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THE NEED FOR MULTI-LEVEL SEISMIC DESIGN CRITERIA

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ABSTRACT

This paper gives the reasons why **there is a need to develop an Earthquake-Resistant Design (EQ-RD) methodology based on multi-level EQ-RD criteria.** It briefly reviews the available philosophies and approaches for the design of civil engineering facilities subjected to normal types of excitations, and then discusses the problems of designing against significant Earthquake Ground Motions (EQGMs), which are considered to be abnormal excitations. The worldwide accepted general philosophy of EQ-RD is discussed, and a critical review of current code procedures follows. The SEAOC Vision 2000 Committee's recent attempt to formulate a conceptual framework for Performance-Based Seismic Engineering (PBSE) of buildings subjected to significant EQGMs is discussed in tandem with a discussion of information needed for conducting Performance-Based EQ-RD (PB EQ-RD). A conceptual comprehensive approach for PB EQ-RD based on multi-level criteria is proposed. A minimum of four discrete performance EQ-RD objectives are recommended. At least two of the four performance levels are recommended for preliminary EQ-RD, and all four performance levels are necessary to check the acceptability of the final design.

KEY WORDS

Comprehensive design; design earthquake ground motions; multi-level design criteria; performance-based earthquake-resistant design; performance design objectives; performance levels.

INTRODUCTION

The total design process of a civil engineering facility usually involves several phases, of which the following four are the most important: ***(1) conceptual overall design, or planning phase; (2) preliminary design phase, which usually involves approximate analysis; (3) rigorous analysis and final design phase; and (4) acceptability check of final design and detailing phase.*** Before starting the design process, it is necessary to establish the design criteria. Biggs (1986) defines design criteria as those rules and guidelines which must be met to ensure that the objectives of the design are satisfied. There are three major objectives: ***(1) safety; (2) performance of function; and (3) economy.***

Safety must be regarded as the most important objective, because structural failure usually endangers human life and always involves economic losses due to physical and functional damages. It must be recognized that no structure is totally safe; that is, there is always some finite probability of failure due to human errors in design and construction, or unforeseen natural catastrophe. The degree of safety required depends on the function of the structure, which determines the uncertainties in performance and the penalty for failure. Even though a structure is safe against collapse, it may deflect or vibrate excessively so as to interfere with the intended use. ***Functional requirements*** must be met if the structural design is to be satisfactory.

Having satisfied objectives (1) and (2), the structure must be designed for minimum cost. However, there may be a trade-off between objectives (2) and (3), and a final decision must be based on a ***minimum cost/benefit ratio***. The cost of the structure may not be considered in isolation. The important consideration is the cost of the total project and the most economical structure may result in higher costs of other nonstructural systems. The structural cost consists of the total for materials, fabrication, erection and maintenance. Minimizing the amount of material used does not necessarily ensure minimum cost, because this may result in excessive fabrication (e.g., steel connections) and erection costs, which are a large part of the total, as well as increased costs of maintenance (repairs) and loss of function during the service life of the structure.

REVIEW OF DESIGN PHILOSOPHIES AND APPROACHES

In the available literature on design, different terms such as "Design Requirements," "Design Principles," "Fundamental Basis of Design," and "Design Philosophy" have been used to denote the total design process, including selection of the design criterion or criteria. Herein the term "Design Philosophy and Design Approaches" will be used, with intended emphasis on the numerical analysis and design phases of the total process. Before discussing the importance of selecting a rational design philosophy and design approach when the potential sources of earthquake hazards, particularly when the excitations due to EQ ground motions (EQGMs) dominate the design, it is convenient to do a critical review of the main design philosophies and design approaches that have been proposed and used in practice for normal excitations.

Linear Elastic Design Philosophy

The two following approaches, which have been developed and used in present codes and therefore in practice, are based on the assumption that the structure will behave in its linear elastic range: ***Allowable-Stress or Working Stress or Service Stress Design Approach*** (according to this approach, the structure and its members are designed to support the working or service loads without exceeding certain specified allowable stresses); ***Strength Design Approach*** [although this approach is based on the assumption of linear elastic behavior of the structure, the structural members are designed on the basis of their critical section yielding strength capacity when subjected to factored service or working loads (excitations)].

Limit Design or Plastic Design or Collapse Design Philosophy

According to this philosophy, the structure is designed on the basis of its collapse strength against properly factored service or working loads (excitations): ***Rigid-Plastic Design Approach*** (this approach is based on the assumption that the structure's members have sufficient ductility to allow the development of a collapse mechanism ignoring the elastic deformations); ***Elastic-Plastic Design Approach*** (in this approach, the elastic and plastic deformations are considered in the redistribution of the internal forces due to the plastic deformations).

Serviceability Limit States Philosophy

This philosophy considers the performance of the structure under the normal service or working excitations as in the case of allowable stress approach, but is also concerned with the other requirements besides the stresses for ensuring a satisfactory use of the building according to its occupancy, including the possible consequences of excessive deformations and/or deformation rates and vibrations on the persons occupying the building, and on the nonstructural components (such as cracking, slipping etc.). *Note that the limit state defines a deformation condition of the structure at which it or any part of it ceases to perform its intended function. Thus, limit states are usually called limits of usefulness.*

Strength Limit States Philosophy

The design based on this philosophy will consider the safety or load-carrying capacity of the building when it is subjected to the critical combinations of the factored service loads, including not only the plastic strength of the members but also the effects of normal classic fatigue, low cyclic fatigue, incremental collapse, fracture etc. The LRFD approach for steel structures has been developed based on this philosophy.

Comprehensive Design Philosophy

In a discussion of the problem of strength and deformation capacities of buildings under extreme environments, Bertero (1980) points out that the possible occurrence of a severe event, such as an earthquake, poses special problems in the design of new buildings and the evaluation of the adequacy of existing buildings. The question is whether is it necessary only to prevent collapse and subsequent loss of life, or whether the expense of damage should be limited as well. A solution is offered by the philosophy of comprehensive design, which was discussed by Sawyer (1964), who proposed *a comprehensive design procedure that correlates the resistance of a structure at various failure stages (limit states or limits of usefulness) to the probability that possible disturbances can reach the intensity required to induce such failure stages, so that the total cost (including the first cost and the expected losses from all the limit stages) is minimized.* As illustrated in Fig. 1, under increasing loads structures generally fail at successively more severe failure stages with increasingly less probability that the load will reach the required intensity levels. The relationship shown in Fig. 1 gives possible structure failure states versus a monotonically increasing pseudo-static load for a typical statically indeterminate reinforced concrete building. For EQ disturbances, the relationship is more complicated because of the effect of the cumulative damage induced by repeated cycles of reversal deformation. Owing to the variability of loss for a given load (or the variability of load for a given loss), this relationship represents the mean values of the random variables involved. The full distribution, as shown in Fig. 2, can sometimes involve large variances (Tichy, 1964). This should be clearly understood by the analysts and designers so that they will not put all their trust in numerical results obtained via just one deterministic analysis, no matter how sophisticated a computer program is used.

COMPREHENSIVE EQ-RD: NEED FOR MULTI-LEVEL DESIGN CRITERIA

For buildings whose design is dominated by severe environmental conditions such as EQGMs, it is required that the strength, deformation and energy dissipation capacities of the building be established at each main limit state. Furthermore, to improve seismic hazard abatement, existing buildings must be continuously assessed for danger under the extreme environmental conditions that can be induced by EQs, necessitating comprehensive analyses of the buildings to predict their strength, deformation and energy dissipation capacities at each of the main limit states (performance levels). Thus, to tackle these problems efficiently it is clear that multi-level analysis and design criteria are needed, and from the above brief discussion of the existing design philosophies it appears that the comprehensive design philosophy is the most attractive one for solving them. As is shown below, the comprehensive design philosophy covers not only all the requirements for the worldwide accepted philosophy for EQ-RD, but also the more detailed performance design objectives that have been included in the definition of all PB EQ-RD adopted recently by the Vision 2000 Committee (SEAOC, 1995).

General Philosophy of EQ-RD

The general philosophy of EQ-RD for nonessential facilities has been well established and accepted worldwide, and it proposes to prevent: ***(1) structural and nonstructural damage in frequent minor earthquake ground shaking, (2) structural damage and minimization of nonstructural damage during occasional moderate earthquake ground shaking, and (3) collapse or serious damage in rare major earthquake ground-shaking.***

This general philosophy demands the use of multi-level design criteria and it qualitatively agrees with the comprehensive design concept or philosophy but, as is discussed below, present practical applications of this general philosophy fall short of realizing its objectives, mainly because it does not define specifically (quantitatively) the earthquake ground-shaking and the degree of damage that has to be prevented, and also because seismic code EQ-RD procedures, following the traditional design procedures for normal types of excitations (loading), emphasize the use of just the life-safety performance level as a design criterion. To remedy this, the Vision 2000 Committee has adopted the following more detailed and specific definition of PB EQ-RD.

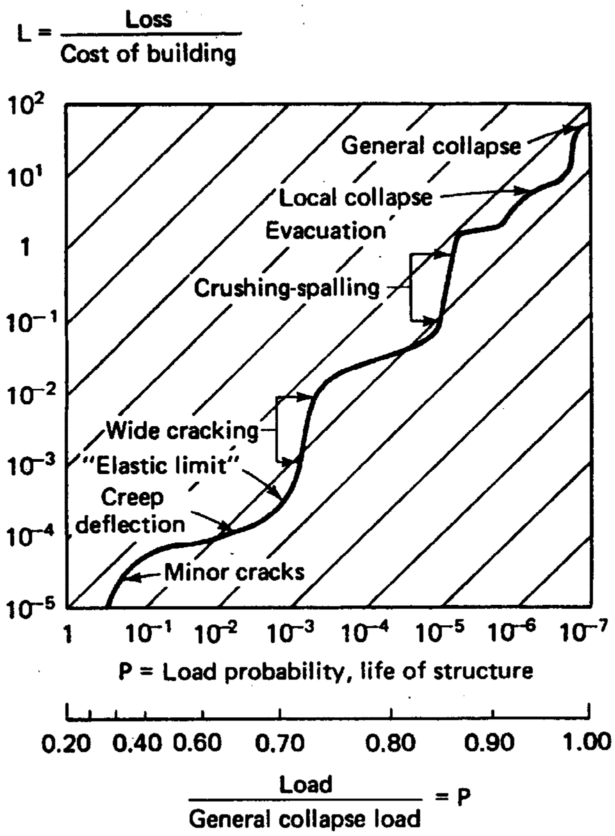

Fig. 1. Losses versus load probabilities during the service life of a RC structure (after Sawyer 1964)

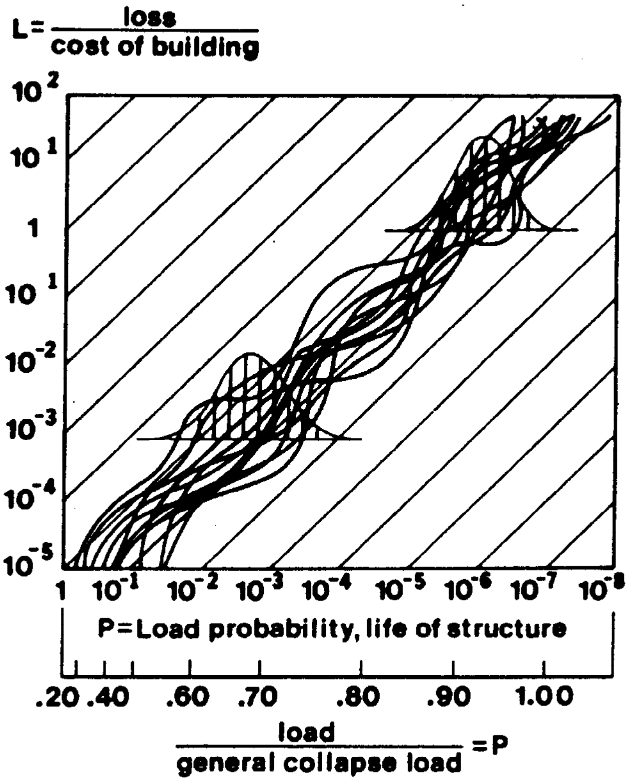

Fig. 2. Distribution of losses versus load probabilities during the service life of a RC structure (after Tichy *et al.* 1964)

Definition of PB EQ-RD

Performance-based EQ-RD consists of selection of appropriate systems, layout, proportioning and detailing of a structure and its nonstructural components and contents so that at specified levels of ground motion and with defined levels of reliability, the structure will not be damaged beyond certain limiting states. At any particular EQ demand level, a given structure will respond within a particular damage state. An infinite spectrum of limiting damage states, ranging from no damage to complete collapse, exists. For purposes of PB EQ-RD, four specific limiting damage states, or performance levels, are defined. ***The performance level is by itself independent of the seismic hazard***; however, when coupled with a specific ground motion criterion, it becomes a ***performance design objective***. Typically, a project should be designed for a spectrum of seismic design objectives, ***ranging from no damage*** for earthquake ground-shaking which is likely to affect the building relatively frequently to avoiding collapse for infrequent extreme events. The SEAOC Vision 2000 Committee has defined four performance levels: ***Fully Operational, Operational, Life-Safe*** and ***Near Collapse***. Furthermore, this Committee has defined as a minimum ***three standard design objectives***. Thus, it is obvious that PB EQ-RD involves multi-level seismic design criteria.

From the above definitions and discussion, it is clear that earthquake-resistant design must involve consideration of serviceability and strength limit states and should include the cost of losses. Furthermore, in view of the uncertainties involved in defining the levels of the EQGMs and in predicting the real mechanical behavior, it will be necessary to use a probabilistic approach in such a design. ***Thus, it becomes clear that among the different existing design philosophies the ideal one for PB EQ-RD is the comprehensive design philosophy.***

Current Seismic EQ-RD Approaches: A Critical Review from the Point of View of the Accepted EQ-RD Philosophy on Which PB EQ-RD Approaches Should Be Based

When Vision 2000 began to develop the work plan to produce design and construction standards that will yield buildings with predictable EQ performance, one of the first questions and problems that needed to be tackled was whether it will be possible to conduct PB EQ-RD using the present seismic codes' EQ-RD approaches, which in the U.S. are based on just a one-level design objective. To answer this question, it is necessary to review first what is needed to be able to produce EQ-RD and construction of predictable performance.

Information Needed for Conducting PB EQ-RD of Buildings. As briefly discussed above, the ideal design philosophy for conducting a PB EQ-RD seems to be the comprehensive design philosophy. According to this philosophy, *the ideal design is that which results in minimum total cost of the facility, which includes not only the initial cost of construction but the cost of all possible losses (physical and functional) at all the possible limit states that the facility can reach or be subjected to during its service life and the needed repair and/or upgrading work, as well as the cost of its demolition.* Thus, it is clear that the comprehensive design philosophy and consequently the PB EQ-RD are based on the use of the so-called limit states design philosophy, but goes beyond this philosophy. The comprehensive design philosophy that recognizes the uncertainties involved in defining each of the different excitations to which a facility can be subjected, and particularly their critical combinations (i.e., the design excitations) at each of the different limit states as well as the uncertainties in defining the engineering parameters controlling the mechanical behavior of the facility, is a ***probabilistically formulated limit state design philosophy***. To summarize: to conduct PB EQ-RD it is necessary to apply the comprehensive design philosophy, which is a probabilistically formulated Limit State Design philosophy based on the use of ***multi-level design criteria***, and the use of this philosophy requires the following information:

- The different sources of excitations (loads) to which the facility to be designed can be subjected during its service life.
- Definitions of the limit states (performance levels) that need to be considered.
- The variation in the intensity of each of the excitations that can act on the facility during its service life and the probability that the combinations of these excitations can reach the required intensity to induce each of the limit states (failure stages) that need to be considered.
- The types of failures (limit states) of the different components, structural and nonstructural, of the entire facility system, associated with the types of excitation and the increasingly small probability that the excitations will reach the intensity levels required to induce such failures.
- The costs of the losses (physical and functional) and repairs associated with each of the different limit states (failure stages) that need to be considered.

Thus, as is the case with any type of engineering design, the most important information for PB EQ-RD is that concerning the sources of excitations, their variation in intensity with time and their corresponding probability of reaching the intensity required to induce any of the limit states that have to be considered. Once this information is available, the owner, together with the designer, has to decide on the performance levels (limit states) that should be considered in the design together with the recurrence periods over which such levels are reached in accordance with the controlling excitations at these levels. For example, the owner may desire a design and construction that will perform as stated in Table 1. According to the expected intensity and duration of the EQGM excitations and the combination of other significant potential seismic hazards and loading conditions in the owner-desired recurrence periods, the designer has to analyze whether it will be economically feasible to design for such requirements and then to offer alternative recurrence periods for the different limit states. Assuming that a compromise is reached on the recurrence period of the limit states as indicated in Table 1, ***the design criteria*** in the form of ***PB EQ-RD objectives*** has been established, and the next step is to conduct the necessary analysis and preliminary design to comply with the established ***multi-level design criteria.***

The necessary analysis and preliminary designs are commonly based on idealized mechanical behavior under simplified excitations because it is not usually possible to consider actual behavior and the true history of disturbances. Sources, treatment and effects of the different types of excitations are summarized in Fig. 3. Structures are usually subjected to unpredictable fluctuations in the magnitude, direction and/or position of each of the individual excitations that may act on them during their service life, and the extreme values between which each of these excitations will oscillate are the only characteristics that can be estimated with some accuracy. These types of action are classified in Fig. 3 as generalized or variable-repeated excitations. The types of failures associated with variable-repeated excitations are classified as long-endurance fatigue, low-cycle fatigue, and incremental collapse. Long-endurance fatigue is only critical for very special structures. Failure prediction is clearly essential in designing against extreme environments and requires knowledge of the strength ***at different levels of structural deformation.*** The discussion above points out the difficulty in predicting strength and deformation capacities and the need for a probabilistic approach, or, at least, for considering the bounds and ranges of probable mechanical behavior and possible excitations.

Table 1. Initial selection of performance levels (SEAOC 1995)

Performance Levels	No Damage	Damage Control			
		No struct. damage, minor nonstruct. damage	Minor struct. damage, moderate nonstruct. damage	Life safety and economic repairability	Life safety but no economic repairability
Limit States	Service	Continuous Operation	Immediate Occupancy	Life Safety	Impending Collapse
Owner desired recurrence period*	10 years	30 years	50 years	450 years	900 years
Compromise recurrence period	8 years	20 years	40 years	450 years	700 years

* note that the values of recurrence periods given herein are arbitrarily selected to illustrate the procedure

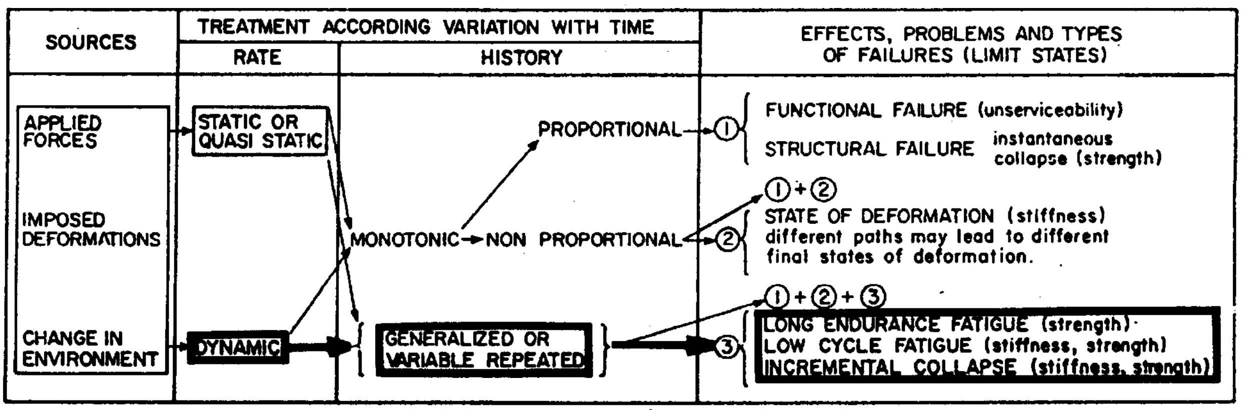

Fig. 3. Sources, treatment and effects of excitations on structures (Bertero 1980)

Based on the possible different types (dynamic characteristics) of EQGMs, such as impulsive or harmonic, and on the relative intensity of the other types of excitations, such as the gravity loads that can be acting simultaneously with the expected future EQGMs, Bertero *et al.* (1991) give a detailed discussion of what is needed regarding the EQGMs, as well as the prediction of the mechanical behavior (dynamic response) up to each of the limit states involved in the desired performance design objectives of PB EQ-RD. This is done considering the different types of failures illustrated in Fig. 3. From this information, it is clear that except for the rare case in which it is desired to keep the entire building serviceable under even the maximum capable EQGM, in which case ***linear elastic analysis and design based on one-level design criteria***, can be used; in all the other cases estimation of the damage potential of the EQGMs and preliminary design and analysis of the entire building demand the use of approaches and procedures ***based on multi-level design criteria and on nonlinear dynamic analyses.*** Regarding the expected EQGMs, the essential information needed is: ***the time history of the expected EQGMs at the different recurrence periods corresponding to the performance levels that should be considered.*** Note that because of the uncertainties in predicting such EQGM time histories it is necessary to specify for each recurrence period a suite of EQGM time histories. With this information, engineers can compute the specific detailed information needed to conduct the preliminary EQ-RD and the needed acceptability analyses. The specific information to be obtained from the processing of the time history of the EQGMs at each of the recurrence periods that need to be considered are the following ***smoothed inelastic design response spectra (SIDRS)*** for: strength, total acceleration, velocity, displacement, energy input, and energy dissipation. These spectra have to be computed considering the different levels of ductility ratio, μ, and damping coefficient, ξ, that can be developed and accepted according to the desired performance at the recurrence period under consideration. These spectra should include as a particular case the ***Smoothed Linear Elastic Design Response Spectra (SLEDRS)*** which is for μ=1.

From the above discussion it becomes clear that the use of multi-level design criteria requires the consideration and processing of a lot of information, which makes it difficult for practical application. However, its use is needed for calibrating the practical simplified design procedures that have been used or proposed based on the use of just one design criterion, which usually is formulated considering the minimum requirements of life safety.

CRITICAL REVIEW OF CURRENT U.S. CODE EQ-RD APPROACHES

As discussed in detail in Bertero *et al.* [1991], the current code EQ-RD approaches for most buildings are based on the use of a strength (base shear) SLEDRS for just one performance level, the Life Safety level corresponding to a return period of 475 years. Taking advantage of the dissipation of energy that can be developed through plastic deformation of ductile structures, the U.S. seismic codes have introduced an EQ-RD approach that reduces the demanded linear elastic strength (base shear) through ***a reduction factor called the response modification factor, R, by the NEHRP recommendations (FEMA, 1992), or the structural system factor, R_w, by the SEAOC blue book (1990).*** To keep code design procedure as simple as possible using only linear elastic methods of analysis (which allows use of the principle of superposition), the U.S. codes base their design on either the allowable or service stress approach (UBC), or the first significant yielding of the most stressed section (NEHRP). There is no doubt that this is the simplest approach, except for the case of buildings where prescriptive EQ-RD can be used. However, as shown by Bertero *et al.* (1991), blind use of the current linear elastic code approaches, ***the so-called static equivalent lateral force*** (ELF) and even ***the linear dynamic response spectrum***, which are based on the use of R factors whose values depend only on the type of structural system, independent of the period of the structure and of the EQGMs' dynamic characteristics, and of the relative importance of the other types of excitations (loads) that can act simultaneously with the effects of the EQGMs, can result in designs that can have quite different performance, and in several cases in undesirable performance. Furthermore, a main weakness of the ELF approach, as well as of any other of the current code EQ-RD approaches, is that ***they are based on just one performance design objective: life safety.*** Although the code requires checking the deformations (lateral interstory drift indices) from elastic analysis under the design lateral forces against the specified values of the maximum allowable lateral drift values under working load conditions, and these deformations, modified by a factor that the NEHRP recommendations called the deflection amplification factor, C_d, and by a factor $3(R_w/8)$ in the 1994 UBC code regulations, have to be equal to or smaller than specified maximum acceptable values, it has to be noted that: first, the deformations obtained from the elastic analysis under the reduced forces for the life safety EQGMs with a return period of 475 years do not in general represent the deformations that can be expected under the service EQGMs, i.e., the EQGMs that can occur with a lower return period; and secondly that these elastic deformations amplified by the specified or recommended deflection amplification factor in general do not result in a reliable prediction of the actual inelastic deformation that will occur under the critical EQGMs with a return period of 475 years.

In judging the different code EQ-RD approaches that are based on designing for strength (base shear), as well as for those new approaches that have been suggested as promising for PB EQ-RD and which are also based on just using strength as the main design criterion or parameter, the following should be kept in mind: first, that the defined performance levels are based on different degrees of acceptable damage and damage is more a consequence of the history of deformation and rate of deformation than of strength, and secondly that for the performance levels accepting damage through the yielding of the structure as a mechanism, the use of the yielding strength as a design parameter is completely insensitive to the amount of deformation, i.e., to the amount of damage, and therefore cannot be used alone to conduct the required PB EQ-RD.

From the above discussion, it is obvious that the current code ELF EQ-RD approach, based on just one performance level and design objective and on the use of specified linear elastic strength spectrum that is reduced through specified values for the R factor cannot result in general in the design of buildings with predictable performance. Because this ELF approach is the most used approach for EQ-RD of buildings, it would be highly desirable first to investigate the kind of buildings to which it can be applied to achieve predictable performance, and secondly, what simple modifications can be introduced to extend the applications of this ELF approach to the PB EQ-RD of other types of buildings. There is no doubt that this is one of the most challenging tasks for the practical implementation of performance-based EQ-RD. To accomplish this, it will be necessary to calibrate the needed simplifications to reduce the actual multi-level requirements of the comprehensive design philosophy to the use of just one performance level and linear elastic analyses. This calibration can be done through the use of a ***comprehensive EQ-RD approach*** based on multi-level performance design objectives that the author and his associated researchers have developed and applied (Bertero *et al.*, 1994). A detailed description of the proposed comprehensive EQ-RD approach has been presented by the author in the report of SEAOC Vision 2000 Committee (1995), where it is pointed out that the preliminary design of the building based on multi-level criteria (performance design objectives) can be carried out: designing for just the one limit state (performance level) that appears to control the design, and then checking for all the others; or designing simultaneously for the demands of two or all the main limit states. It is recommended to design simultaneously for at least two limit states: for example, for the design of a tall building in the San Francisco Bay Area it is recommended to carry out the preliminary EQ-RD for service (or fully operational) and life safety. No matter how many levels are used in the preliminary design, the acceptability check of the final design should be conducted considering all the recommended levels, which for the PB EQ-RD are four.

It should be clearly noted that the author is not proposing that the comprehensive EQ-RD approach, which is based on multi-level design criteria, be implemented immediately in present seismic codes. This approach is proposed for use in investigating how reliable, simple and practical seismic code procedures based on just a single design criterion (single performance design objective) can be developed.

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