An Overview of PEER's Performance-Based Earthquake Engineering Methodology

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ABSTRACT: Various analytical approaches to performance-based earthquake engineering are in development. This paper summarizes the approach being pursued by the Pacific Earthquake Engineering Research (PEER) Center. It works in four stages: hazard analysis, structural analysis, damage analysis, and loss analysis. In the hazard analysis, one evaluates the seismic hazard at the facility site, producing sample ground-motion time histories whose intensity measure (*IM*) is appropriate to varying hazard levels. In the structural-analysis phase, a nonlinear time-history structural analysis is performed to calculate the response of the facility to a ground motion of given *IM* in terms of drifts, accelerations, ground failure, or other engineering demand parameters (*EDP*). In the third, damage-analysis, phase, these *EDP*s are used with component fragility functions to determine measures of damage (*DM*) to the facility components. Finally, given *DM*, one evaluates repair efforts to determine repair costs, operability, and repair duration, and the potential for casualties. These measures of performance are referred to as decision variables (*DV*), since they can be used to inform stakeholder decisions about future performance. Each relationship, from location and design to *IM*, *IM* to *EDP*, *EDP* to *DM*, and *DM* to *DV*, involves uncertainty and is treated probabilistically. PEER is currently exercising and illustrating its methodology on six real facilities, called testbeds, each of which explores a different aspect of PBEE.

1 INTRODUCTION

Performance-based earthquake engineering (PBEE) in one form or another may supercede load-and-resistance-factor design (LRFD) as the framework under which many new and existing structures are analyzed for seismic adequacy. A key distinction between the two approaches is that LRFD seeks to assure performance primarily in terms of failure probability of individual structural components (with some system aspects considered, such as the strong-column-weak-beam requirement), whereas PBEE attempts to address performances primarily at the system level in terms of risk of collapse, fatalities, repair costs, and post-earthquake loss of function.

Initial efforts to frame and standardize PBEE methodologies produced SEAOC's Vision 2000 report (1995) and FEMA 273 (1997), a product of the ATC-33 project. The authors of these documents frame PBEE as a methodology to assure combinations of desired system performance at various levels of seismic excitation. The system-performance states of Vision 2000 include fully operational, operational, life safety, and near collapse. Levels of excitation include frequent (43-year return period), occasional (72-year), rare (475-year) and very rare (949-year) events. These reflect Poisson-arrival events with 50% exceedance probability in 30 years, 50% in 50 years, 10% in 50 years, and 10% in 100 years, respectively. The designer and owner consult to select an appropriate combination of performance and excitation levels to use as design criteria, such as those suggested in Figure 1.

FEMA 273 expresses design objectives using a similar framework, although with slightly different performance descriptions and levels of seismic excitation. Each global performance level is detailed in terms of the performance of individual elements. A design is believed to satisfy its global objectives if structural analysis indicates that the member forces or deformations imposed on each element do not exceed predefined limits. Performance is binary and largely deterministic: if the member force or deformation does not exceed the limit, it passes; otherwise, it fails. If the acceptance criteria are met, the design is believed to assure the performance objective, although without a quantified probability. Other important pioneering PBEE efforts include ATC-32 (1996a), ATC-40 (1996b), and FEMA 356 (2000).

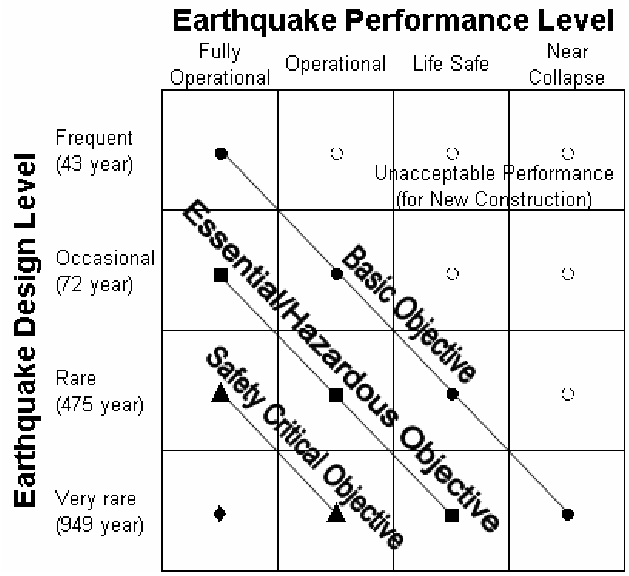

Figure 1. Vision 2000 recommended seismic performance objectives for buildings (after SEAOC, 1995).

2 PEER APPROACH

The Pacific Earthquake Engineering Research (PEER) Center, based at the University of California, Berkeley, is one of three federally funded earthquake engineering research centers. Currently in its sixth year of a ten-year research program, PEER is focusing on developing a PBEE methodology to replace the first-generation efforts. A central feature of PEER's approach is that its principal outputs are system-level performance measures: probabilistic estimates of repair costs, casualties, and loss-of-use duration ("dollars, deaths, and downtime.")

The objective of the methodology is to estimate the frequency with which a particular performance metric will exceed various levels for a given design at a given location. These can be used to create probability distributions of the performance measures during any planning period of interest. From the frequency and probability distributions can be extracted simple point performance metrics that are meaningful to facility stakeholders, such as an upper-bound economic loss during the owner-investor's planning period.

Figure 2 illustrates the PEER methodology. As it shows, PEER's PBEE approach involves four stages: hazard analysis, structural analysis, damage analysis, and loss analysis. In the figure, the expression $p[X|Y]$ refers to the probability density of X conditioned on knowledge of Y, and $g[X|Y]$ refers to the occurrence frequency of X given Y (equivalent to the negative first derivative of the frequency with which X is exceeded, given Y). Equation 1 frames the PEER methodology mathematically. Note that Figure 2 omits conditioning on D after the hazard analysis for brevity, but it is nonetheless implicit.

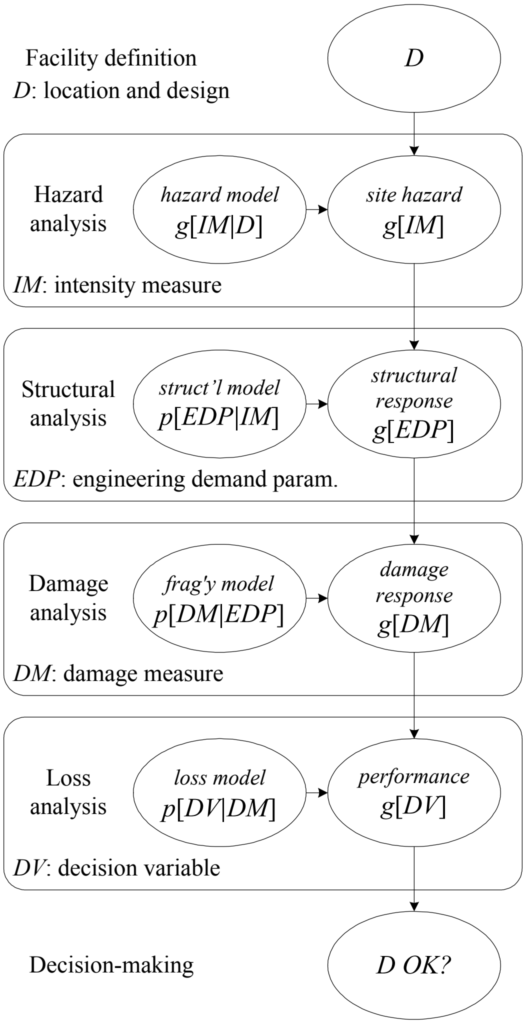

Figure 2. PEER analysis methodology.

$$g[DV|D]=\iiint p[DV|DM,D]p[DM|EDP,D]\, p[EDP|IM,D]g[IM|D]dIMdEDPdDM \quad (1)$$

Hazard analysis. In the hazard analysis, one considers the seismic environment (nearby faults, their magnitude-frequency recurrence rates, mechanism, site distance, site conditions, etc.) and evaluates the seismic hazard at the facility considering the facility location and its structural, architectural, and other features (jointly denoted by design, D), to produce the seismic hazard, $g[IM|D]$. The hazard curve describes the annual frequency with which seismic excitation is estimated to exceed various levels. Excitation is parameterized via an intensity measure (IM) such as $S_a(T_1)$, the damped elastic spectral acceleration at the small-amplitude fundamental period of the structure. In our analyses to date, the hazard analysis includes the selection of a number of ground-motion time histories whose IM values match three hazard level of interest, namely, 10%, 5%, and 2% exceedance probability in 50 years.

PEER researchers have used S_a so far in our analyses, and have established procedures to select design ground motions consistent with the site hazard (e.g., Somerville and Collins, 2002). We will also test nine alternative *IM*s (see Bray, 2002, for a list) that might estimate performance with less uncertainty. We will test each IM for conditioning on magnitude, distance, and possibly other parameters that might relate to performance. (These are the efficiency and sufficiency tests described by Luco and Cornell, 2001). Most of the candidate *IM*s are scalars; some are vectors (e.g., Pandit et al., 2002). Some are more relevant to excitation of structures (e.g., Cordova et al., 2001), while some focus on ground failure (Kramer and Mitchell, 2002).

Structural analysis. In the structural analysis, the engineer creates a structural model of the facility in order to estimate the uncertain structural response, measured in terms of a vector of engineering demand parameters (EDP), conditioned on seismic excitation and design ($p[EDP|IM,D]$). *EDP*s can include internal member forces or local or global deformations, including ground failure (a preliminary list is provided in Porter, 2002). The structural analysis might take the form of a series of nonlinear time-history structural analyses. The structural model need not be deterministic—some PEER analyses have included uncertainty in the mass, damping, and force-deformation characteristics of the model.

Damage analysis. EDP is then input to a set of fragility functions that model the probability of various levels of physical damage (expressed via damage measures, or DM), conditioned on structural response and design, $p[DM|EDP,D]$. Physical damage is described at a detailed level, defined relative to particular repair efforts required to restore the component to its undamaged state. Fragility functions currently in use give the probability of various levels of damage to individual beams, columns, nonstructural partitions, or pieces of laboratory equipment, as functions of various internal member forces, story drift, etc. They are compiled from laboratory or field experience. For example, we have compiled a library of destructive tests of reinforced concrete columns (Eberhard et al., 2001). The result of the damage analysis is a probabilistic vector of DM. Note that component damage may be correlated with structural characteristics of D, even conditioned on EDP.

Loss analysis. The last stage in the analysis is the probabilistic estimation of performance (parameterized via various decision variables, DV), conditioned on damage and design $p[DV|DM,D]$. Decision variables measure the seismic performance of the facility in terms of greatest interest to stakeholders, whether in dollars, deaths, downtime, or other metrics. Our loss models for repair cost draw upon well-established principles of construction cost estimation. Our model for fatalities, currently in development, draws upon empirical data gathered by Seligson and Shoaf (2002) and theoretical considerations elaborated by Yeo and Cornell (2002). Later research will address injuries. Note that location aspects of D are relevant to many *DV*s such as repair cost.

Decision-making. The analysis produces estimates of the frequency with which various levels of DV are exceeded. These frequencies can be used to inform a variety of risk-management decisions. If one performs such an analysis for an existing or proposed facility, one can determine whether it is safe enough or has satisfactorily low future earthquake repair costs. If one re-analyzes the same facility under redesigned or retrofitted conditions, one can assess the efficacy of the redesigned facility to meet performance objectives, or weigh the reduced future losses against the upfront costs to assess the cost-effectiveness of the redesign or retrofit. For example, if one refers to the reduction in the present value of future losses as *benefit* (*B*) then the expected benefit during time *T* of a retrofit measure that changes the design of a facility from *D* to *D'* can be calculated as

$$E[B|T,D,D'] = T\int DV g[DV|D]dDV - T\int DV g[DV|D']dDV \qquad (2)$$

3 FEATURES OF THE PEER FRAMEWORK

PEER's approach satisfies at least four important desiderata of PBEE: a system-level performance assessment, probabilistic characterization of performance, a foundation in existing disciplines, and a thoroughly testable, empirical basis.

System-level performance assessment. While the PEER approach produces intermediate outputs that are component-specific (e.g., drift at a given story level, bending moment at a particular point in a particular beam, or post-earthquake operability of a particular piece of equipment), the final output is a rich description of the performance of the whole building or bridge in economic, life-safety, and post-earthquake operability terms. We are currently identifying a set of simple scalar performance metrics—key aspects of the available DVs—that will be most meaningful to various facility stakeholders. For example, although the PEER methodology is capable of producing a full probability distribution of uncertain future repair cost, the investor in a large commercial building may wish to know only "the loss" in "the earthquake," which might be defined as the mean repair cost given the occurrence of an earthquake whose magnitude and distance range contribute most substantially to overall losses (the mode in a risk de-aggregation).

Treatment of uncertainty. Uncertainty enters into the analysis at each stage. In the hazard analysis, it is uncertain what levels of seismic intensity (*IM*) the facility will experience during its lifetime. The detailed ground motions given those *IM*s are also uncertain. In the structural analysis, the reactive mass, viscous damping, and structural force-deformation behavior are all uncertain, as Ellingwood et al. (1980) described during the development of LRFD. Furthermore, the selection of elements and other modeling assumptions during the structural analysis add a measure of uncertainty to the performance estimate. Similarly, uncertainties enter into the damage and loss analysis stages. All these sources of uncertainty are recognized by the PEER methodology.

We have begun to probe their relative impacts on performance uncertainty, initially using a simple deterministic sensitivity study, common in decision analysis, called a tornado-diagram analysis, which measures the change in output performance resulting from varying one uncertain input from a lower-bound to upper-bound value, while holding all others at their best-estimate value. Such an analysis can identify sources of uncertainty whose further exploration might reduce total uncertainty. It can also identify parameters whose contribution to uncertainty is small enough that the parameter can be treated deterministically in future analyses.

Figure 3 illustrates the results of one such analysis for one of several testbed facilities we are examining. Each bar in the figure measures the change in damage factor (repair cost as a fraction of replacement cost) that results from varying an input parameter from its 10th to 90th-percentile value, while holding all others at their median (50th percentile). The figure shows that, for this building, the greatest impact on uncertain loss during the next 50 years results from uncertainty of the fragility of the building components (i.e., the structural response that causes them to enter various damage states). Other major contributors are the maximum S_a the building will experience during the next 50 years and the details of the ground motion given that level of S_a.

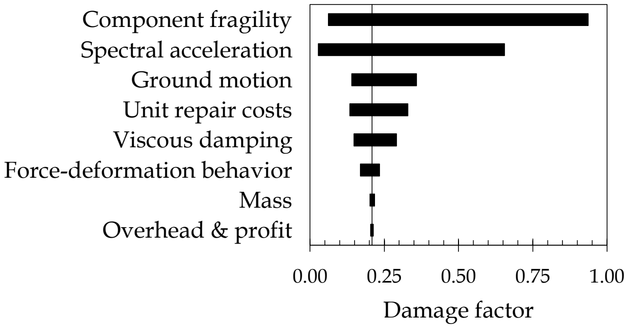

Figure 3. Sensitivity of future repair cost to uncertain input parameters for Van Nuys testbed.

Other factors examined include the unit costs that the repair contractor will charge, the viscous damping assumed in the structural model, uncertainties in the force-deformation behavior of the structural model, the reactive mass, and the contractor's overhead and profit. Uncertainties not examined include the effects of post-earthquake demand-driven cost inflation (so-called *demand surge*), uncertainty of seismic hazard parameters, union versus non-union labor, building-code changes, and others. Details can be found in Porter et al. (2002). Similar studies are underway for other testbed facilities.

Moving beyond the simple probing of sources of uncertainty, PEER researchers have explored simulation to quantify uncertain performance (Beck et al., 2002), and more recently, developed a first-order, second-moment (FOSM) methodology to calculate total uncertainty of future repair costs (Baker and Cornell, 2003). One of the several advantages of the FOSM approach is that it avoids some of the computational expense of simulation procedures. Both approaches treat both types of uncertainty (variously called aleatory and epistemic, randomness and uncertainty, or irreducible and reducible).

Familiar disciplines. Notice that the hazard analysis can be performed by engineering seismologists or geotechnical engineers who need little specialized expertise in the subsequent analytical stages. The structural analysis employs only concepts familiar to structural engineers. Although component fragility functions may be unfamiliar to many practicing structural engineers, damage analysis has a long heritage in nuclear engineering and process safety. Even the loss analysis uses well-established concepts. For example, repair costs are commonly estimated by construction contractors.

This last point is particularly important because it allows us to accommodate the widely varying performance metrics of concern to diverse categories of decision-makers. State transportation-department officials for example, care about different measures of performance than do institutional owner-occupants of modern laboratory facilities. However, as these performance metrics can be evaluated given a detailed picture of the facility's physical damage, one need not know the details of how the damage state came to occur.

Testable, empirical basis. A final feature of interest is that each analytical stage employs only testable, verifiable, and improvable assumptions. For example, because damage is defined at the level of individual elements whose detailed characteristics are known, we can compile and use laboratory and field data to create empirical component fragility functions. Thus we do not rely on expert opinion to establish general levels of interstory drift that produce certain damage states, as prior methodologies have done.

Where reducible uncertainties strongly contribute to performance uncertainty, we can pursue a program of research to improve the accuracy of performance estimates. For example, in Porter et al. (2002), we employed data from diverse beam-column tests to create some fragility functions, and subsequently found that the fragility functions contributed strongly to uncertainty in future repair cost. PEER could perform additional tests that focus on narrower categories of beam-columns, and thus potentially reduce the uncertainty caused by broad grouping.

4 OPENSEES AND OTHER SOFTWARE

PEER researchers have developed sophisticated open-source finite-element software called OpenSEES, which implements much of the methodology. It contains a variety of 2D and 3D elements, material models, and section models. Its analytical capabilities include linear equation solvers, eigenvalue solvers, integrators, solution algorithms, convergence tests, and constraint handlers. OpenSEES also includes reliability and sensitivity-analysis capabilities to handle many of the uncertainties in seismic performance (Haukaas and Der Kiureghian, 2001). Extensive online resources and documentation are available at http://opensees.berkeley.edu/.

In addition to creating OpenSEES, PEER researchers have compiled an online database of strong-motion records, currently including 1,557 records from 143 earthquakes from tectonically active regions (http://peer.berkeley.edu/smcat/).

5 TESTBEDS

To exercise and illustrate our methodology, we have selected six testbeds—real, existing facilities—each of which explores a different aspect of the research. The facilities include two buildings, two bridges, a network of highway bridges, and a campus of buildings. The two buildings and two bridges are summarized here.

Van Nuys. The Van Nuys testbed building is a 66,000-sf hotel located in California's San Fernando Valley and built in 1966. In plan, the building is rectangular, 63 ft by 150 ft, 3 bays by

8 bays, 7 stories tall (Figure 4). Its structural system is a reinforced concrete moment-frame with flat-plate slabs. Reinforcing steel lacks ductile detailing. Prior to the 1994 Northridge earthquake, lateral resistance was provided primarily by the perimeter moment-frames, with some stiffness and strength provided by the interior gravity frames. The building is founded on reinforced-concrete drilled piers.

It was strongly shaken and damaged in the 1971 San Fernando and 1994 Northridge earthquakes. Repair after Northridge involved a change of structural system that will not be addressed by the present study. PEER researchers working on the Van Nuys testbed are focusing on estimating structural and architectural damage, collapse potential, repair cost, and repair duration.

Figure 4. Van Nuys testbed building in 2000 (author photo).

UC Science Building. The UC Science Building testbed is a modern reinforced-concrete shearwall structure completed in 1988 to provide high-technology research laboratories for organismal biology (Figure 5). The building is 203,800 square feet overall, and contains research laboratories, animal facilities, offices, and related support spaces. The building is six stories plus a basement, and is rectangular in plan with overall dimensions of 306 feet by 105 feet. The structural system comprises reinforced-concrete shear walls in both directions, waffle-slab diaphragms supported on 20-inch deep joists, and a 38-inch deep continuous mat foundation.

PEER researchers working on the UC Science Building testbed are focusing on estimating contents and equipment damage and the life-safety and operational consequences of such damage. One particularly interesting aspect of the research is that we are performing shake-table tests of various equipment components to establish their fragility functions and to inform the formulation of a general theoretical framework for estimating the fragility of laboratory equipment.

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Figure 5. UC Science testbed building.

Humboldt Bay Bridge. The subject bridge is one of three that cross Humboldt Bay on California State Route 255 (Figure 6). Owned and maintained by the California Department of Transportation, the bridge (no 04-0229) is a 1,080-ft, nine-span composite structure built in 1972. In 1992, it carried average daily traffic of 4,600 to 15,800.

It is interesting because it is fairly representative of older AASHTO-Caltrans girder bridges with moderate traffic loads, designed before ductile detailing was common. Furthermore, the bridge is founded on fairly poor soils, so permanent ground deformation is a serious concern. Caltrans recently completed a seismic retrofit to mitigate the potential for unseating and diaphragm damage; a second retrofit is planned to strengthen the piers, pilecaps, and pilegroups.

Figure 6. Humboldt Bay Bridge (G. Deierlein photo).

I-880. Our other bridge testbed is a more-recent highway viaduct structure on I-880 in Oakland, CA (Figure 7). It is a prestressed concrete, multi-span box-girder structure, 3,734 ft long, 71.5 ft wide, built in 1998. It is one of seven design packages that replaced the section of I-880 damaged in the 1989 Loma Prieta Earthquake. This structure is interesting in part because it reflects fairly up-to-date design practices. Because of its location and high traffic load, its post-earthquake functionality is critical, and its closure would be very costly.

Figure 7. I-880 testbed bridge (author photo).

Analytical results for each testbed will be published in a single, combined report that documents all aspects of the research. Further details on each testbed, including seismic hazard, detailed geotechnical and structural models, and interim analytical results are currently available at www.peertestbeds.net.

6 PRACTITIONER PARTICIPATION

To ensure that PEER produces a methodology that is relevant to practitioners and facility owners, each testbed includes research by one or more of our business and industry partners (BIPs).

Degenkolb Engineers of San Francisco has performed a FEMA-356 analysis of the Van Nuys testbed, which it will compare with the PEER approach and analytical results. Engineers from Rutherford and Chekene of San Francisco are working closely with PEER on the assessment of the UC Science building for the purpose of developing equipment retrofit measures for the owner. Degenkolb will provide a practitioner critique of our methodology, with particular attention to advantages and development needs.

Two professional bridge-design firms, Lim and Nascimento Engineering of San Bernardino, CA, and Imbsen & Associates, Inc., of Sacramento, CA, are likewise engaged in a critique of PEER's analysis of the Humboldt Bay Bridge and I-880 viaduct, respectively. They will compare the methodology with any equivalents in Caltrans practice, focusing on technical merit, advantages, and shortcomings of the PEER approach. These firms will offer their opinions of any new value PEER brings to bridge-design practice in terms of new services, valuable information, or increased design efficiency. Finally, they will examine the extent to which current practitioners are prepared to perform similar analysis and identify any major perceived developmental needs of the methodology.

7 CONCLUSIONS, FUTURE DIRECTIONS

This paper has summarized the development of a performance-based earthquake engineering methodology by the Pacific Earthquake Engineering Research Center. The methodology seeks to provide a probabilistic description of the system-level performance of bridges and buildings in terms of greatest meaning to owners and other stakeholders, namely, uncertain future repair costs, casualties, and post-earthquake operability (dollars, deaths, and downtime).

The research explores geotechnical and structural modeling, damageability of structural and nonstructural components and contents, and the human and socioeconomic consequences of physical damage. The research is being pursued using a framework that includes four distinct stages: hazard analysis, structural analysis, damage analysis, and loss analysis, to produce a probabilistic estimate of various system-level performance metrics. A sophisticated open-source analysis package, OpenSEES, provides extensive tools to facilitate the PEER analyses.

Many theoretical and practical questions remain to be resolved during the second half of PEER's 10-year research program. Are alternative intensity measures better indicators of seismic performance than damped elastic spectral acceleration? How few structural analyses can we use and still produce a robust estimate of uncertain future performance? Under what conditions can structural response (*EDP*) be treated as a state variable, so that damage can be modeled conditioned solely on *EDP* and the generic performance of damageable components, so as to avoid treating possible correlation with the structural characteristics of the individual facility in question? How should "the earthquake" be defined for decision-makers who want a performance metric based on a single, easily-imagined event?

Practical issues to be addressed include the question of whether the PEER methodology can be implemented so as not to excessively tax the skillset of practicing engineers. What is required to demonstrate that PEER's approach offers new value to owners and engineers, either in terms of reduced costs for given performance objectives, or new services and risk-management information that current approaches do not reliably provide?

This paper is necessarily too brief to explore the variety of interesting and important research projects PEER researchers are pursuing. Perhaps it dwells excessively on aspects of the research of greatest interest and familiarity to the present author. If so, he apologizes and refers the interested reader to PEER's web page (http://peer.berekeley.edu/), its report series, and the contributions of other PEER authors in these proceedings, to explore PEER's PBEE efforts in greater depth.

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