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Trying to define performance-based seismic engineering—is there a consensus?

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ABSTRACT

The current direction for future codes appears to be headed towards a form of performance-based engineering (PBE). For the field of earthquake engineering the title is performance-based seismic engineering (PBSE). The problem seems to be that the term PBSE has different meanings for different engineers, as well as the public-at-large.

For example, a building code is generally considered to be a prescriptive design procedure; however, codes will often state performance objectives in the body of the code or in a commentary. To some, this means that the building code is performance-based engineering. To others, the code is a prescriptive design with goals of stated performance; thus, to be PBSE it requires a special procedure to better evaluate the performance potentials.

Other questions relate to using a PBSE procedure as an alternative to the code to obtain equivalence to the code objectives, as a supplement to the code to validate code objectives, or as a process to establish different performance objectives.

INTRODUCTION

Performance-based seismic engineering (PBSE) is a term being used to describe currently advancing techniques to improve procedures for design, evaluation, and upgrade of buildings to resist earthquake-induced ground motion. Performance engineering, as a generic term, does not have a precise definition and tends to have a variety of meanings to different people.

As performance-based seismic engineering (PBSE) is taking on a life of its own, how should it relate to building codes? First, we must define performance-based seismic engineering, since there does not appear to be a clear definition:

- Does it relate to a performance specification as opposed to a prescriptive code approach?
- Is it a prescriptive code approach with multi-levels of performance goals?
- Is it an alternative to the code provisions to illustrate conformance with the intent of the code?

Is it all of the above, some of the above, or none of the above?

During the past few years there have been many studies, some resulting in published documents, that address various issues of PBSE. These include publications such as FEMA 273 (BSSC 1997), ATC 40 (ATC 1996), SEAOC Vision 2000 (SEAOC 1995), and Tri-Services (Army 1986, WJE 1996). These documents provide procedures that can be used as supplements to or substitutes for the seismic provisions of current modal prescriptive building codes.

<u>Prescriptive procedures</u>.

Model codes are generally referred to as prescribed requirements as opposed to performance requirements. In this terminology, the engineer follows the prescribed requirements to design the building. It is assumed that the finished product will satisfy performance objectives, such as those stated in the Structural Engineers Association of California commentary (SEAOC 1990):

- *Structures designed in conformance with these recommendations should, in general, be able to:*
    1. *Resist a minor level of earthquake ground motion without damage.*

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2. *Resist a moderate level of earthquake ground motion without structural damage, but possibly experience some nonstructural damage.*

3. *Resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with structural as well as nonstructural damage.*

For earthquake resistant design, it is assumed that the lateral force resisting system will make excursions into the nonlinear inelastic regions of the capacities of the structural materials. Therefore, the true performance of a seismic code-designed buildings using a static linear elastic procedures is just not predictable with any degree of confidence and the engineer must rely on experience, judgement, instinct, and good fortune. The code provides for an elastic strength that is a fraction of the full linear-elastic demands of major earthquakes and relies on special prescribed details to provide ductility for the extreme nonlinear-inelastic demands. The primary objective of the code is to provide life-safety (strength and ductility) and some damage control (drift limits).

It should be noted that code procedures have served us well and generally provide us with safe buildings. When deficiencies in the code provision are discovered, corrective clarification or modifications are made. There is no substitute for good engineering judgement, thus, as long as some flexibility is allowed, the code procedure can continue to serve us well.

Although there are some people that believe model codes are performance engineering because performance goals are stated and the requirements are based on providing these goals, for purposes of this paper the model codes will be categorized as prescriptive procedures.

Performance procedures.

Performance-based procedures can provide engineers with the added flexibility required to interpret and improve on codified procedures. This sets the stage for the purpose of PBSE guidelines. PBSE can be expressed in a variety of ways. Examples follow:

1. Code Validation: Validate a code-designed building for the code performance goal of life safety.
2. Alternative Procedure: Alternative method to code procedure to get a more efficient structural design that satisfies the intent of the of the code (i.e., may not satisfy the letter of the code, but provides equal or better performance).
3. Enhanced Performance: Provide a higher performance objective than required by code provisions.
4. Reduce Existing Hazards: Provide a lower than code level of performance to allow a voluntary (non-mandated) seismic upgrade to reduce hazards of existing buildings, (i.e. some improvement at a reasonable cost is better than doing nothing because of excessive costs).
5. Multi Level Objectives: Provide a multi-level performance menu that matches probabilistic earthquakes with a variety of performance objectives.

PBSE can be broken down to two major components: (1) the demands of the earthquake ground motion that cause the building to shake, and (2) the capacity of the building to resist the shaking.

Demands of the earthquake can be presented in terms of response spectra or time-histories. For purposes of this paper, we will focus on response spectra. Response spectra can be used to determine the peak response of a linear-elastic structure to earthquake ground motion. However, because structures generally respond in a nonlinear-inelastic manner during the strong ground motion of a major earthquake, the linear elastic response spectra need to be modified. This can be done by the use of inelastic response spectra, the application of modification factors based on ductility, or the substitution of surrogate damping to approximate the effects of hysteric behavior. The modifiers generally reduce the forces and accelerations and result in equal or slightly modified displacements.

The capacity of the structure must take into account the nonlinearity of the force-displacement relationships as the structure exceeds the elastic limits and various components of the structure yield. A generally acceptable method of approximating the inelastic properties of a structure is by use of pushover analyses. This procedure helps to identify the sequence of yielding components and the redistribution of the forces. The resulting pushover curve gives a graphical representation of the maximum force the structure can resist and the maximum lateral displacement the structure can sustain before forming collapse mechanisms or vertical instability.

Performance capabilities of the structure to resist earthquake forces can be determined by comparing inelastic capacities of the buildings to inelastic demands of the earthquake. If the capacity of the building exceeds the demands of the earthquake, the performance goals are satisfied.

PBSE METHODOLOGIES

For this paper I have chosen four publications as references for discussion of PBSE methodologies.

Guidelines and Commentary for the Seismic Rehabilitation of Buildings (BSSC, 1997). This document is presently in an advanced draft stage that is undergoing an evaluation by means of case histories of real buildings. The guidelines present a multi-level performance menu that matches probabilistic earthquake ground motion with a variety of performance objectives.

Methodologies range from linear static analysis to inelastic time-history. Although a tremendous amount of talent and money has gone into the development of this document, results of reviews and case history studies illustrate the difficulties in developing a set of guidelines that are both meaningful and all inclusive. Because of the abundance of rigid requirements, the present draft acts more like a prescriptive code than being a set of performance standards that can be flexibly applied by a knowledgeable engineer with good judgement and ingenuity.

Seismic Evaluation and Retrofit of Concrete Buildings (ATC, 1996). This document, which was funded by the Seismic Safety Commission of the State of California, is limited to concrete buildings and emphasizes the use of nonlinear static procedures (i.e., pushover) in general and focuses on the capacity spectrum method. As a performance based methodology, the procedure appears to allow more flexibility and requires the necessity of experience and judgement on the part of the engineer. However, there are still some portions of the procedures that require research and development, such as the method for substituting damping to represent inelastic response spectra (Freeman, 1998).

Vision 2000, Performance Based Seismic Engineering of Buildings (SEAOC, 1995). This document was prepared by the Structural Engineers Association of California for the California Office of Emergency Services. It had a goal "to develop the framework for procedures that yield structures of predictable seismic performance." This is an interesting concept. The goal appears to be saying structures should be designed such that their performance can be easily predictable, rather than having a goal to develop procedures that can predict the performance of any building. The document appears to have a lot of interesting information; however, I have found it difficult to understand where it is going. It seems to be saying that framework for performance based seismic engineering must first be developed into guidelines and then into code provisions before it can be readily applied in building design. In my opinion this may be the wrong approach, one that leads to a prescriptive code rather than a performance based design.

TriServices Seismic Design Procedures (Army, 1986, and WJE, 1996). As a supplement to the U.S. Army Corps of Engineers model code seismic design standard, "Seismic Design Guidelines for Essential Buildings" (Army 1986) was developed for essential buildings. The procedure presented in the guidelines considers a two-level approach to seismic design that attempts to evaluate the inelastic performance of structures. First, the building is designed to resist the lower level earthquake by elastic behavior. Then the building is evaluated for its ability to resist the higher level earthquake by inelastic behavior. Two methods are presented for the inelastic evaluation. One is an elastic analysis procedure with qualifications and limits. The second method is an early version of the capacity spectrum method. Although the guidelines were primarily developed for essential buildings, such as hospitals and emergency response facilities, guidelines were also presented for standard occupancy facilities. The guidelines were revised and reformatted in an unpublished manuscript (WJE, 1996) that was used as a basis for the California Seismic Safety Commission Report (ATC, 1996).

DISCUSSION ON PBSE METHODOLOGIES

The methodologies summarized above, as well as earlier work done by engineers and researchers (Mahaney and Freeman, 1996) have provided an abundance of background information for developing PBSE guidelines and recommendations. Engineers with experience, knowledge, and a good sense of how buildings work at limit states, can and have successfully been doing PBSE for decades. An early version of PBSE procedures was presented by the Portland Cement Association (Blume, et al, 1961) using pushover, reserve energy techniques and reduced spectra. However, can PBSE be developed into published guidelines in a code-like format for general use? The answer to this question goes somewhat into how we define PBSE.

Multi-level performance menu

If the sole purpose of PBSE is to provide a variation of performance levels such as collapse prevention, life safety, immediate occupancy, and operational levels (BSSC, 1997), then modification of existing codes could be used. For example, use occupancy factors, I (SEAOC 1990) or vary force reduction factors, R (BSSC, 1995). The FEMA 273 (BSSC, 1997) linear static procedure is an extension of this, using demand capacity ratios instead of R factors. This provides a means of providing enhanced performance objectives by use of a linear static force procedure. Variations in earthquake probabilities can also be incorporated by modifying seismic zone coefficients for varying return periods. Although this approach does not necessarily give the designer a better insight on how the building will perform, it does give him the opportunity to explain to the client how enhanced performance objectives can be obtained. It should be noted that as one approaches the immediate occupancy and operational performance levels, the objectives will require the structure to remain more nearly elastic, thus reducing the need for inelastic analysis procedures. If a structure is designed to remain elastic for a moderate earthquake, it is likely that the demands for the major earthquake will not produce excessive excursions into the inelastic range. This is dependent on the ratio of the demands of the two earthquakes.

Some may not consider this approach to be performance-based engineering, but would categorize it as a static code approach with a variety of performance objectives.

Performance evaluation procedures

A true performance evaluation procedure will most likely require some form of nonlinear inelastic analysis. Linear-elastic procedures really cannot give a good evaluation of inelastic failure mechanisms (Freeman, 1992). Static, nonlinear pushover procedures appear to give credible results (ATC, 1982) if the engineer is aware of the limitations and is able to do parametric studies to mitigate the limitations. The nonlinear inelastic procedures are helpful in validating code-designed buildings for performance goals and in providing an alternative to some code requirements by rational methods. In other words, inelastic procedures can provide more confidence in code designs, and/or a more efficient and economically designed building.

The pushover curve appears to be a useful tool for most of the approximate inelastic procedures (Freeman, 1995). An interesting observation regarding various approximate inelastic procedures is, although they take different approaches to reach a conclusion, they all have much in common and tend to give similar results when assumptions are consistent (Freeman, 1995 and 1998).

RECOMMENDATIONS

1. There is a need to more clearly define PBSE. There should be a difference between (1) those criteria that provide performance goals (single level or multi-level), and (2) methodologies that attempt to predict how buildings will actually perform.
2. PBSE should be kept as an option or alternative to code procedures. It should not be presented as a design code.
3. Codes procedures should be maintained as a base line for design. Code sections relating to alternative procedures should include statements on acceptability of PBSE on the basis of rationality.
4. If a two-level approach is used, one level could be a minor-moderate earthquake (i.e., 25 to 50 year return period) that requires the buildings to remain essentially elastic. This could require a prescriptive code procedure. The second level would be the major earthquake that may require PBSE as the ratio of the two earthquake demands exceed a prescribed value based on building type.
5. PBSE methodologies should be reviewed to identify the areas they have in common as well as those that seem to be in conflict with each other. Many misunderstandings of the various methodologies are due to a lack of communication and of clear definitions of terminology.

CONCLUSIONS

It appears that PBSE is being used as a phrase to cover anything other than currently used standard model codes. This leads to some confusion. Where the process of selecting enhanced performance and/or multi level objectives may be PBSE to some people, others may believe that PBSE is the process of using nonlinear, inelastic analytical procedures to more accurately estimate performance.

In cases where PBSE is used to justify code compliance to satisfy mandatory requirements, it is important to establish guidelines to enable building officials to rule on acceptability. However, when PBSE is used as a process between design professional and owner/developer in the decision making process of establishing design criteria, there is no need to formalize such procedures as part of regulatory code documents. There is a need to clarify the meaning of the term PBSE and to establish new terminology to distinguish between (1) code validation, (2) alternate procedures, (3) enhanced performance, (4) reduction of existing hazards, and (5) multi level objectives.

The opinions and interpretations expressed in this paper are those of the author. They are being presented as a means of opening up discussion on this topic in the hopes of establishing consensus on definitions and methodology procedures for performance-based seismic engineering (PBSE).

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