender with the proposed enhancements and risk analysis. The lender agreed to waive the earthquake insurance if the enhancements were implemented. This made the effective return over 77%. Importantly, most of the return was in "hard dollars;" an insurance check that did not have to be written every year.

Insurance versus seismic upgrade for enhanced performance

The owner of a large precast concrete tilt-up warehouse south of San Francisco leases the building to several tenants. Recognizing the vulnerability of the older style of construction close to the Hayward fault, the owner purchased earthquake insurance on the property. The insurance covers 60% of the capital losses but has a 10% deductible that must be paid by the owner before any recovery from the insurance company. This policy ensures that, at most, the owner will recover only about 50% of the losses after an earthquake. The insurance company recently raised the cost of insurance to about 2.5% of the maximum recoverable amount. This means that the owner would have to suffer a complete loss every 40 years, on average, to justify the cost of insurance.

The owner was concerned about the volatility of the insurance market, especially considering that the rental market did not allow him to pass on insurance costs to the tenants. The owner wanted to develop a mitigation plan that would reduce the dependence on insurance. Performance-based engineering procedures were used to devise the mitigation solution and estimate capital losses in a design level event. The scope of the retrofit solution was adjusted to bring the median losses to approximately 15% of the projected replacement cost of the building. The reduction in expected loss made insurance far less attractive, or necessary, as a risk management tool. The cost of the strengthening solution was estimated at $130,000.

Based on financial analysis (Figure 6) the owner decided to cancel his insurance policy and invest the cost of the premium toward mitigation. This will finance the retrofit over a four-year period. The owner has made the decision to accept the risk over the next four years that a damaging earthquake could occur. After the mitigation is completed, however, the owner's investment will be generating a positive return on investment. They will achieve an equal measure of capital protection without having to buy insurance. Furthermore, the retrofit will reduce business interruption losses, for which they were not previously insured. The application of performance-based engineering and risk analysis procedures was able to offer the owner a quantitative motivation to change the way they were spending money. The result was that the owner got more value without additional cost.

Current condition (with insurance)				
Year 1-				
	Max. potential loss	$3,000,000		
	Annual expected loss		($15,000)	
	Annual expected insurance recovery		$7,500	
	Annual insurance cost		($40,000)	
	Total annual costs			($47,500)
Mitigation condition (without insurance)				
Year 1-4				
	Max. potential loss	$3,000,000		
	Annual expected loss		($15,000)	
	Annual expected insurance recovery		$0	
	Annual insurance cost		$0	
	Annual mitigation cost		($40,000)	
	Total annual costs			($55,000)
Year 5 and beyond				
	Max. potential loss	$750,000		
	Annual expected loss		($3,750)	
	Annual expected insurance recovery		$0	
	Annual insurance cost		$0	
	Annual mitigation cost		$0	
	Total annual costs			($3,750)
Net rate of return on mitigation over 20 years				62%

Figure 6: Example analysis of value of insurance versus mitigation

REFERENCES

ATC, 1996, *The Seismic Evaluation and Retrofit of Concrete Buildings, Volumes 1 and 2*, ATC-40 Report, Applied Technology Council, Redwood City, California, www.atcouncil.org.

BSSC, 2000, *A Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, prepared by the Building Seismic Safety Council; published by the Federal Emergency Management Agency, FEMA 356 Report, Washington, DC, www.fema.gov.

Deierlein, G., and S. Hamilton, Probabilistic framework of performance-based fire engineering and design, *Proceedings from the 2003 Designing Structures for Fire Conference –Baltimore, 2003*, Society of Fire Protection Engineers.

Hamburger, R. O., Development of next generation performance-based seismic design guidelines, *Proceedings of the International Workshop on Performance-based Seismic Design,* Bled, Slovenia, published by the Pacific Earthquake Engineering Research Center (PEER), 2004.

Moehle, J.P., "A Framework for Performance-Based Engineering", *Proceedings of the Tenth US-Japan Workshop on Improvement of Structural Design and Construction Practices*, Maui, Hawaii, 2003, Applied Technology Council, Redwood City, California, www.atcouncil.org or peer.berkeley.edu.

Whittaker, A. S., R. O. Hamburger, C. Comartin, R. Bachman and C. Rojahn, "Performance based engineering of building structures,"*Proceedings*, 73rd Shock and Vibration Symposium, SAVIAC, San Diego, CA, 2003.