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IMPLEMENTING PERFORMANCE BASED SEISMIC DESIGN IN STRUCTURAL ENGINEERING PRACTICE

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ABSTRACT

The first building code provisions for earthquake resistive design in the United States were developed more than 70 years ago. These provisions and the related engineering design procedures were intended primarily to avoid earthquake induced building collapse and loss of life. This same life-safety performance objective remains the fundamental basis for code provisions today. Recently, however, as the reliability of design and construction practice in meeting this objective has improved, there has been increasing demand for engineers to provide building designs capable of meeting other objectives including minimization of damage, occupancy and business interruption. A number of programs for the development of performance based design procedures have been initiated in response to the demand that other performance objectives be considered in the design process. However, the current lack of reference performance standards, reliable consensus-backed design procedures, general economic and competitive pressures and a lack of control over much of the design process are significant barriers to implementation of performance based design by structural engineers.

KEYWORDS

Earthquake performance; Performance-based design; Earthquake resistive design; Performance standards; Performance Objectives; Damage states; Design Earthquakes, Design procedures; Structural Design

INTRODUCTION

Structural design of buildings in the United States is closely controlled by the provisions of the prevailing building codes. These building code provisions are intended to be a minimum standard, enforced for protection of the public welfare. The seismic resistive design provisions of these building codes are typically based on either of two closely related resource documents: the SEAOC *Recommended Lateral Force Requirements* (SEAOC, 1991), or, the *NEHRP Recommended Provisions* (FEMA, 1995). The primary intent of code provisions based on these documents is to provide buildings that are capable of resisting collapse when subjected to the very infrequent, but relatively severe earthquake events that can affect them. Commentary to the provisions indicate an expectation that conforming buildings will also be capable of withstanding more frequent, less severe events with relatively limited levels of damage and that buildings conforming to special provisions provided for the design of buildings housing critical post-earthquake recovery functions, such as hospitals, will be able to survive very strong earthquakes with so little damage that they could quickly be restored to service. Regardless of these implied tiers of performance, the fact remains that the code provisions were empirically developed, based on the observation of past earthquake damage, to avoid the occurrence of damage with potential to result in collapse.

Experience in recent California earthquakes, including the 1989 Loma Prieta and 1994 Northridge events, indicates that modern code provisions in zones of high seismicity are relatively reliable in avoiding life threatening building damage. Both events, having large magnitudes, and epicentral locations close to large populations centers, resulted in fewer than 100 fatalities. However, the economic losses associated with these earthquakes, $7 billion for Loma Prieta and approximately $30 billion for Northridge, were unacceptably large, given that events of this size can be experienced relatively frequently in zones of high seismicity. As a result, public officials, and members of the insurance and financial industries called for building construction practices that more effectively limit damage in future earthquakes.

In response, a number of projects have been initiated to develop performance based design procedures. Simply stated, the intent of performance based design is to allow construction of structures with predictable seismic performance and to provide owners and designers with the capability to select alternative performance goals for the design of different buildings. Important projects that have been undertaken to develop performance based design procedures include: *Vision 2000* (SEAOC, 1995), a project of the Structural Engineers Association of California (SEAOC); *Guidelines and Commentary for Seismic Rehabilitation of Buildings* (ATC, 1995) a Federal Emergency Management Agency (FEMA) project being jointly executed by the Applied Technology Council (ATC), Building Seismic Safety Council (BSSC) and American Society of Civil Engineers (ASCE); and a FEMA funded project conducted at the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley. The EERC project lays out a long term research program for the development of reliable performance based design procedures. *The Guidelines and Commentary*, still under development, provide performance based procedures for the upgrade of existing buildings and *Vision 2000* provides both a framework for long term development of performance based design methodologies as well as recommendations for the use of currently available design standards to achieve performance based design for new construction.

The structural engineer attempting to implement performance based design today is faced with many challenges. These include the lack of a set of reference performance standards, the lack of a reliable consensus-backed design standard, general economic and competitive pressures and a lack of control over much of the design process.

PERFORMANCE STANDARDS

In order to implement a performance based design, it is necessary to select one or more performance objectives. A performance objective is simply a statement of the desired building behavior, given that it experiences earthquake demands of specified severity. Most descriptions of the performance based design process indicate that the building user community would be given a choice with regard to the performance objectives for each building. In order for such a choice to be useful, it becomes necessary to be able to define the various behavior alternatives in terms meaningful to the lay person.

There are a number of ways to characterize building behavior. Reliability analysts have characterized behavior in terms of margin against specified failure states, or probability of failure at a given demand level. Researchers have suggested the adoption of damage indices dependent on the amount of inelastic energy dissipation experienced by various building components. Both concepts are difficult for design engineers to visualize and nearly impossible to relate to the building user community. Most design engineers can best visualize behavior in terms of damage states, defined by such parameters as the quantity of unrecoverable drift, as well as the extent and severity of cracking, spalling, buckling, yielding and fracturing of the various building components.. However, these concepts are also of little use to the building user community.

Behavior parameters important to building users include: the potential for loss of life, the cost of repairing any damage sustained, and the amount of time during which the building is out-of-service while it is repaired, or in extreme cases, replaced. While these parameters are quite meaningful to the public, and therefore can serve as a basis for selecting between building performance alternatives, they are not particularly useful as a basis for design. There is, unfortunately, no direct way that an engineer can design for such performance specifications as a business interruption of two weeks or a repair cost that is 20% of replacement value. Therefore, as a prerequisite to practical implementation of performance based design, there is a need to establish corresponding relationships between the behavior parameters that are meaningful respectively to the building users, design professionals, researchers and reliability analysts. Since there is an infinite spectrum of potential behavior states that a building could experience, ranging from a complete absence of damage and earthquake effects to complete collapse, this is not a trivial task.

The most practical approach would seem to be the adoption of a limited series of standard behavior states, from which design performance objectives could be developed, and for which defining parameters meaningful both to the building user and technical communities could be established. Both the *Guidelines and Commentary for Seismic Rehabilitation* and *Vision 2000* projects have identified similar series of standard behavior state definitions, albeit with slightly different designations. These are described in Table 1. In addition to the definitions indicated in the table, a series of detailed matrices, describing permissible damage levels for the various structural and non-structural components that comprise typical buildings, are also provided in the documents. Although these definitions only qualitatively define parameters useful to the

Table 1. Standard Performance Level Definitions

Designation		Description
Guidelines and Commentary (ATC, 1995)	Vision 2000 (SEAOC, 1995)	
Operational	Fully Operational	Only very minor structural or non-structural damage has occurred. The building retains its original stiffness and strength. Non-structural components operate and the building is available for normal use. Repairs, if required, may be instituted at the convenience of the building users. The risk of life threatening injury during the earthquake is negligible.
Immediate Occupancy	Functional	Only minor structural damage has occurred. The building structure retains nearly all its original stiffness and strength. Non-structural components are secured and if utilities are available, most would function. Life safety systems are operable. Repairs may be instituted at the convenience of the building users. The risk of life threatening injury during the earthquake is very low.
Life Safety	Life Safe	Significant structural and non-structural damage has occurred. The building has lost a significant amount of its original stiffness, but retains some lateral strength and margin against collapse. Nonstructural components are secure, but may not operate. The building may not be safe to occupy until repaired. The risk of life threatening injury during the earthquake is low.
Collapse Prevention	Near Collapse	A limiting damage state in which substantial damage has occurred. The building has lost most of its original stiffness and strength and has little margin against collapse. Nonstructural components may become dislodged and present a falling hazard. Repair is probably not practical.

building user community (i.e., extent of risk to life safety, potential range of repair costs, time out of service) they do at least provide a preliminary basis for discussion in terms meaningful to those who must choose the design performance levels.

In order to complete the specification of design performance objectives, it is necessary to select particular earthquake demand levels for which the various performance levels are to be attained. This can be done either on a probabilistic or deterministic basis. The building user community, and many design engineers, most easily relate to the deterministic approach in which a specific magnitude event on a defined fault or source zone is selected as the basis for design. Such an approach is most useful for determination of the "worst case" design performance objective in regions with seismicity controlled by one or more major active faults or source zones. As an example, if told that the worst earthquake ever expected to affect a planned building is an M7.5 event on a fault located 10 miles away, the average building user is capable of determining what performance is acceptable should that event occur. However, in regions remotely located from such active sources this approach is less meaningful. In addition, the deterministic approach is not particularly useful, even in near source regions, for determining secondary performance objectives such as the design earthquake for which the Immediate Occupancy or Operational performance levels should be attained. Continuing with the example cited above, it would be difficult for that user to determine what performance should be specified for an M6.0 event on the same fault without knowing the likelihood of such an event. However, if told that an M6.0 event has an average return period of 100 years, the user could determine an appropriate performance level for such an event, based on economic analysis.

Unfortunately, most building users are unsophisticated and are not able to perform economic analyses based on probabilistically defined events or to make rational choices between performance objectives. To the lay person, any event with a return period significantly exceeding their expected life, or even the period of time during which they expect to own or occupy a building sounds improbable, and given a choice, such building users would often select performance objectives that provide for lower levels of performance than provided by current building code provisions. In such an environment the structural engineer will often be faced with the requirement to select the design performance objectives on behalf of the building user. This is highly undesirable as the engineer may inherit significant liability if, after the occurrence of an event, the user is dissatisfied with the performance achieved. Consequently, a series of standard performance objectives, appropriate for design of different classes of buildings, are urgently needed. Such standards would relieve unsophisticated users of the need to make a difficult selection for which they are unprepared.

Such a series of standard performance objectives, recommended by *Vision 2000*, are indicated in Figure 1. Each of the diagonal lines in the figure indicates design performance levels and earthquakes recommended for

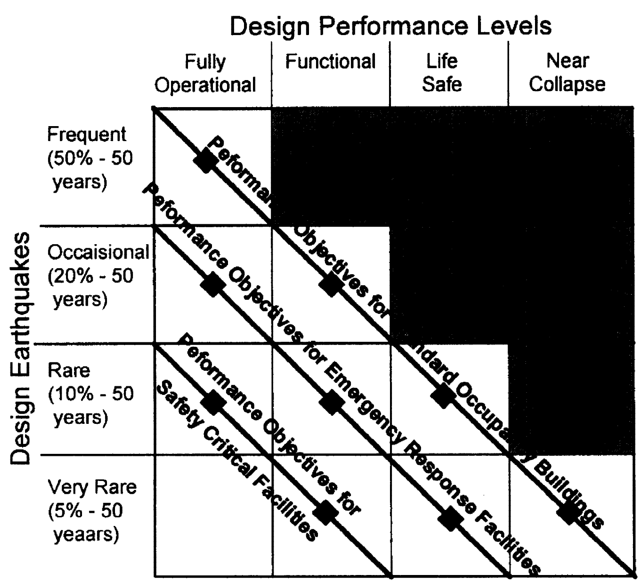

Figure 1 - Vision 2000 Performance Objectives

the design of buildings of different occupancies and uses. Individual, informed building users could of course select more stringent performance objectives, if desired. Adoption of such a standard would relieve the design engineer from the need to recommend a specific design basis and the average building user from having to select such a basis. It should be noted that the performance standards recommended by *Vision 2000* are a refinement of the objectives perceived to be fulfilled by current codes. No detailed cost-benefit study of these standards has been conducted. However, such studies should be performed prior to adoption of these or similar standards. It should also be noted that these cost-benefit studies should not be performed on the basis of individual buildings, but rather, on the basis of the entire building stock within a region. Since damaging earthquakes are relatively infrequent events, even in regions of high seismicity, the optimal economic selection for an individual owner of a building may result in unacceptable regional economic losses when a large earthquake actually does occur, if all owners in the region have selected this apparent optimum. Design standards should be set sufficiently high such that initial capital outlays for building design and construction costs exceed the optimal choice for individual buildings but prevent such unacceptably large regional losses.

DESIGN STANDARDS

The engineer attempting a performance based design today must do so in the absence of a standard for such work. Consequently, specific design procedures must be developed for each project. Two basic approaches are commonly used. The first approach is to adopt a criteria based on modification of the current building code provisions. The second is to attempt to predict behavior through evaluation of the inelastic demands on the various elements that comprise the structure against available data relating inelastic demands to behavior states.

The first approach, in which project specific design criteria are developed based on modifications of the building code, is the most common. Typically, the engineer will either increase the lateral forces used for design, or decrease the permissible drifts limits in order to attain better performance. This approach is actually adopted by the building codes themselves for the design of emergency response and other important facilities. Building codes based on the SEAOC provisions, utilize an occupancy importance factor I, ranging from 1 to 1.5, which is applied to the design forces in order to attain better performance. Essentially, this I factor has the effect of increasing the severity of earthquake required to produce yielding in the structure, or alternatively, reduces the amount of ductility required to resist a given design event. In the *NEHRP Recommended Provisions*, more stringent drift limits are specified as a method of improving performance. For most structures, this has the same effect as an I factor in that the structure is designed with a greater elastic strength in order to -provide the additional required stiffness. Another method of developing project specific performance design criteria, based on the current building code, is to substitute site specific estimates of ground motion for the default demands contained in the building code.

The principle problem with developing performance based criteria from the current building codes is that the performance provided by the building code itself is not well defined or understood. Therefore, it becomes very difficult to judge the probable benefits in performance likely to be attained by designing for an arbitrary modification of the basic code criteria. Nevertheless, many engineers currently adopt this approach because it is simple and readily acceptable to building officials. Further, although the actual performance to be attained by the building is not well understood and can not be explained to building users, these users are comfortable with explanations that a design is being conducted for a specified increase over the building code requirements.

An approach more likely to provide the desired performance in design events is to use various structural analysis techniques to predict levels of damage in the various building elements, based on the inelastic demands predicted for these elements. This is the approach adopted by the BSSC *Guidelines and Commentary for Seismic Rehabilitation of Buildings*. Despite the more rational basis for performance based design using this approach, there are a number of problems with its implementation today. These include the lack of sufficiently accurate analytical techniques for practical prediction of demands on the various elements of complex structures, a lack of sufficient data to calibrate inelastic element demands against building performance levels, and an unwillingness on the part of building officials to accept designs developed using this technique.

The practical lack of reliable analytical techniques and tools is a significant potential problem. Most design today is still performed using linear static lateral force analyses. Building behavior in earthquakes, however, is neither static nor linear. Consequently, this approach has limited ability to accurately predict building performance. Linear dynamic analysis is widely regarded by many practitioners today as the current state of the art of structural earthquake analysis. While this analysis technique is commonly available, and more accurate than the linear static technique for structures with moderate inelastic demands, it is not significantly better that the static technique for structures with large ductility demands. A few design offices have begun to utilize non-linear analyses in design work. Typically, these analyses are performed using the so-called *pushover* approach, in which a series of incremental static analyses are performed on models of the structure that have been progressively degraded in stiffness to represent the onset of inelastic behavior in the structure. Based on recent studies conducted by the BSSC *Guidelines and Commentary* project, such analyses appear to provide a reasonable estimate of inelastic demand distributions and damage in structures dominated by first mode response. However, in other studies (SAC, 1995) this technique has been demonstrated to be a poor predictor of the distribution of damage in long period structures.

Nonlinear dynamic analysis techniques should be able to overcome most of the inaccuracies inherent in these other procedures. However, these techniques and the software required to utilize them are not yet sufficiently developed to allow practical design office implementation for any but the most simple structures. Further, the accuracy obtained by this technique is closely related to the assumed constitutive relationships for the various building elements. Until consensus backed modeling rules for element behavior can be developed, this approach will not be practical for general design office application. Consequently, the engineer is most commonly faced with a need to use a relatively simple, but inaccurate, analysis approach to predict element demands.

Even if accurate analysis of a structure's response to earthquake demands can be made, there is a serious lack of data that would support the determination of building performance based on these predicted demands. The *BSSC Guidelines and Commentary* represents an important advance in this area in that it provides a comprehensive set of guidelines on limiting inelastic demand levels for various categories of elements and performance levels. However, much of this work was judgmentally rather than empirically determined and extensive verification of these guidelines should be performed.

The reaction of building officials to designs conducted by alternative criteria is perhaps the largest barrier to implementation of analytically based performance designs. Prior to issuing a building permit for new construction, the building official typically conducts a review of drawings and supporting calculations to determine compliance with the code. While the code permits any approach that is rational, and based on principles of engineering mechanics, building officials seldom have the ability to verify the adequacy of designs conducted by anything except the prescriptive pre-qualified approaches contained in the code. Consequently, the process of obtaining permits for designs conducted by alternative rational analyses is often difficult, and sometimes, practically impossible.

ECONOMIC AND COMPETITIVE PRESSURES

Some of the most significant barriers to the implementation of performance based design are the economic and competitive pressures faced both by the design office and building user. Most building developers in today's market are not interested either in personal occupancy or long term ownership of the property. As a result, earthquakes of sufficient size to cause significant damage to a building are unlikely to occur during the time the developer controls the building. Knowing this, most developers are unlikely to invest in the construction of a building with enhanced earthquake performance characteristics unless they believe the added cost will increase either the rental or sales value of the property. Unfortunately, neither is the case.

Despite public statements to the contrary following damaging earthquakes, the public generally believes that the building codes provide adequate protection against earthquake induced losses. The public is generally ignorant about the performance standards inherent in the building codes or the likely behavior of buildings in earthquakes. Most people regard earthquake risk in one of two ways. Some people, particularly those who reside in areas of low seismicity, believe that it is impossible to build safe structures and that if a big earthquake occurs, everything will collapse. Others believe that the building code is a panacea and that any building conforming to a recent code is unlikely to be seriously damaged in any earthquake. Individuals holding either belief are unlikely to discriminate in their selection of a building based on potential earthquake performance. Consequently, there is limited market value added to a building designed and constructed for such enhanced performance.

An exception to this are those buildings developed specifically for the occupancy of a business or institution that is knowledgeable in earthquake risk management. Most large corporations and institutions today have an in-house risk management group, responsible for positioning the organization against large catastrophic losses. In recent years, a number of such organizations with properties in regions of high seismicity have attempted to implement performance based design concepts in the development of new properties. In some cases, however, the additional cost inherent in the development of buildings with enhanced earthquake performance characteristics have been larger than could be justified by management and more conventional design approaches were adopted.

The adoption of a performance based design approach can result in a significant increase in building development costs. This increase results both from the provision of a more redundant and substantial lateral force resisting system within the structure as well as from increased effort required in the design process. Design procedures conforming to current code requirements employ simple analytical techniques and evaluate building response to only a single earthquake demand level. As previously indicated in Figure 1, performance based earthquake designs typically address multiple performance goals. In order to reliably provide buildings capable of meeting these multiple performance objectives, it is not only necessary to employ more complex and time consuming analytical techniques, but also to evaluate the building's probable performance for several earthquake demand levels. As a result, engineering offices are unlikely to provide performance based design services unless the building developer specifically requests such an approach, or it is required by the building code. Since developers are unlikely to request performance based design, adoption of performance based requirements by the building codes will be necessary prior to widespread adoption of this approach. However, even adoption of performance based approaches by the building codes will be difficult to accomplish as significant resistance will occur based on economic grounds.

DESIGN PROCESS CONTROL

Perhaps the most significant barrier to the adoption of performance based earthquake resistive design is the lack of control exercised by the structural engineer over the building design process. The role of the structural engineer is typically limited to designing and detailing the structural components of the building. Design criteria development, and discussions with the building developer are typically handled by, or through, the architect, who has limited understanding of earthquake performance issues and consequently, is not an effective advocate for performance based design issues. The basic site selection, building configuration and even the framing system used for the building, all highly important factors in determining the building's performance, are typically decided by the architect and developer, often with minimal consultation by the structural engineer. Many structural engineers find it difficult to persuade the architect that a selected system is less than appropriate for a building, for fear that the architect will find another structural engineer who will support the original design concept, regardless of whether or not it will perform adequately.

Even if the necessary design procedures were available today and the engineer had the ability to design structures with predictable and acceptable seismic performance characteristics, this would not assure that the buildings themselves would meet the intended seismic performance objectives. Buildings are a complex collection of systems, including the structure, but also including mechanical, fire protection, electrical, architectural and other types of systems. The performance of the individual components of these non-structural systems can be as important to the overall earthquake performance of a building as is the performance of the structure, particularly for enhanced performance objectives that address building operability. Yet the structural engineer has little participation in the design of these systems for seismic resistance and is often unaware of any of the details for installation of these systems. Consequently, poor earthquake performance of these systems is common, even in buildings that have been designed to very stringent structural standards.

An example of such behavior is the performance of the Olive View Hospital, in Sylmar, California, during the 1994 Northridge Earthquake. The Olive View Hospital was constructed to replace a previous facility, destroyed by the 1971 San Fernando Earthquake. As a result, it was designed to criteria that were substantially in excess even of those enforced by the State of California for construction of hospitals, since the 1971 event. Located within a few kilometers of the epicenter for the Northridge Earthquake, this building experienced very strong ground motions in that event, with recorded accelerations at the roof of the structure exceeding 2g. The building structure behaved very well and could be said to meet the performance requirements for the Operational performance level. However, utility piping within the building failed, resulting in extensive water damage to the facility and forcing its closure. As a result, the building's performance, as opposed to the structure's performance, was at something below the Immediate Occupancy level. While this performance was still excellent, it did not meet the intent of the design - to provide immediate post earthquake health care service.

If reliable performance based design is to be implemented, the structural engineer will have to obtain an enhanced role in the overall design process. This role must include direct communication with the building users as well as greater power to determine the overall building configuration and framing systems and oversight role with regard to the design and installation of non-structural building components.

SUMMARY

The adoption of performance based seismic design will require significant change in current structural engineering practice. It will require the adoption of standard performance objectives for different classes of construction, development of substantially more complex and time consuming analytical procedures as well as direct communication between the engineer and building users. Finally, structural engineers will require greater involvement in the overall site selection, building layout and conceptual design process as well as substantially increased oversight of the design and installation of all systems for adequate seismic resistance.

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