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CHALLENGES AND PROGRESS IN PERFORMANCE-BASED EARTHQUAKE ENGINEERING

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1. INTRODUCTION

Performance-based earthquake engineering (PBEE) implies design, evaluation, and construction of engineered facilities whose performance under common and extreme loads responds to the diverse needs and objectives of owners-users and society. It is based on the premise that performance can be predicted and evaluated with quantifiable confidence in order to make, together with the client, intelligent and informed trade-offs based on life-cycle considerations rather than construction costs alone.

PBEE is a desirable concept whose implementation has a long way to go. There are legal and professional barriers, but there are also many questions whether PBEE will be able to deliver its promises. It appears to promise engineered structures whose performance can be quantified and conforms to the owner's desires. If rigorously held to this promise, performance-based engineering will be a losing cause. We all know that we cannot predict all important seismic demands and capacities with perfect confidence, even in a probabilistic format. There are, nevertheless, compelling reasons to advocate PBEE as a critical area for research and implementation. The objective of seismic engineering should be to design and build better and more economical facilities. Both terms are relative to the status quo. In the writer's opinion, significant improvements beyond the status quo will not be achieved without a new and idealistic target to shoot for. We need to set this target high and strive to come close to its accomplishment. We may never fully reach it, but we will make significant progress if we have a well defined target. PBEE is the best target available, and we need to focus on it.

Earthquake engineering practice is undergoing drastic changes triggered by a variety of reasons. Improved knowledge about earthquake occurrences and ground motion and structural response characteristics is certainly one of them. The realization from recent earthquakes in the U.S. and Japan that monetary damage can surpass expectations by a large amount is another one. Perhaps most important is the realization that present code design procedures cannot be rationalized sufficiently by first principles to satisfy (a) the designer's desire for a logical explanation of the rules of the game, (b) the owner's desire for sound judgment on the costs and benefits of earthquake protection, and (c) society's needs for informed decision making in the face of random (and often highly uncertain) seismic demands as well as uncertain seismic capacities of existing and even new man-made construction.

By now it is widely acknowledged that seismic design should explicitly consider multiple performance objectives. There is a minimum level of protection demanded by society in order to safeguard adequately against partial collapse that endangers human lives. But society has responsibilities in addition to life safety, including continuing operation of critical facilities, protection against the discharge of hazardous materials, and protection against excessive damage that may have far-reaching consequences for society on a local, regional, national, or international level. Moreover, educated owners want options for maximizing the return on their investment or for providing life safety protection to the inhabitants of their facilities beyond the minimum required by society. These options differ between developers and, for instance, corporate owners whose livelihood may depend on the resumption of operation soon after an earthquake.

PBEE implies, for example, accepting damage in seismic events, if that proves the most economic solution. This requires, however, that structural engineers be able to predict these damages and their likelihood in order to make informed decisions. Implementation of such a design decision process necessitates a shift away from the dependence on empirical and experience-based conventions, and towards a design and assessment process more firmly rooted in the realistic prediction of structural behavior under a realistic description of the spectrum of loading environments that the structure will experience in the future. This implies a shift towards a more scientifically oriented design approach with an emphasis on more accurate characterization and predictions, often based on a higher level of technology than has been used in the past.

This higher level of technology needs to be developed through research. Among others this research should lead to

- The development of methodologies on which future seismic design codes and practices can be based. Such methodologies need to incorporate new developments in demand and capacity descriptions and need to be based on deterministic as well as probabilistic concepts. The application of these methodologies should result in performance that can be quantified and should produce consistent seismic protection for existing and new structures.

- The development of more reliable analytical procedures that permit a performance evaluation of a wide variety of soil-foundation-structure systems and their components, of nonstructural systems, and of building contents, at all levels of performance, ranging from cosmetic structural or nonstructural damage to structural degradation leading to collapse, and with due consideration given to the uncertainties inherent in the assessment of seismic demands and capacities.

Performance-based design by itself will not accomplish improved or more predictable structural performance. Design provides only a set of drawings and instructions to the builder. The quality of the built product will depend on the clarity of the documentation and its communication, and the capability and willingness of the builder to implement the instructions. Thus, performance-based <u>design</u> must be followed by performance-based <u>construction</u>, in which construction engineering services and quality control play key roles.

A rigorous implementation of PBEE may well necessitate radical changes in engineering/construction practices and redirection of R&D. Architects, engineers, and contractors will have to work together rather than take on adversary positions, and academic researchers will have to interact, much more than in the past, with AEC practitioners who will lead the implementation process. Society will set the performance objectives, and AEC researchers and practitioners will have to find ways to fulfill them. This will be the challenge of PBEE.

PBEE has no future unless it becomes an attractive process for all stakeholders. In addition to AEC practitioners, stakeholders include, among others, planners, building officials, facility managers, owners, lenders, and insurers. Identification and involvement of all stakeholder groups early in the research and development effort is critical.

2. A GLOBAL FRAMEWORK FOR PBEE

In the USA, several conceptual frameworks for PBEE have been developed in recent professional efforts (SEAOC Vision 2000, FEMA 273, ATC-40). They differ in details but not in concepts. Figure 1 illustrates a global framework, which identifies processes, concepts, and major issues that need to be addressed. The issues encompass seismological, geotechnical, structural, architectural and MEP (nonstructural), and socio-economic considerations. The following research agenda focuses on structural and interface issues, and uses this global framework as a background.

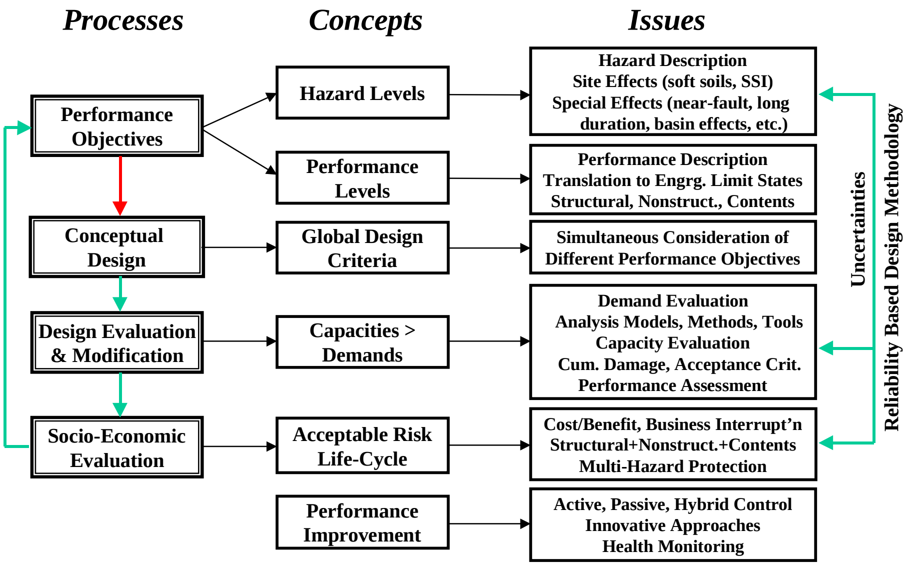

Figure 1. A Global Framework for Performance-Based Earthquake Engineering

3. A GLOBAL RESEARCH AGENGA – STRUCTURAL/NONSTRUCTURAL ISSUES

The focus of this discussion is on issues that are dominated by structural considerations. The agenda follows the path outlined in Figure 1, from process to concept to issues. The emphasis is on PBEE for buildings, but much of the agenda is applicable, or extendable, to infrastructure and industrial facilities.

3.1 Performance Objectives – Performance Levels – Performance Description

Performance Objectives. Vision 2000 defines performance objective as "an expression of the desired performance level for each earthquake design level". Implicit in this definition is the identification of specific performance levels and the discretization of earthquake design levels, usually expressed in terms of specific return periods. Identification of performance levels and discretization of earthquake levels is convenient but not necessary. More general, a performance objective can be expressed in terms of minimizing total "expected" costs (initial plus insurance plus maintenance plus losses times their annual probabilities) subject to constraints such as a tolerable annual probability of exceedance of a life threatening limit state (e.g., collapse). It is recognized that such an expression of a performance objective is more difficult to realize, but research may show that it can be accomplished in a probabilistic approach.

Performance Levels and Performance Description. Desired performance is usually expressed in socio-economic terms. Expressions such as "collapse", "near collapse", "collapse prevention", "life safety", "operational", "fully operational", "damage control", "immediate occupancy", and "serviceability" are used in various documents. Different expressions may be employed for desired performance of structural, nonstructural, and contents systems. Engineering input is much needed to identify performance levels that can be described in engineering terms and to establish an emphasis on performance levels that can become the focus of engineering design decisions. It may be necessary to establish a hierarchy of performance levels, with an initial focus on those that can be implemented in the near future, and long-range research on other performance levels that are of interest to society but whose implementation is far from realization.

Translation of Performance Description into Engineering Limit States. For practical reasons, engineering design needs to be based on physical parameters that can be associated with engineering limit states. Examples of such parameters are strength, stiffness, global and interstory drift, deformation capacity, and energy dissipation capacity. Well established engineering limit states are the elastic limit, maximum component strength, and to some degree the inability to maintain gravity load carrying capacity (limit state of partial or complete system collapse). Very few of these parameters and limit states are contained explicitly in the socio-economic description of performance levels. PBEE can not be attempted unless the performance descriptions associated with various levels of desired performance are translated into engineering limit states that can become targets for design. This applies to performance levels of structural, nonstructural and contents systems.

3.2 Conceptual Design – Global Design Criteria

In the conceptual design phase a structural system needs to be configured that is capable of fulfilling diverse requirements at various performance levels. This design phase is critical since most of the important design decisions are being made in it. Later design phases serve primarily to evaluate, fine tune, and detail an already existing system. The success of PBEE will depend strongly on the guidance that can be provided for conceptual design. Engineers are used to design for strength and elastic stiffness, with an implicit understanding of the importance of ductility, and with a single-level design in mind. PBEE will impose diverse multi-level requirements whose relationships to well understood ground motion and engineering parameters need to be established and quantified in order to provide targets for strength, stiffness, and ductility design. Different performance levels may control different aspects of the design, and simultaneous consideration of different performance objectives will become a fundamental aspect of conceptual design.

3.3 Design Evaluation and Modification

This process is at the core of PBEE and requires extensive research. It encompasses all aspects of demand and capacity predictions needed to carry out design evaluation through assessment of performance at different levels (or estimation of total costs) and to modify design decisions if the stated performance objectives are not met (or the costs are unacceptable). From an engineering perspective, satisfactory performance implies that the demands imposed by earthquakes do not exceed the capacities the structural, nonstructural, and contents components and systems are capable of providing. Demands and capacities are general terms that take on a specific meaning for different parameters that may control component and system performance at the various performance levels.

3.3.1 Demand Prediction

Performance assessment must be based on a probabilistic hazard representation and a prediction of seismic demands and capacities for all important components of the complete soil-foundation-structure system and of nonstructural and content systems. At this time neither capacities nor demands can be predicted with good accuracy, because of insufficient knowledge, lack of tools, and randomness and modeling uncertainties. We must try to improve description of the randomness and reduce the modeling uncertainties, but we must acknowledge that we will not be able to eliminate either. Appropriate analysis methods need to be developed to provide adequate yet simple means of demand prediction. Nonlinear inelastic time history analysis is desirable but likely not necessary in many cases. Research on the most effective demand prediction methods needs to be performed, with emphasis on the following aspects:

- Assessment of the quality of demand prediction that can be achieved by various analysis methods (elastic-static, elastic-dynamic, inelastic-static, and inelastic-dynamic).
- 3-D analysis procedures for soil-foundation-structure systems.
- Sufficiently realistic modeling of strength, stiffness, and mass irregularities in plan and elevation.
- Sufficiently realistic modeling of component behavior under cyclic loading.
- Modeling of nonstructural components and systems.
- Validation of modeling and analysis procedures through the utilization of laboratory and field experimentation, earthquake damage data, and vibration measurements from instrumented structures.

The following fundamental issue in demand prediction at a performance level associated with collapse safety deserves particular attention. Structural components will deteriorate in strength and stiffness when subjected to large deformation demands. The predicted deformation demands may be severely underestimated if these deterioration phenomena, particularly strength deterioration, are ignored in analytical modeling. If performance assessment is carried out only at the component level it may be feasible to account for this underestimation by means of a “demand uncertainty factor”, even though such a factor is of questionable value because of the history dependence of deterioration. For performance assessment at the structural system level (see Section 3.3.3), incorporation of component deterioration is a necessity. A structure can collapse only if either P-delta instability occurs (which is accelerated by component strength deterioration) or components deteriorate to the extent that they are no longer capable of resisting their share of gravity loads. Thus, a realistic prediction of closeness to collapse of a structural system can only be accomplished through incorporation of component deterioration. Research is needed to quantify deterioration and incorporate it in analytical models.

In summary, the profession needs a tool kit that permits a comprehensive performance evaluation of new and existing structures.

3.3.2 Capacity Evaluation

This topic requires perhaps the most extensive research effort within PBEE. It is concerned with the quantitative assessment of all physical characteristics that significantly affect performance at the various performance levels, considering structural components, nonstructural components and systems, and facility contents. Capacity evaluation of structural systems is a separate issue that is discussed in Section 3.3.3.

Capacities of Structural Components. In concept, capacities are associated with states of acceptable damage at various performance levels. In the engineering context, acceptable damage may be measured in terms of strength (for components with negligible inelastic deformation capacity) or deformations associated with a physical description of damage (e.g., extent of cracking, % loss in strength capacity).

For higher performance levels (associated with continuing operation or damage control) these engineering descriptions do not correlate well with the socio-economic descriptions of interest to society. Thus, research is needed to translate engineering descriptions of damage into socio-economic terms such as cost of repair (including consequences of possible downtime).

For low performance levels (associated with collapse prevention) damage is associated with deterioration in strength and stiffness, with strength deterioration being the much more important deterioration phenomenon. A fundamental issue for capacity evaluation is cumulative damage, i.e., the dependence of capacity on the load or deformation history. A realistic prediction of deformation capacities will necessitate cumulative damage modeling, for the reason illustrated in

Figure 2. In case of a near-fault pulse-type ground motion the response of a component could be of the type shown in Figure 2(a), whereas in case of a more distant but long duration earthquake the response could be of the type shown in Figure 2(b). The deterioration behavior, and therefore the performance of the component, will be very different in the two cases. Using a history independent deformation capacity (e.g., δ_{al} in Figure 2) would be misleading for both cases. Much research is needed to improve this aspect of PBEE.

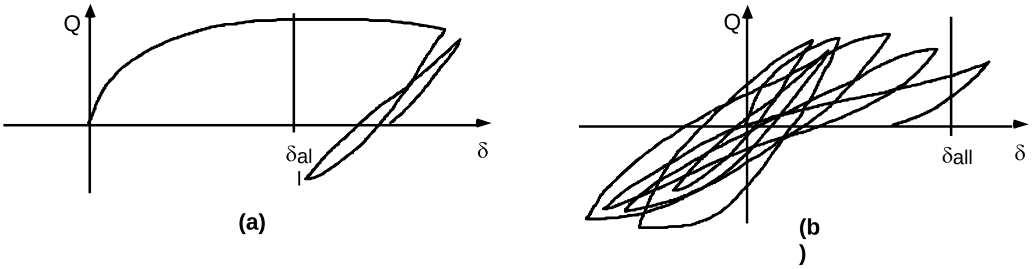

Figure 2. Different Response History for the Same Structural Component

Research implies extensive experimentation on, and analytical modeling of, component behavior. Experimental research needs to be performed with history dependent cumulative damage modeling in mind. This necessitates the development of a testing protocol that focuses on the evaluation and documentation of all important response parameters, and provides representative loading histories that can be employed for performance assessment. Different loading histories will need to be developed for "ordinary" ground motions, near-fault (pulse-type) motions, and soft soil (harmonic) motions.

Capacities of Nonstructural and Contents Components and Systems. There is no doubt that PBEE will not be realizable without an emphasis on nonstructural and contents issues and business interruption losses. Any increase in construction costs can hardly be justified based on structural considerations alone, even if a life-cycle cost-benefit analysis is performed. But nonstructural considerations and business losses may tip the scale.

In this context, "nonstructural" refers to facility components and systems that are not structural, including architectural (cladding, ceilings, doors/windows, partitions, etc.) and mechanical, electrical, and plumbing components (elevators, lights, piping, ducts, HVAC systems, security systems, fire protection systems, telephone and other communication systems, etc.). Contents, which may be lumped into "nonstructural", refers to equipment and stored goods that are not considered as parts of the facility lifeline systems.

Capacity assessment of such components and systems implies seismic qualification testing at different performance levels. The research issues associated with qualification testing are the identification and quantification of governing performance parameters (acceleration, velocity, or displacement sensitive performance) and the development of testing protocols that cover the range of demands anticipated at various performance levels.

3.3.3 Acceptance Criteria for Performance Assessment

Criteria for establishing whether a facility meets a certain performance objective involve a combination of checks made at the local components and the overall systems levels. Acceptance implies that available capacities exceed imposed demands, with due consideration given to randomness and uncertainties in capacity and demand evaluation (discussed later).

Acceptance Criteria for Structural Performance at the Component Level. Research issues associated with component demand and capacity evaluation have been discussed in the previous two sections. At high performance levels the emphasis needs to be on relating structural damage parameters to socio-economic descriptions of desired performance, and at low performance levels the emphasis needs to be on a history dependent assessment of strength deterioration. Acceptable deformation may be associated with the onset of significant deterioration if the integrity of the component is critical to the stability of the structural system, or it may be larger if significant deterioration has tolerable consequences. It is a matter of research to find out when the latter applies, and to define the engineering parameters to be used in acceptance criteria (strength, deformation, or hysteretic energy dissipation).

Acceptance Criteria for Structural Performance at the System Level. It is likely cost-ineffective to base acceptance only on component criteria, particularly for existing structures that may have several non-conforming components. At high performance levels, failure to meet a local acceptance criterion in a small number of components may have little consequence on performance associated with immediate occupancy or continuing operation. Research is needed to define and quantify system damage parameters and establish acceptance criteria for such parameters.

At the collapse safety level acceptable performance implies that the structural system must have sufficient integrity to prevent, with only a tolerably low probability of failure, partial or global collapse (failure to provide adequate gravity load resistance). Again, failure to meet a component acceptance criterion may not lead to these limit states. Component deterioration, or even complete loss of resistance, can be tolerated if its consequences on system performance are acceptable. Until recently the issue of system performance in the presence of element deterioration or loss of strength has barely been touched upon except for several studies that employed system damage indices to measure closeness to failure. The consequences on structure safety of recently observed fractures at welded steel beam-to-column connections, which lead to a rapid loss in bending resistance, has necessitated studies on this subject. Much more work in this area is needed to apply PBEE effectively, particularly to existing structures.

Acceptance Criteria for Nonstructural Components and Systems. There is little information in the open literature on the relationship between structure response parameters and cost and consequences of nonstructural damage. Issues that need to be addressed are descriptions of nonstructural performance levels, relations to limit states of behavior, consequences of nonstructural damage on facility operation and safety, and relations to engineering parameters that can be obtained from structural analysis. For instance, interstory drift may be the only relevant parameter for deformation sensitive nonstructural components, provided the structure deforms in a shear mode. For wall structures, which deform in a flexural mode, damage to many deformation sensitive nonstructural components may be governed by vertical displacements caused by wall elongation and shortening. For other nonstructural components, particularly mechanical components, the magnitude of floor acceleration will be the governing performance criterion. Anchorage requirements and functionality will depend on floor accelerations.

The writer believes that great strides in earthquake loss reduction can be made by a much increased focus of the engineering profession on mitigation of nonstructural damage. This will require a drastic change in current practice, in which the responsibility for seismic performance of nonstructural components is usually passed on to manufacturers whose knowledge of earthquake behavior is rudimentary or nonexistent. Much research and development is needed to provide the engineer with the background and tools needed to take on this additional responsibility.

Acceptance Criteria for Contents. There is no doubt that earthquake losses and post-earthquake recovery are greatly affected by damage to facility contents. In the context of PBEE something must be done to quantify and improve the performance of contents. Ignoring the problem will not do justice to the noble concept of PBEE. Since most content damage is acceleration sensitive, it should be possible to devise engineering based performance criteria. They may not be enforceable, but they provide the owner with another important option over which he/she has control. It is highly desirable to include performance levels for contents in PBSE frameworks and to initiate research and development that provide a sound foundation for effective content performance control.

4. A GLOBAL RESEARCH AGENDA – INTERFACE ISSUES

Most fundamental issues in PBEE require extensive interaction between different disciplines. The focus of the following research agenda is on structural aspects of interdisciplinary issues that are fundamental to PBEE development.

4.1 Hazard Description

There appears to be a widespread perception that uniform hazard spectra, derived from probabilistic seismic hazard curves, will provide adequate information for performance based design and evaluation. These spectra, which account for the contributions of all seismic sources that may affect the site, are usually not representative of any one earthquake. In many cases spectral accelerations (or displacements) obtained from these spectra provide adequate information to describe the seismic demands imposed on structures, in many other cases they do not. Actual time history records show significant variations in spectral ordinates, and the frequency characteristics of time history records, which control higher mode effects and to some extent inelastic response of structures, are masked by period specific spectral hazard analysis. Perhaps most important, the effects of pulse-type near-fault ground motions are hidden away in a uniform hazard spectrum. By now it is widely acknowledged that spectra of these ground motions look very different from uniform hazard spectra and that the effects of these motions on the inelastic response of multi-degree of freedom structures cannot be deduced from an elastic response spectrum.

Thus, in addition to further refinements in uniform hazard spectra the need exists to consider separately the effects of near-fault ground motions. This requires the generation of magnitude, distance and directivity dependent near-fault ground motions that can be used for performance evaluation. This, as well as the development of procedures for generating soft-soil ground motions, should be short-range research objectives for PBEE. A long-range research objective should be the development of source mechanism, magnitude, and distance dependent bins of ground motions that will, ultimately, replace the use of spectra for performance evaluation – at least at low performance levels at which significant inelastic response is anticipated. Uniform hazard spectra will then still be useful for conceptual design, but their use for performance evaluation should be phased out with time.

The structural engineering contribution to this research needs to focus on the issue of the most appropriate representation of ground motion for performance evaluation. This issue deserves much attention because performance evaluation is an engineering issue and every effort needs to be made to reduce the uncertainties caused by simplifications in the hazard description. There are many other seismic hazard related issues that contribute to uncertainty and need to be evaluated more accurately, including ground motion duration effects that affect cumulative damage, basin effects that may be critical for long period structures, and the existence of collateral hazards.

4.2 Reliability-Based Design Methodology

Performance evaluation in PBEE is greatly complicated by randomness of the seismic input at the site and of capacities of structural components and systems, and uncertainties inherent in modeling of seismic input, in force-deformation modeling of components, and in the simplifications of the employed analysis method. Thus, there is no doubt that PBEE must be formulated in a fully probabilistic reliability format. This applies to the formulation but not necessarily to the engineering implementation, which needs to be simple enough to be usable by the profession. It will be perhaps the greatest challenge of the PBEE research effort to devise practical procedures that are simple to implement yet incorporate a realistic assessment of all sources of randomness and uncertainty.

From an owner's perspective the relevant objective may be to protect a facility for a specified performance level (e.g., immediate occupancy) with a given annual probability of exceedance. Or it may be to minimize life cycle costs. We are far from being able to accommodate such an owner objective at this time. The emphasis in research needs to be on reducing the uncertainties, establishing measures of uncertainties and randomness, and developing a methodology that accounts for these phenomena in the design and evaluation process. This research should have high priority.

4.3 Soil-Foundation-Structure System Performance

PBEE is concerned with the performance of all parts of the facility system, which includes also the foundation and the soil on which it is supported. Foundations are part of the structural system, but are neglected subsystems because the responsibility for their performance is shared between structural and geotechnical engineers. Soil-structure interaction effects caused by shaking, settlement, lateral spreading, liquefaction, and other soil failures are phenomena that may have negligible to overriding influence on performance. The disregard of these phenomena in a PBEE research agenda would be a fatal omission.

4.4 Cost/Benefit Analysis - Life-Cycle Considerations

PBEE must have benefits, or it is a losing cause. These benefits must be discernible in order to make PBEE an accepted alternative to present design procedures. A measure of benefit is the change in the cost/benefit ratio achieved by implementing PBEE rather than present code design procedures. Cost/benefit analysis may be based on a single facility, a portfolio of facilities, or a community. It may be based on the structural system alone or may incorporate nonstructural and content systems. It may be based on direct losses (cost of repair) or it may incorporate indirect losses (e.g., business interruptions, effects on a community). It should include too the costs to reduce further the annual individual fatality probability. It may focus on benefits achieved only through improved seismic performance, or it may incorporate additional benefits achieved through improved performance under other hazards (multi-hazard performance). In all cases it needs to consider a life-span over which the facility is expected to be in operation.

In view of the fact that PBEE needs to be "sold" to all stakeholders, there is a need for research on cost/benefit analysis that will permit an objective evaluation of the benefits that can be achieved through implementation of PBEE.

4.5 Research Issues in Construction Engineering and Quality Control

In many cases the construction process is the weak link in PBEE. Many issues concerned with construction engineering and quality control need to be considered; even though most of them are professional and do not lend themselves to research. There is one overriding issue, however, that needs a research focus. This is the issue of management of the design/construction processes. In this respect, and in most of the other aspects discussed here, the emphasis in PBEE must be on teamwork and collaboration between all members (disciplines) of the design/build team, including architects, structural, geotechnical, mechanical, and electrical engineers, all construction entities, as well as owners or their representatives. PBEE is not a structural engineering issue; it is an issue for all parties involved in the design/build effort.

5. RECENT PROGRESS IN PBEE RESEARCH

Performance-based earthquake engineering has become the focus of much research in Japan and the United States, and in other places. A compendium of papers on fundamental issues of PBEE, as well as a series of research recommendations, are published in a book containing the proceedings of an international workshop on future design methodologies (Fajfar and Krawinkler, 1997). Joint research is performed as part of the US-Japan Cooperative Research Program on Urban Earthquake Disaster Mitigation, and is summarized in the proceedings of a recent workshop (US-Japan, 1999). The Pacific Earthquake Engineering Research (PEER) Center, whose membership includes most of the Western US research universities, has PBEE as its primary focus. This Center has structured its research program along the following five thrusts:

- Socio-Economic Performance
- Hazard Assessment
- Global Assessment/Design Methodology
- Demand Assessment
- Capacity Assessment

In each thrust several coordinated research projects are being carried out, with the aim of developing knowledge that can be assembled into a comprehensive performance-based design approach. The target of this research is to develop a preliminary assessment methodology in about two years and to have in place a comprehensive reliability-based performance assessment methodology about three years later. This is an ambitious plan, considering the multitude of socio-economic and engineering issues that will have to be addressed.

The implementation of a PBEE approach in engineering practice will be a great challenge to researchers and engineers alike. Only close collaboration among academicians and professionals will make such an implementation possible, and close collaboration of researchers across national boundaries will greatly facilitate and accelerate the development and implementation process.

ACKNOWLEDGMENTS

This paper is a modified version of an internal (unpublished) paper the author has written about a year ago for the Pacific Earthquake Engineering Research Center. The author is happy to report that much progress has since been made on the comprehensive research agenda laid out in the paper. In putting his thoughts on paper, the author drew heavily from knowledge of others whose thinking has greatly influenced the writer’s perspective. This influence came from the study of publications and, perhaps more so, from many technical discussions with colleagues and friends who have been contributors to basic concepts of PBEE for many years. Professor Hiroshi Akiyama is one of the individuals whose thinking has had a great influence on the direction PBEE has taken in the recent past, and on the writer’s understanding of PBEE. Professor Akiyama’s contributions to this field are numerous and outstanding, and with their focus on energy principles they have been trend setting and clearly ahead of their time. It is a great pleasure and honor for the writer to be permitted to count Professor Akiyama among his closest colleagues, and to be part of this celebration honoring his contributions to the profession.

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