13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1039

FINANCIAL FORMULATION AND APPLICATION OF PERFORMANCE-BASED ENGINEERING PROCEDURES

Craig COMARTIN[1] and Evan REIS[2]

SUMMARY

Experienced engineers are recognizing the technical superiority of performance-based engineering procedures (PBE) for the seismic evaluation, retrofit and design of facilities. PBE also promises significant improvement in the capability to manage seismic risks effectively and efficiently from a business perspective. This paper illustrates a reformulation of conventional PBE into a financial context conducive to use directly by facility owners and managers.

The fundamental principles underlying PBE are relationships between the intensity of earthquake shaking, the resulting structural response, and the consequent performance (e.g. Immediate Occupancy, Life Safety, Collapse Prevention) of a facility. A financial formulation extends the description of performance in terms of expected losses (e.g. casualties, capital loss, loss of revenue) measured in monetary terms. Integrating over a range of seismic hazard generates expected losses due to earthquakes over the useful life of a facility. This format is compatible with economic decision processes that are used routinely in the business environment to manage risks. Business owners are able to weigh the value of seismic risk mitigation against competing capital demands, using data on benefits, costs and uncertainty to project a return on investment at an appropriate discount rate. These formulations extend the focus of PBE beyond the realm of public policy and into the business and economic arenas.

The paper includes examples of successful applications including the economic justification for the use of higher priced unbonded braces in a $200 million research laboratory at the University of California, Berkeley. In another application, a lender for a $5 million automobile dealership in the Bay Area removed earthquake insurance requirements based on the results of a financial PBE analysis of expected losses.

Among the engineering challenges to using financial analysis in PBE are: quantifying uncertainties in estimating seismic performance, making comparisons to alternative investments, and communicating its value to the business community. Meeting these challenges can add great value the services that engineers provide to their clients.

[1] President, CDComartin,Inc.,
[2] President, Certus Consulting Inc.

INTRODUCTION

Traditionally, building codes have been prescriptive. Design professionals follow procedures required by the code to check their designs using specified demand and acceptability criteria. The procedures for earthquakes are based on forces that are adjusted to allow the use of linear structural analysis. The implied result of this process is that the facility constructed in accordance with the code-based design will perform adequately when subjected to actual earthquakes. Code procedures, however, do not result in explicit determination of performance parameters (e.g. damage, casualties). The implied performance expectations for code-based designs arise primarily from reliance upon the collective judgment and experience of the writers and developers of the provisions.

In the post fifteen years significant progress has been make in the application of performance-based engineering to the evaluation and design of structures for earthquakes [1,2]. At the same time, similar technical procedures provide the basis for the HAZUS regional catastrophic loss model in the United States [3,4]. Currently, the Pacific Earthquake Engineering Center (PEER) is focusing on a formulation of performance-based engineering that frames decisions about seismic performance in terms of the expected losses at a particular facility, building, or structure [5]. In this form, PBE provides building owners with improved information for making better decisions in a financial context.

The following section briefly reviews the basic concepts of performance-based engineering for earthquakes. This procedure relates displacements to damage as a measure of performance. Using a performance-based analysis, an engineer can convert the damage associated with various levels of performance to estimates of economic losses. Since the intensity of seismic shaking that causes the losses can be characterized probabilistically, the potential losses are a measure of seismic risk associated with the subject facility. This format allows an engineer or the facility owner/manager to use conventional risk analysis techniques to investigate risk management alternatives. Several actual examples from practice illustrate this economic formulation of performance-based engineering. Finally, some selected references provide sources of more detailed information.

PERFORMANCE-BASED ENGINEERING

These procedures use displacement and/or deformation as the primary engineering demand parameter (*EDP)*. Performance-based analysis procedures are nonlinear, allowing for inelastic behavior of structural components. The illustrations in this paper rely on nonlinear static procedures (pushover analysis) as the engineering analysis technique. Other alternatives procedures are also applicable performance-based engineering. Nonlinear static procedures have gained popularity for performance analysis, because they generate relationships between a representative global engineering demand parameter (e.g. displacement at the roof level of a building) and a lateral force measure (e.g. base shear). The structural analysis model comprises an assembly of all the components of the building or structure that resist seismic actions. The engineer increases the force measure monotonically on the structural model and plots the resulting displacement to generate a capacity, or pushover, curve for the structure. (See Figure 1).

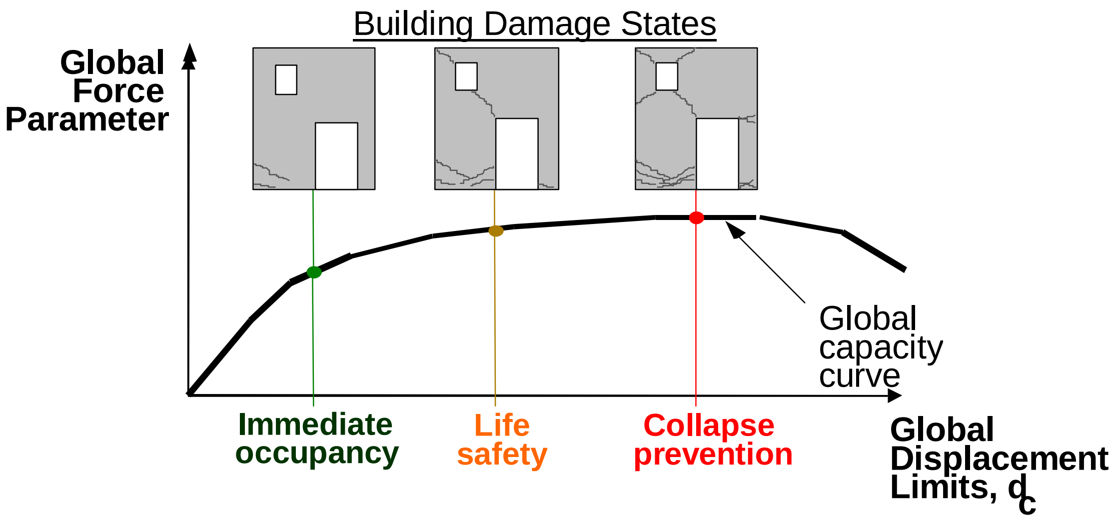

Figure 1: Capacity (pushover) curve

For small lateral forces, displacements are approximately proportional to forces (elastic response) and little damage occurs in a facility. As the displacement increases the components of the structure begin to respond inelastically and damage increases. At some point the damage will become significant enough to require the building to be shut for repairs. Performance-based seismic procedures call this limit "Immediate Occupancy." As the building is pushed further, structural damage becomes significant. At some point the damage impairs the lateral and/or vertical load carrying capacity such that safety is no longer reliable. The global displacement at which this occurs is the "Life Safety" limit. Beyond this point, structural damage becomes extreme leading to a "Collapse Prevention" displacement limit at which the structure is unstable. In the post-elastic region, small changes in forces can result in large changes in displacements. This is one of the reasons why performance-based procedures emphasize displacements rather than forces.

Nonlinear static procedures use spectral representations of ground motion as an intensity measure (*IM*) for seismic shaking and pushover curves to estimate maximum global displacement. The two most common methods are the capacity spectrum method of *ATC 40* [1] or the coefficient method of *FEMA 356* [2]. The intensity measure could be a specific event (deterministic analysis) or a level of shaking with a specified chance of being exceeded in a given time period (probabilistic analysis). The resulting displacement is called a performance point [1], or target displacement [2] for the given ground motion intensity. For example, Figure 2 illustrates a case in which the example building would be expected to meet the Life Safety limit for the assumed level of shaking. Damage, however, would limit occupancy for some time for repairs.

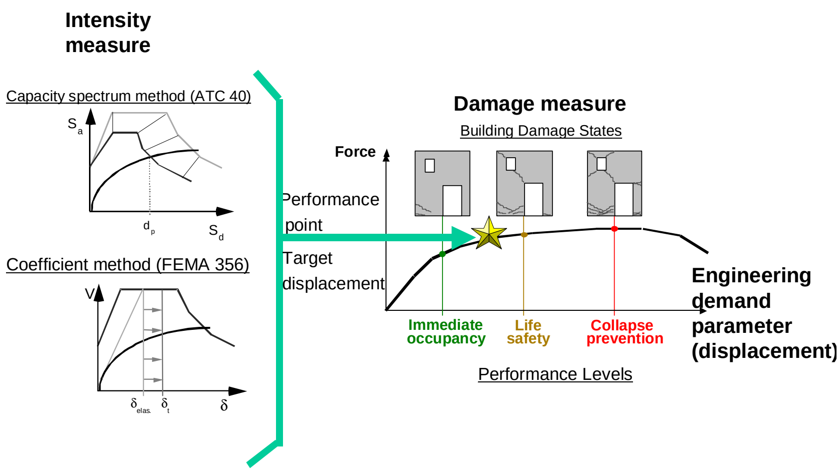

Figure 2: Intensity, engineering demand, and damage

In practice, engineers use performance-based engineering procedures to match performance levels (i.e. Immediate Occupancy, Life Safety, Collapse Prevention) with a seismic hazard level. The performance objective might be Life Safety for shaking with a 10% chance of being exceeded in 50 years. For new construction, an additional objective might be to achieve Immediate Occupancy for shaking with a 50% chance of being exceeded in 50 years. The performance-based approach, as an alternative, or supplement, to code procedures, uses improved engineering techniques to add more explicit information about actual performance to the evaluation and design effort.

TRANSLATING PERFORMANCE TO LOSS

Each of the performance levels effectively defines a specific amount of damage for the building or structure. Since the analysis utilizes a component model, the consequences of the global displacement are component deformations that are indicative of local damage. Below the Immediate Occupancy limit, damage to structural components would not be significant. Architectural features might experience some relatively minor damage (e.g. cracking of partitions, dislodged ceiling tiles). Building systems might suffer temporary problems (e.g. damaged lighting fixtures, water pipe leakage). The building contents also might be disrupted (e.g. overturned bookcases, damaged computer monitors). In total, the cost to repair the damage to the building and its contents represent a capital loss for the owner. These might also be indirect losses associated with the impediments to the function of the facility after the earthquake. For example, a hospital might be satisfactory for occupancy after an earthquake, but surgeries might not be possible until repairs are made to the ventilation system. The loss of revenue associated with this restriction is known as a downtime loss.

At the Life Safety performance level, capital losses may increase dramatically. Significant structural damage is expensive to repair. Furthermore, the repairs are likely to require that the building be partially or completely vacated for an extended period of time. This could effect downtime losses as well. At the Collapse Prevention level, the structure may be a total loss. Downtime losses can exceed capital losses in many cases. At the this level, losses associated with deaths and injuries might also be significant.

For each performance level, the engineer can estimate each type of loss (casualties, capital loss, downtime loss). Tabulating these losses provides a further enhancement in the characterization of performance. For an example, a building at the Life Safety performance limit might be characterized by:

- negligible losses due to casualties,
- 50% capital loss of the building and its contents (in terms of replacement value),
- downtime losses equivalent to one year of revenue associated with the functional use of the facility.

This basic analysis process for an individual building has recently been added to HAZUS [6].

The pushover curve for a building actually represents a continuum of performance for a building. The performance levels are milestones on this continuum. Each point along the curve also represents expected losses (casualties, capital, downtime) as a function of the engineering demand parameter (See Figure3a and c). These relationships allow the engineer to offer some very useful information to a building owner beyond whether or not a building conforms to a design code. For example, imagine an industrial facility located 10km from a fault on which a 6.8M is a possible scenario. With a response spectrum representative of this event and a capacity curve representative of the facility the engineer can use nonlinear static procedures [1,2] to estimate the expected maximum displacements for the scenario earthquake. From this information it is possible to advise the facility owner as to the expected losses from the event.

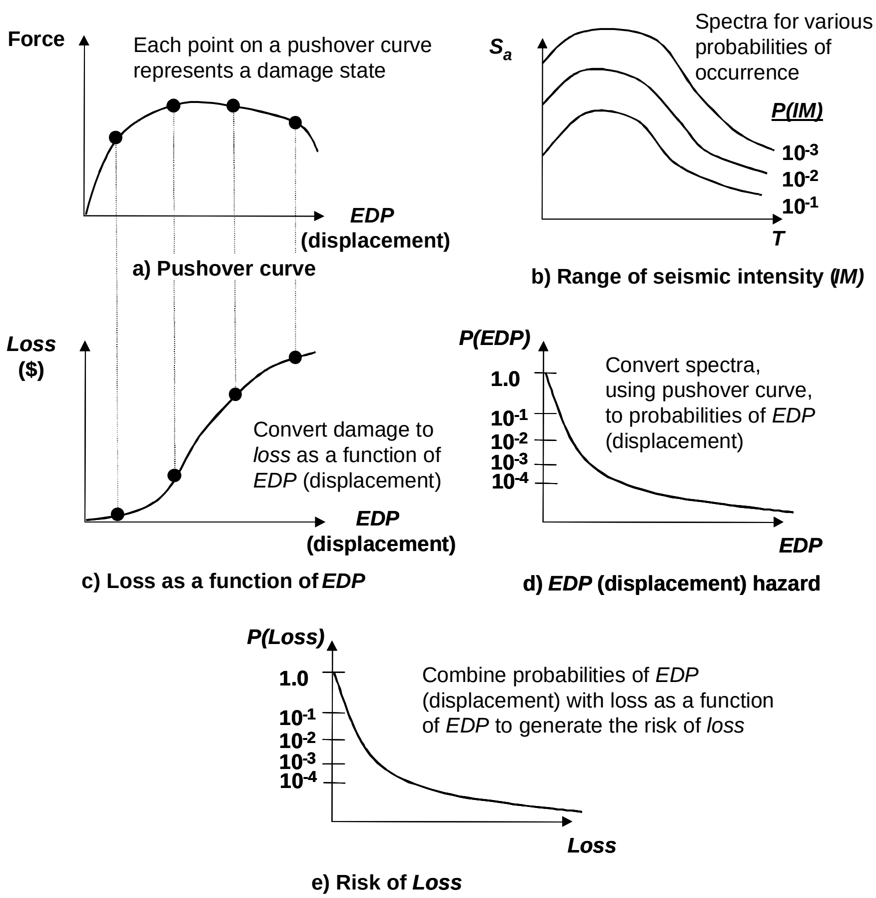

Figure 3: Translating damage to loss to risk

RISK ANALYSIS

The conversion of losses to risk further expands the benefits of performance-based engineering. This is readily accomplished by representing seismic hazard at a facility site with a series of uniform hazard spectra over a range of hazard levels (Figure 3b). The engineer can then use these with a pushover curve for the facility to estimate the maximum engineering demand (e.g. global displacement) over the hazard range Figure 3d). This relationship combined with that expressing loss as a function of the engineering demand parameter (Figure 3b) extends the representation of seismic hazard to the risk of incurring losses (Figure 3e).

- A point on the capacity/demand curve in Figure 3e represents the annual probability of exceeding the corresponding loss.
- The annual probability is plotted directly against loss, so that the area under the curve represents the expected annual loss due to earthquakes for the facility.
- Multiplying the expected annual loss by the expected life of the facility produces the total expected losses.
- A discount rate representing the time value of money (often assumed to be a prevailing short term interest rate less inflation) can be used to adjust the expected total losses to a net present value.

The use of performance-based engineering to characterize losses in terms of risk enables the engineer and facility owner to answer important questions in economic terms. For example:

Should the owner retrofit a facility to reduce earthquake losses?

The engineer formulates a pushover curve for the existing building and uses nonlinear static procedures to estimate displacements for various probabilities of exceedence. These are converted to losses and discounted 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 constructs a revised pushover curve and re-calculates the present value of the expected losses for the retrofitted facility. These should be less then 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. Most often, the benefit is divided by the cost to generate a ratio indicative of the value of the retrofit investment.

For a new facility, is it more efficient 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 expected losses for each. 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 annual expected earthquake losses. 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 annualized losses (from code design to upgraded criteria) represents the return on the investment.

Is earthquake insurance a good investment?

An economic analysis can identify the optimal investment in risk reduction. Beyond some level the incremental return on investment drops. An owner may choose to supplement the design with risk transfer through insurance. 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 purchase insurance 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.

UNCERTAINTY AND RELIABILITY

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. Thus the risk-based approach to seismic performance 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 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 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, 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

Selection of of a cost-efficient structural system

UC Berkeley is building a new state-of-the art laboratory building named Stanley Hall. 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 relatively new system in the United States at the time, 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 the new system that is more expensive than a conventional design to meet the minimum requirements of the State of California Building Code.

UC Berkeley – Stanley Hall

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

Figure 4: UC Berkeley, Stanley Hall

Engineers developed pushover curves for both the proposed unbonded brace frame system and a conventional braced frame design to meet the minimum requirements of the code. The unbonded brace design was estimated to be approximately $1.2 million more expensive than the conventionally braced system. Then they analyzed each system and quantified the potential loss of capital, contents and research revenue using the basic procedures outlined in the previous sections. The results predicted that the unbonded brace system would reduce annual losses due to earthquakes by $139K (Figure 5). Using a discount rate of 5%, the net present value of this reduction is $2.5M or more than twice the extra cost (Figure 6). The equivalent return on investment using the unbonded braces in place of the conventionally braced frame was approximately 11%. The analysis showed that the investment would theoretically pay for itself in approximately 15 years, far less than the 50 year projected lifetime (Figure 7).

Recognizing the uncertainties involved, the engineer varied the basic parameters to explore the sensitivity of the results to the basic assumptions. Also, the analysis does not include some of the 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 considerations, provided convincing evidence that investment in improved performance was a good one for the University.

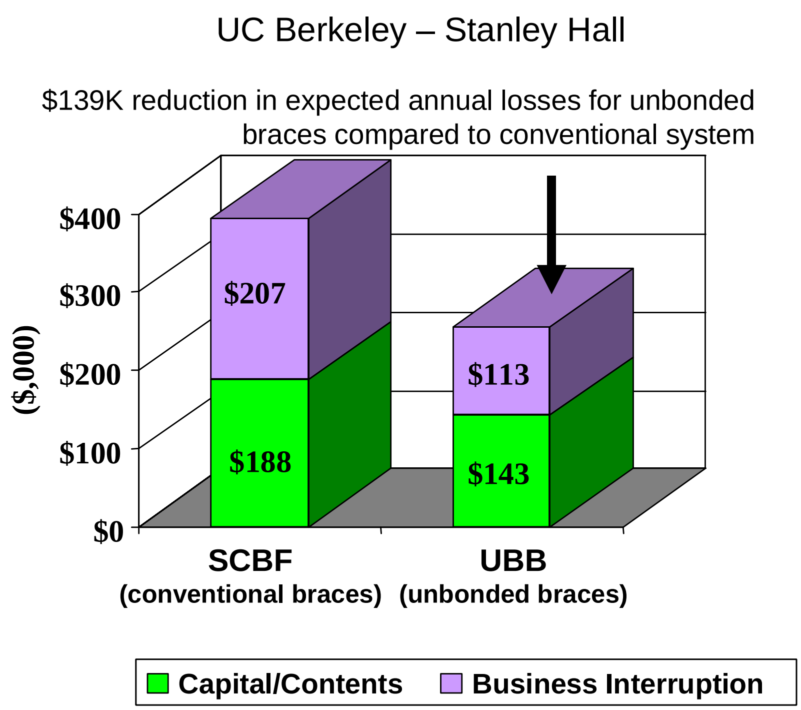

Figure 5: Reduction in expected annual earthquake losses attributable to the use of unbonded braces in place of conventional braces

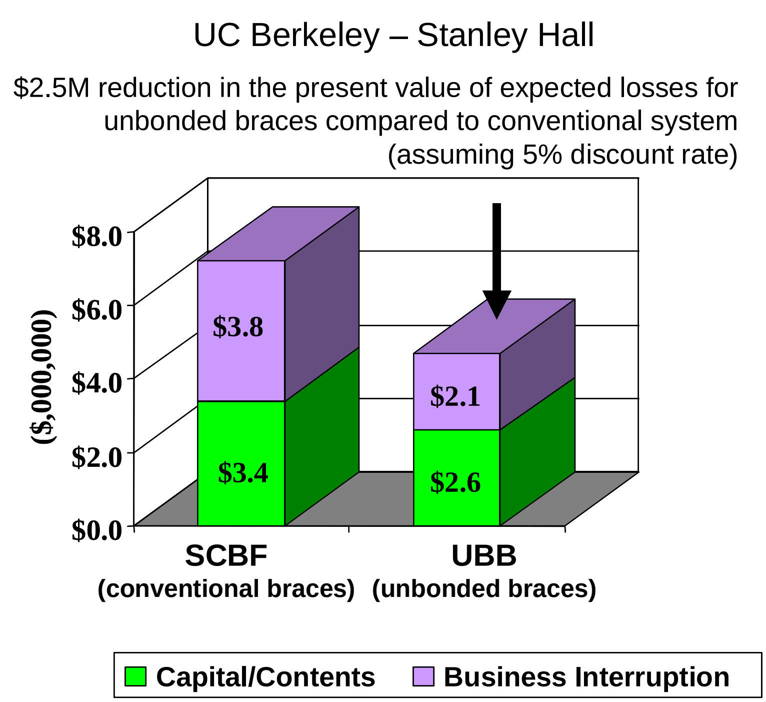

Figure 6 - Reduction in the net present value of expected earthquake losses attributable to the use of unbonded braces in place of conventional braces

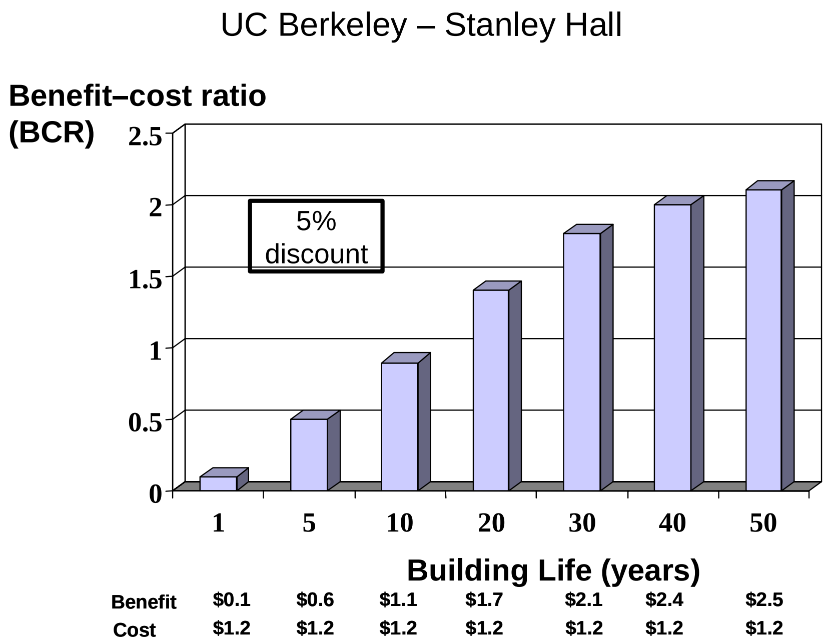

Figure 7 - Ratio of benefits to costs for use of unbonded braces in place of conventional braces

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 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.

Engineers performed a nonlinear performance based analysis of the building to estimate potential losses in a design level earthquake. The result was 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 engineer of record to develop 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 $200K.

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.

Assessing the value of insurance versus performance based engineering

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 purchases 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 asked the engineers to develop a mitigation plan that would reduce the dependence on insurance. The engineers used performance-based engineering procedures to devise the mitigation solution and estimate capital losses in a design level event. They adjusted the scope of the solution 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 $130K.

Based on the financial analysis (Figure 8) 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. Using performance-based engineering and risk analysis, the engineer 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 8: Example analysis of value of insurance versus mitigation

CONCLUSION

The performance-based approach is an important step forward in earthquake analysis and design. It is becoming increasingly popular among experienced engineers. It is relatively easy to enhance PBE to predict future losses and convert them to risks. With this formulation, engineers and owners can deal with seismic issues using conventional risk analysis techniques. As illustrated in the examples, this facilitates the investigation and evaluation of many risk management alternatives. The approach provides the owner with much more information than that available from traditional engineering analyses and code-based designs. This adds significant value to services that can be provided by a competent structural engineer.

REFERENCES

1. 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.
2. 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.
3. Kircher, Charles A., Aladdin A. Nassar, Onder Kustu and William T. Holmes, 1997. “Development of Building Damage Functions for Earthquake Loss Estimation,” *Earthquake Spectra*, Vol. 13, No. 4, Earthquake Engineering Research Institute, Oakland, CA, www.eeri.org.

4. National Institute of Building Science (NIBS), 1999. *HAZUS99 Technical Manual*. Developed by the Federal Emergency Management Agency through agreements with the National Institute of Building Sciences, Washington, D.C., www.nibs.org or www.fema.gov.
5. 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.
6. National Institute of Building Science (NIBS), 2002. *HAZUS99 Advanced Engineering Building Module Technical and User's Manual*, developed by the Federal Emergency Management Agency through agreements with the National Institute of Building Sciences, Washington, D.C., www.nibs.org or www.fema.gov.