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STATE-OF-THE-ART REPORT ON: DESIGN CRITERIA

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ABSTRACT

The main objectives of this paper are: first, to discuss the ***main purpose of seismic design***, and to clarify what is understood by "***design criteria***" by discussing their role in the ***overall design process*** and the importance of properly selecting and establishing them to ensure that the main objectives of the design are satisfied; and second, to discuss the state of the art in earthquake-resistant design (EQ-RD) criteria. After a review of the general philosophy of EQ-RD and the available design philosophies and approaches, it is concluded that the most attractive design philosophy for EQ-RD appears to be the ***comprehensive design philosophy***. Recent proposals for new approaches to EQ-RD of buildings aimed at designing buildings with more predictable performance are reviewed. Then the paper focusses on the recently proposed ***performance-based seismic engineering of buildings*** and the design criteria involved in the different approaches that have been suggested for conducting ***performance-based EQ-RD***. Emphasis is placed on discussing the multi-level design criteria that need to be adopted to cover the main performance design objectives recommended in the proposed ***comprehensive EQ-RD approach***. The difficulties encountered in the practical application of this approach are discussed, and some recommended procedures for ***acceptability checks*** involved in a proposed ***simple force/strength approach*** are critically reviewed. The need to develop EQ-RD approaches that are based on ***multi-level probabilistic structural performance criteria*** is stressed, and recent studies in this area by Wen and his associates are briefly reviewed. Recommendations for research to improve the state of the art in EQ-RD criteria, and consequently the state of the practice in EQ-RD, are formulated.

KEY WORDS

Allowable stress design; comprehensive design; design criteria; design philosophy; earthquake-resistant design; life-safety; limit design; multi-level design criteria; performance-based seismic design; performance design objectives; performance levels; plastic design; probability of failures; reliability; structural safety.

INTRODUCTION

Main Purpose of Design. From the structural engineering point of view, the main purpose of design is to devise a technically and economically ***efficient system*** to resist and transmit the forces and/or deformations induced by the excitations imposed by the environment in which the facility is to be built. Thus, ***the purpose of structural design is to produce optimum structures***, as has long been stated clearly by several authors (Gallagher, 1973; Rosenblueth, 1974; Esteva, 1980). As pointed out by Rosenblueth (1974), "*Optimization should consider not only the initial cost of the structure, but also: the benefits to be derived from the structure while it survives; the present values of maintenance, damage and failure costs; and the probabilities that the structure might suffer damage or failure as a function of time.*" Thus, a rational approach to design requires computing the probabilities that a structure will undergo given degrees of damage and the probability that it will suffer failure. Generically, these quantities are referred to as ***probabilities of failure***. Their complements, or probabilities of survival, are called ***reliabilities***. Gallagher (1973) pointed out that, "*In contrast to analysis technology, optimal structural design technology has not yet enjoyed the predicted and/or expected acceptance in practical design, and that it is difficult to ascertain the full range of considerations responsible for the slow acceptance of the available design technologies in the computational aspects of practical design.*" This statement is still valid today.

Esteva (1980) discussed the nature and objectives of EQ-RD as follows: "*Engineering design is rooted in society's need to optimize. It implies considering alternate lines of action, assessing their consequences, and making the best choice. In earthquake engineering, every alternate line of action includes the adoption of both a structural system and a* ***seismic design criterion****, while the assessment of consequences implies estimating structural response and hence expected cost of damage. The choice is based on comparison of initial, maintenance and repair costs for the various alternatives.*" After also considering the approximations implicit in conventional criteria for prediction of structural response and the general goal of optimization in terms of direct particular objectives, Esteva concludes that: "*Achievement of the foregoing objectives requires much more than dimensioning structural members for given internal forces. It implies explicit consideration of those objectives and of the problems related to nonlinear structural response and to the behavior of materials, members and connections when subjected to several cycles of high-load reversals. It implies as well the identification of serviceability conditions and formulation of acceptance criteria with respect to them.*" Esteva's publications make it clear that achievement of optimum EQ-RD and EQ-resistant construction (EQ-RC) requires more than independent structural analysis, studies of the mechanical behavior of a structure, and dimensioning of structural members for given internal forces. It requires both a clear understanding of the role of each of the above aspects and an overall grasp of their intimate relationship in each phase of the ***total design process***.

Total Design Process. As is discussed in two companion papers (Bertero, R.D. *et al.*, 1996; Bertero, V.V., 1996), 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.*** The first, and perhaps most difficult, technical problem in carrying out this total process is the formulation of the ***design criteria***.

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. The three major objectives are ***(1) safety, (2) performance of function, and (3) economy***. ***Safety*** is 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 error in design and construction, or unforeseen natural catastrophe. The required degree of safety depends on the function of the structure, which determines the uncertainties in performance and the penalty for failure. Even if a structure is safe against collapse, it may deflect or vibrate excessively and interfere with its 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.

EQ-RD Criteria and Their Function. In discussing the problems of EQ-RD, Housner *et al.* (1982) noted that when formulating the ***design criteria*** it is necessary to keep in mind that, fundamentally, ***they are a means of specifying the desired earthquake-resistant capability of the structures and the facilities***. The objectives of the criteria are twofold: first, to provide levels of EQ resistance for the various parts of the project that are consistent relative to each other; and second, to provide a level of EQ resistance that is appropriate to ***the desired performance of the facility***. The above author pointed out that the primary function of design criteria in general, and EQ-RD design criteria in particular, is to ***restate a complex problem that has unknowns and uncertainties in an unambiguous, simplified form having no ambiguities***. The design criteria should provide clearly stated guidelines for the designers. In the preparation of the design criteria, allowances must be made for the uncertainties, and it is necessary to be cognizant of all the unknowns for which allowances must be made.

Housner *et al.* (1982) made some observations regarding the establishment and implementation of EQ-RD, and, in order to assist the project engineer in setting and implementing EQ-RD criteria, formulated a series of questions that he or she should consider while keeping in mind that "*the main purpose of the criteria is to specify the desired performance of the structure or facility under future conditions.*" Housner *et al.* (1982) make it clear that to formulate rational and reliable design criteria for EQ-RD, the designer must have a good overall grasp of all of the main aspects of the EQ-RD problem and of the ***philosophies, approaches and methods*** that are available in practice to conduct the total design process successfully.

Review of the Design Philosophies and Approaches

Herein the term "Design Philosophies and Design Approaches" denotes the total design process, including selection of the design criteria, 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 EQ hazards, particularly the excitations due to EQ ground motions (EQGMs), dominate the design, it is convenient to review critically the main design philosophies and design approaches that have been proposed and used in practice for normal excitations. This has been done in a companion paper (Bertero, 1996), in which the following philosophies are identified and discussed.

- ***Linear Elastic Philosophy:*** *Allowable Stress or Service Stress Approach; and Strength Design Approach.*
- ***Limit Design or Plastic Design or Collapse Philosophy:*** *Rigid Plastic Design Approach; and Elastic Plastic Design Approach.*
- ***Serviceability Limit States Philosophy.***
- ***Strength Limit States Philosophy.***
- ***Comprehensive Design Philosophy.***

It should be noted that in these design philosophies the "***Capacity Design Philosophy,***" which some authors have referred to in the design literature (Paulay *et al.*, 1992), is not included because according to the above adopted definition of design philosophy ***capacity design*** is a highly recommended ***procedure or design strategy*** that can be used in the application of each of the above identified overall design philosophies. Now, the questions that have to be answered are: "***Can any of the above available design philosophies be used efficiently and reliably to solve the problem of attaining optimal EQ-RD of civil engineering facilities?;***" and "***Does application of current code seismic code design procedures lead to efficient EQ-RD?***" To answer these questions, it is necessary to review the main problems and issues involved in EQ-RD of these facilities. It has to be kept in mind that while an efficient EQ-RD is necessary, it is not sufficient: it must be accompanied by sound EQ-RC.

Main Problems and Issues Involved in EQ-RD and EQ-RC. The general aspects and problems involved in EQ-RD and EQ-RC for buildings (on which the following discussion will concentrate) have been discussed by Bertero (1982). From analysis of these general aspects and the results from studies on the importance and effects of the aspects, it appears that the principal issues that remain to be resolved for the improvement of such design are related to the following three basic elements: ***EQ input, demands on the building,*** **and** ***supplied capacities to the building.*** The first of these, the EQ input element, involves the following interrelated issues: ***Design EQs, design criteria,*** and ***selection of design methodology.*** The importance of proper establishment of the design EQs is reflected by ***the need to know against what we have to design the building. Design criteria*** should reflect in a transparent way the general philosophy of EQ-RD, which has been well established and is accepted worldwide. However, as will be discussed below, current code design methodologies in the U.S. fall short of realizing the goals and objectives of this philosophy (Bertero, 1992).

General Philosophy of EQ-RD. What can be considered the general philosophy of EQ-RD of buildings sheltering other than essential and hazardous facilities was introduced in the U.S. for the first time in the Commentary of the 1967 edition of the Structural Engineers' Association of California (SEAOC) Blue Book (1967), and it has changed very little since then. Essentially, this EQ-RD philosophy states that the design should accomplish the following objectives:

1. Prevent nonstructural damage in minor EQ ground shakings, which may occur frequently during the service life of the structure
2. Prevent structural damage and minimize nonstructural damage during moderate EQ ground shakings, which may occasionally occur
3. Avoid collapse or serious damage during severe EQ ground shakings, which may rarely occur

The ideal philosophy of EQ-RD should attempt to realize all of the objectives of the above general philosophy by providing all the needed stiffness, strength and energy dissipation capacity with the minimum possible extra cost in initial construction as well as in its maintenance during its service life and the slightest possible sacrifice in the architectural features required for the design of the building for just gravity loads.

U.S. Code Philosophy. The primary function of a building code is *to provide minimum standards to assure public safety.* In view of this, it is not surprising that SEAOC has established a seismic code philosophy that is in accordance with the above primary function of building codes. *Thus, the basic philosophy of the SEAOC seismic code, as well as of most of the other seismic codes, has been to protect the public in and about buildings from loss of life and serious injury during major EQs.* ***In few words, current code design methodology is based on a one-level design EQ.*** Moreover, the SEAOC commentary states that, "*the protection of life is reasonably provided but not with complete assurance.*" To summarize, ***the primary goal of the U.S. seismic provisions is to protect life.*** *The secondary goal is to reduce (not eliminate) property damage.* The questions that need to be answered are: First, ***Does the application of current seismic code provisions accomplish the above goals?***; and second, ***Are these goals sufficient?***

Uang *et al.* (1991) have shown that the UBC- (or SEAOC-) specified seismic design procedure cannot adequately control the general demands that can be imposed by service EQGMs. The author has long believed that it will be very difficult to satisfy the criteria for all three objectives of seismic design philosophy by keeping the present building code design methodology, which requires only one level of design EQ (life-safety level), and thus there is a need ***to move from the current code one-level design EQ criteria and methodology to multi-level criteria and methodology based on at least two distinct levels of design EQs: the service-level (functional adequacy) and the life-safety level EQs.*** In 1974, Bertero *et al.* developed and applied a nonlinear EQ-RD procedure for multi-story steel frames based on two levels of design EQs. This procedure was extended to the optimal EQ-RD of RC ductile moment-resisting frames employing a computer-aided iterative technique (Zagajeski *et al.*, 1977). The idea of using two levels of design EQ is not new. In the U.S., its application and introduction into seismic codes were discussed in the 1970s. The 1981 Japanese Building Standard Law (BSL) explicitly specifies a *two-level design EQ: moderate EQGMs*, which occur several times during the service life of the building with almost no damage, and *severe EQGMs*, which occur less than once during the use of the building and would not cause collapse or harm to human lives. While buildings not higher than 31 m (102 ft.) can be designed under just moderate EQGMs, buildings higher than 31 m must be designed for the both levels.

Recently, SEAOC, recognizing the need to design structures with more predictable performance, has developed a conceptual framework for what is called **Performance-Based Seismic Engineering of Buildings (PBSEOB)** (SEAOC, 1995), which considers multi-level EQ-RD criteria.

MAIN ISSUES IN IMPROVING THE DESIGN CRITERIA FOR EQ-RD OF STRUCTURES

As discussed earlier, the information needed to improve prediction of EQ responses of structures can be grouped into the following three basic elements: *EQ input, demands on the structure, and supplied capacities to the structure.* These three basic elements of the EQ response problem are discussed briefly below.

EQ Input: Establishment of Design EQs and Design Criteria. The design EQs depend on the design criteria, or *the limit states controlling the design.* Conceptually, the design EQ should be that EQGM, out of all probable EQGMs at the site, which will drive a structure to its critical response. In practice, the application of this simple concept meets with serious difficulties because, firstly, there are great difficulties in predicting the main dynamic characteristics of ground EQGMs which have yet to occur, and, secondly because even the critical response of a specific structural system will vary according to the various limit states (performance levels) that could control the design. Seismic codes specify design EQs in terms of a building code zone, a site intensity factor, or a peak site acceleration. Reliance on these indices, however, is generally inadequate, and methods using *ground motion spectra (GMS), and Smoothed Linear Elastic Design Response Spectra (SLEDRS)* based on *effective peak acceleration (EPA)* have been recommended (ATC 3-06, 1978). While this has been a major improvement conceptually, great uncertainties regarding appropriate values for EPA and GMS, as well as for other recommended parameters, persist.

Estimation of Reliable Demands. The major uncertainties in the estimation of the potential demands are due to difficulties in predicting the following: (1) the critical seismic excitations and hazards at the site during the service life of the structure (lack of properly established design EQGMs and critical load combinations); (2) the state of the entire soil-foundation-superstructure-nonstructural components and contents system when the critical EQGM occurs [proper selection of the mathematical model(s) to be analyzed]; (3) internal forces, deformation, stresses and strains induced in the model (structural and stress analysis); and (4) realistic supplies of stiffness, strength, stability, and capacity to absorb and dissipate energy (i.e., realistic hysteretic behavior) of the entire facility system.

Prediction of Supplies. The supplies to a facility include not only supplies to its bare superstructural system, but also supplies that result from the interaction of the bare superstructural system with the soil-foundation and the so-called *nonstructural components* of the facility. When such interactions occur, *neglecting them in the selection of numerical characteristics for the design of the structure could lead to completely unrealistic evaluation of the demands, and consequently could result in a poor final design of the entire building system.* In considering the basic general design equation (***Demands* ≤ *Supplies***), the designer might be tempted to increase *supplies* in order to overcome the problems created by the uncertainties in the values of *demands.* However, supply must be increased very carefully, because it may considerably increase the demands.

Directions Toward Solutions of the Main Issues in Establishment of Design EQs and Design Criteria

General Remarks Regarding the Need for Reliable Site Seismic Hazard Assessment. Before embarking on the design of a structure at a given site, it is necessary to conduct *an analysis of the seismic suitability of the selected site* i.e., a reliable site seismic hazard assessment is needed. Recent EQs have shown that in order to improve the reliability of this analysis and definition, it is necessary to: (1) improve the *identification of all possible sources of EQs* that can affect the site; (2) *describe fully and reliably the dynamic characteristics of the ground motions at the source*; (3) quantify how the source ground motions are modified (attenuated or amplified) as they propagate from the source to the site (i.e., *improve the so-called Attenuation Law*); (4) identify the types of EQ hazards at the selected site; and (5) estimate the return periods of these EQ hazards at different intensity levels.

Establishment of Design EQ. For any given building to be constructed on a selected site, present U.S. codes define just one level of hazard (EQGM). Analyses of the damages from recent EQs clearly show the need to consider more than one level of EQGM for the design of structures. Since damage involves nonlinear response (inelastic deformation), ***the only way to estimate damage and the actual behavior of a facility under severe EQ excitation is to consider its inelastic behavior***. Guided by this basic concept and by the fact that the damage potential of any given EQGM at the foundation of a structure depends on the interaction of its intensity, its frequency content, and its duration with the dynamic characteristics of the structure, the author believes that one of the most reliable ways to define the damage potential of an EQGM is to compute its energy input, E_I, to the foundation of the structure, together with the other associated parameters which can be obtained through the use of energy concepts (Bertero, 1992).

Use of Energy Concepts in Establishing EQ-RD Criteria

Traditionally, displacement ductility ratio has been used as a criterion to establish *Inelastic Design Response Spectra (IDRS)* for EQ-RD of buildings. The minimum required *lateral strength* of a building is then based on the selected IDRS. As an alternative to this traditional design approach, an energy-based design method was proposed by Housner (1956). However, it is only recently that this approach has gained extensive attention (Akiyama, 1985). This design method is based on the premise that the *energy demand* during an EQ (or an ensemble of EQs) can be predicted, and that the *energy supply* of a structural element (or structural system) can be established. In a satisfactory design, the energy supply is larger than the energy demand. To develop reliable design methods based on an energy approach, it is necessary to derive the energy equations.

Derivation of Energy Equations. Uang *et al.* (1988) give a detailed discussion of the derivation of the two basic energy equations (absolute and relative), and have shown that the maximum values of the absolute and relative energy input, E_I , for any given constant displacement ductility ratio are very close in the period range of practical interest for EQ-RD of buildings, which is 0.3 to 5.0 seconds. Thus, the two energy equations can be written as:

$$E_I = (E_E) + (E_D) \quad \textbf{(1a)} \qquad\qquad E_I = (E_K + E_s) + (E_{H\xi} + E_{H\mu}) \quad \textbf{(1b)}$$

Where: E_I= energy input, E_E = the stored elastic energy, E_D = the dissipated energy, E_K = kinetic energy, E_s = elastic strain energy, $E_{H\xi}$ = dissipated energy due to hysteretic equivalent linear viscous damping, and $E_{H\mu}$ = dissipated energy due to hysteretic plastic deformation.

Comparing this equation with the design equation (**Demands ≤ Supplies**), it becomes clear that E_I represents the *demands*, and the summation of $E_E + E_D$ represents the *supplies*. ***An understanding of Eq. (1) will guide the designer in establishing the design criteria.*** Equation (1a) points out clearly to the designer that to obtain an efficient seismic design, the first step is to have a good estimate of the E_I for the critical EQGM. Then the designer has to analyze whether it is possible to balance this demand with just the elastic behavior of the structure to be designed, or if it will be convenient to attempt to dissipate as much as possible of the E_I using E_D. As revealed by Eq. (1b), there are three ways of increasing E_D: one is to increase $E_{H\xi}$ by increasing the equivalent linear viscous damping, $E_{H\xi}$; another is to increase the hysteretic energy, $E_{H\mu}$; and the third is a combination of increasing $E_{H\xi}$ and $E_{H\mu}$. At present it is common practice to just try to increase the $E_{H\mu}$ as much as possible through inelastic (plastic) behavior of the structure, which implies damage of the structural members. Only recently it has been recognized that it is possible to increase the $E_{H\mu}$ significantly and control damage throughout the structure through the use of *energy dissipation devices*. Furthermore, as discussed by Bertero (1992), increasing E_D by increasing $E_{H\xi}$ has the great advantage that it can control the behavior of the structure under both safety and service levels of EQGMs.

If technically or economically (or both) it is not possible to balance the required E_I either through E_E alone or E_E+E_D, the designer has the option of attempting to control (decrease) the E_I to the structure. This can be done by *base isolation techniques*. A combination of controlling (decreasing) the E_I by base isolation techniques and increasing the E_D by the use of energy dissipation devices is a very promising strategy not only for achieving efficient EQ-RD and EQ-RC of new structures, but also for the seismic upgrading of existing hazardous structures. To use this energy approach reliably, it is essential to be able to select the critical EQGM (design EQ); in other words, the ground motion that has the largest damage potential for the structure being designed. E_I is a promising parameter for assessing the damage potential of these motions, but this parameter alone is not sufficient to evaluate (visualize) the E_D that has to be supplied to balance the E_I for any specified acceptable damage. Additional information is needed.

Information Needed to Conduct Reliable EQ-RD Criteria and Thus EQ-RD of Buildings. Currently, for structures that can tolerate a certain degree of damage, the *Safety or Survival-Level Design EQ* is defined through *Smoothed Inelastic Design Response Spectra, SIDRS*. Most of the SIDRS that are used in practice (seismic codes) have been obtained directly from *Smoothed Elastic Design Response Spectra, SEDRS*, through the use of the *displacement ductility ratio,* μ_δ , or *reduction factors, R*. The validity of such procedures has been questioned, and it is believed that at present such SIDRS can be obtained directly as the mean or the mean plus different values of standard deviation of the *IRS*, corresponding to all the different time histories of the severe EQGMs that can be induced at the given site from EQs that can occur at all of the possible sources affecting the site (Bertero, 1991). While the above information is *necessary* to conduct reliable design for safety, it is *not sufficient*. In other words, *the maximum global ductility demand by itself does not give an appropriate definition of the damage potential of EQGMs*. As discussed previously, it has been shown that a more reliable parameter than those presently used in assessing damage potential is the E_I. This damage potential parameter depends on the dynamic characteristics of both the shaking of the foundation and the whole building system (soil-foundation-superstructure and nonstructural components). Now the question is: ***Does the use of the SIDRS for a specified global*** μ_δ ***and the corresponding*** E_I ***of the critical EQGM give sufficient information to conduct a reliable seismic design for safety?***

From recent studies (Uang *et al.*, 1988; Bertero, 1991) it has been shown that the energy dissipation capacity of a structural member, and therefore of a structure, depends upon both the loading and deformation paths. Although the energy dissipation capacity under monotonic increasing deformation may be considered as a lower limit of energy dissipation capacity under cyclic inelastic deformation, the use of this lower limit could be too conservative for EQ-RD. This is particularly true when the ductility deformation ratio, say μ_δ, is limited, because of the need to control damage of structural and nonstructural components or other reasons, to low values compared to the ductility deformation ratio reached under monotonic loading. Thus, effort should be devoted to determining experimentally the energy dissipation capacity of main structural elements and their basic subassemblages as a function of the maximum deformation ductility that can be tolerated, and the relationship between energy dissipation capacity and loading and/or deformation history. From the above studies, it has also been concluded that damage criteria based on the simultaneous consideration of E_I and μ_δ (given by SIDRS), and the $E_{H\mu}$ are promising parameters for defining rational EQ-RD criteria and procedures. From the above discussion, it is clear that when significant damage can be tolerated, *the search for a single parameter to characterize the EQGM or the design EQ for safety is doomed to fail.* ***If future codes perpetuate simple procedures for seismic design specifying only smoothed strength response spectra, it will be necessary to place more stringent limitations on the type of structural systems that could be used and on how such procedures can be applied, and to have very conservative regulations in the sizing and detailing for ductility and in the maximum acceptable deformations.***

NEED FOR FORMULATION OF CONCEPTUAL EQ-RD CRITERIA AND METHODOLOGY

Current seismic codes, in their attempt to be simple (as they should be), have tried hard to simplify the complex problem of EQ-RD by developing design criteria and procedures based on just one parameter. The result is codes that are not transparent because their regulations do not present in a visible way the basic concepts which govern the EQ-RD of structures. Although it is generally recognized that damage is due to deformation, there is no agreement regarding the main criterion for preliminary EQ-RD of structures. Perhaps as a consequence of past and present code requirements, present practice emphasizes the use of strength in the preliminary design of structures. The reasons for and drawbacks of the insistence on using only strength as primary criterion has been discussed by Bertero (1992). For a long time already it has been recognized by researchers and practitioners that ***to produce serviceable, safe and economical facilities, EQ-RD criteria and methods must incorporate drift (damage) control in addition to lateral displacement ductility as design constraints***. The question is how to achieve such control at the different levels of EQ shaking that can occur during the life of the structure. Bertero *et al.* (1991) discuss in detail the issues involved in achieving such control at the serviceability and safety limit states.

The control of the drift of a structural system under EQ excitation is important for at least three different reasons: (1) to maintain architectural integrity, thereby avoiding unacceptable damage to nonstructural components; (2) to limit structural damage and avoid structural instability (P-Δ) problems; and (3) to avoid human discomfort under frequent minor or even occasional moderate EQ shaking. Story drifts and drift ductility factors may also be useful in providing information on the distribution of structural damage. Unfortunately, conventionally computed story drifts may not adequately reflect the potential structural or nonstructural damage to multistory buildings. In some structures, a substantial portion of the horizontal displacements results from axial deformations in the columns. Story drifts due to these deformations are not usually a source of damage. A better index of both structural and nonstructural damage is the tangential story drift index, R_T (Mahin *et al.*, 1976). Furthermore, some of the nonstructural damages are caused by deformation rates (velocity and/or acceleration), rather than just deformation. For example, the failure of partitions out of their plane is due to the acceleration perpendicular to their plane. Damage to equipment and contents of buildings are also due to deformation rates. Thus, it is also of importance to control the deformation rates to achieve good performance of nonstructural elements, equipment, contents and, in some cases (e.g., when viscous dampers are used) the structure itself.

In response to the noted weakness of present seismic code EQ-RD procedures based on base shear strength, which is insensitive to damage in the inelastic (plastic) range, there have been proposals that preliminary design be based only on lateral stiffness, i.e., only on controlling interstory drift.

Recommended Practical Methods for Designing Considering IDI

Recently, Bonacci (1994) has reviewed the methods useful for estimating response of yielding RC systems to EQs with special emphasis on a comprehensive method that enables the designer to evaluate and control member damage on the bases of an inelastic estimate of nonlinear displacement response. Bonacci's review is a vote of confidence for the method proposed by Gulkan *et al.* (1974) and for that used by Shibata *et al.* (1976) in the well-known proposed ***substitute structural method.*** A simplified method for estimating lateral drift of RC structures has been suggested by Sozen (1983). The method is intended to be used for interpreting experience and evaluating relative merits of different structural schemes and member sizes on the basis of a tolerable damage criterion. The method is conveniently used in preliminary evaluation by simple estimates of the base shear capacity coefficient. Shimazaki (1984, 1988) investigated the effects of strength and stiffness and of the type of EQGM on nonlinear displacement response of SDOF systems. *The results obtained show that the nonlinear displacement response is equal to the linear response spectral values if the system has a certain strength which is determined by dimensionless parameters for strength, initial period, and type of EQGM.*

Recently Qi *et al.* (1991) and Moehle (1992) developed two simple and practical EQ-RD procedures based on displacement (drift) information. One uses displacement information directly, and the other, a ductility-ratio approach, uses it indirectly, establishing ductility requirements as a function of the provided strength and the strength required for elastic response. Priestley (1993), after examining current practice in seismic analysis and design, suggested that our current emphasis on strength-based design and ductility lead us in directions that are not always rational, and advanced a ***pure displacement-based design approach***. This approach is comparatively straightforward for a simple multi-column bridge pier. To carry out the proposed procedure a set of elastic displacement response spectra for different levels of equivalent viscous-damping coefficient, ξ, are required. These spectra are called the ***elastic design displacement spectra for the building site***. An initial estimate must be made of the structural yielding displacement, which could be based on a drift angle, and then the limit to acceptable plastic rotation of critical hinges has to be determined. Priestley claims this approach has considerable flexibility, since plastic hinge rotational capacity can be related to transverse detailing (or vice versa) and their design is not dictated by a somewhat arbitrary decision about force-reduction factors. According to Priestley (1993), it would appear that the above method of displacement-based design could also be applied to multi-story frame or shear wall buildings, provided some additional assumptions are made. The two critical pieces of information required are: (1) *the relation between maximum interstory drift and structural displacement* at the height of the center of seismic force; and (2) the shape of the lateral force vector to be applied. Although the displacement-based design approach appears attractive in principle, it will need to be checked by specific examples covering a wide range of structural types and periods.

The author believes that some of the assumptions made in the proposed displacement-based design methods that have been proposed can be seriously questioned. One of the questioned assumptions is that inelastic displacements are equal to those obtained from a linear elastic response. Because of the limitations involved (due to the assumptions made to simplify the design procedure) in applying each of the practical methods on the basis of the use of just one parameter, whether strength (as in present codes), or lateral drift, and because of the difficulties in specifying very clearly the limitations on the application of these proposed methods, the author believes that to achieve an efficient preliminary EQ-RD, there is a need to consider the following requirements simultaneously: the ***strength*** (based on rational use of μ_δ and ξ), the ***deformation*** (based on the limitation of IDI), the ***deformation rate***, and their combined effect on the ***energy capacity*** of the whole facility system. The need for a rational and transparent approach to the issue of improving EQ-RD criteria and procedures for new facilities and for upgrading existing hazardous facilities has motivated the author and his research associates to attempt to develop and apply ***conceptual comprehensive criteria and methodology for EQ-RD of structures.***

Conceptual Criteria and Methodology for EQ-RD of Buildings

As described by Bertero *et al.* (1993), a new conceptual framework for a seismic code based on the state of the art in EQ engineering has been formulated. This code framework includes "***conceptual criteria and methodology for EQ-RD.***" The methodology consists of: (1) guidelines for conceptual overall design of entire building systems; and (2) a conceptual methodology for numerical EQ-RD of building systems in compliance with the worldwide-accepted EQ-RD philosophy and based on energy concepts, fundamental principles of structural dynamics, mechanical behavior of entire building facilities, and comprehensive design. The numerical EQ-RD methodology considers the desired seismic performance of the entire building system explicitly from the beginning of the EQ-RD process, and concludes by evaluating whether such performance would be achieved. Detailed discussions of the conceptual methodology for EQ-RD are given elsewhere (Bertero *et al.*, 1993), and in a companion paper at this WCEE (Bertero, R. D., *et al.*, 1996). This methodology was also used in the "comprehensive EQ-RD approach" proposed as the most general and comprehensive approach of those included in the conceptual framework for "***performance-based seismic engineering of buildings***" recently proposed by the Vision 2000 Committee of the Structural Engineering Association of California (SEAOC, 1995). The proposed comprehensive EQ-RD approach is illustrated in the flow chart in Fig. 1. As discussed in detail in the SEAOC 1995 report, ***although the proposed approach can be applied for all kinds of structures, its main use will be for carrying out studies to develop simplified practical methods of performance-based EQ-RD of certain types of facilities, such as low-rise buildings having relatively regular structural configurations and***

systems and constructed on normal sites. This comprehensive methodology should be used to calibrate simpler practical performance-based criteria and EQ-RD approaches. Therefore, in practice, the application of this comprehensive approach will be limited to buildings with irregular configurations, structural layout or structural systems; or very tall slender building located on normal or abnormal sites. The importance of the detailed chart in Fig. 1 is that it can be used for the development of any other simplified performance-based EQ-RD approach.

NEED FOR SIMPLIFIED BUILDING CODE EQ-RD CRITERIA AND PROCEDURES

Priestley (1993) stated that, "*Given the wide range and occasional gross nature of the assumptions and approximations inherent in seismic design, we might be better keeping the design and analysis processes simple enough so that we still understand what we are doing.*" The author strongly supports Priestley's cautionary note about the tendency for increased complexity in analysis. What is needed is the development of simplified criteria and numerical EQ-RD procedures for engineered buildings which, backed up by strict code provisions regarding site conditions, load combinations, building configuration, superstructure, nonstructural components and their materials and detailing, and the foundation to be considered, can result in construction with seismic performance that complies with all the performance levels and performance design objectives envisioned in the general EQ-RD philosophy on which the comprehensive performance-based EQ-RD approach has been based.

Proposed Simple Codified Performance-Based EQ-RD Procedures. The author believes that there are two different routes to the development of simplified performance-based EQ-RD procedures that can be codified in current building codes. These two different routes are: (1) ***Use of a Deformation (Displacement) Approach***; and (2) ***Use of a Force/Strength Approach.***

Deformation or Displacement Approach. Discussion of performance-based EQ-RD and the proposed comprehensive approach leaves no doubt that performance, particularly degree of damage, of an entire building system is more a consequence of deformations than of forces, and consequently it appears logical that the design should be based on deformation (displacement or drift spectra) rather than on forces (acceleration spectra). This is how the comprehensive EQ-RD approach starts the sizing of the structure (Bertero, R. *et al.*, 1996). For cases of one-story buildings, the displacement approach proposed by Priestley is attractive. Efforts should be devoted to improving the proposed methodology, particularly the development of reliable design displacement spectra and relationships between equivalent viscous damping and displacement ductility level. Regarding the application of the proposed method to multistory buildings, as pointed out by Priestley (1993) this would need to be checked out by specific examples, covering a wide range of structural types and periods. Furthermore, attempts should be made to extend the proposed methodology to include simultaneous design for at least two performance levels.

Simplified Force/Strength Approach. Inspection of the behavior of engineered buildings during previous EQs around the world shows that there are certain types of buildings, usually low-rise buildings, that can have excellent performance under different levels of EQGMs, even if their design used a very simple force/strength numerical design approach based on just the ***static equivalent lateral force (ELF)*** and ***linear elastic analysis and design procedure***. This excellent performance has been observed when the very simple numerical design approach has been backed up by strict enforcement of very restrictive code regulations regarding the siting conditions, relative importance of the EQGMs among other excitations, and the characteristics of the entire building system. Thus, what is proposed herein is the development of a simplified numerical design procedure for engineered buildings which, backed up by strict code provisions regarding the applicability of such an approach (covering the site conditions, building configuration, superstructure, nonstructural components and their material and detailing, the foundation and the load combinations to be considered) can result in construction with seismic performances that comply with all the performance levels and performance design objectives envisioned in the general philosophy that has been formulated by the Vision 2000 Committee (SEAOC, 1995) and on which the comprehensive performance-based EQ-RD approach illustrated in Fig. 1 has been developed.

Considering that at present the simplest practical design procedure for the design of engineered buildings is based on the use of the ***linear elastic ELF*** procedure that considers just one performance level (the life safety level), it has been proposed to keep this numerical design procedure but to find out how to improve the regulations and their enforcement in the field regarding when and how such a procedure can be applied and result in construction that complies with the general philosophy of the performance-based EQ-RD and EQ-RC. A discussion of the needed simplifications and improvements is given in the SEAOC 1995 report. Herein is presented only a review of some methods of analysis that have been recommended lately for conducting the acceptability checks.

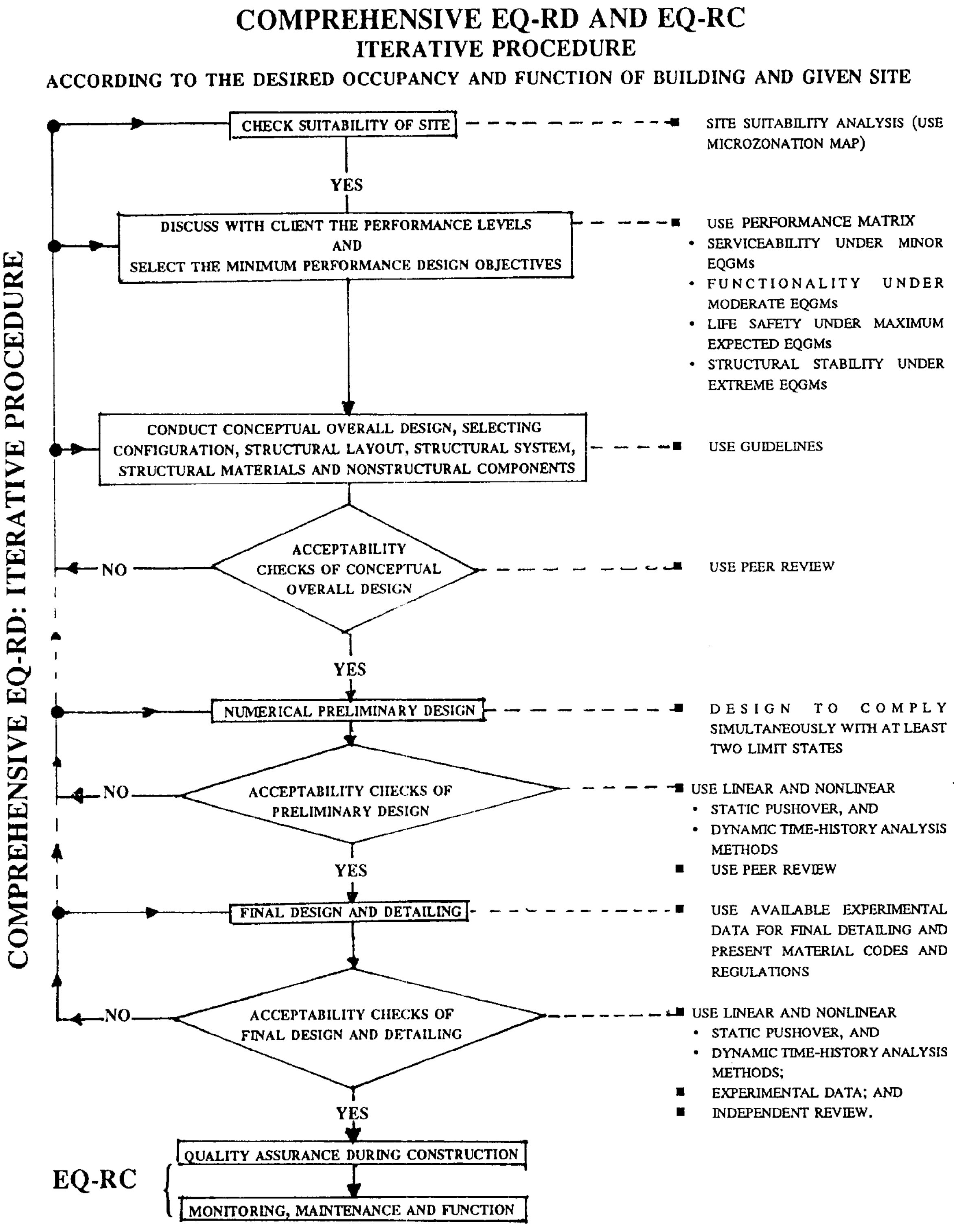

Fig. 1 Flow chart for comprehensive EQ-RD and EQ-RC

Acceptability Checks: Acceptance Criteria. The acceptability checks under the EQGMs (in combination with other loads that can act simultaneously) corresponding to *the service performance level* are straightforward because as the building should remain essentially in its linear elastic range, deformations are directly related to forces, and the principle of superposition applies. On the other hand, for the other three performance design objectives considered in the performance-based EQ-RD (Fig. 1), particularly for *the life safety and impending collapse performance levels*, considerable judgement should be employed in interpreting the results obtained using just linear elastic analyses and when these results are compared with the established values for the parameters controlling the performance (damage) at each of these performance levels.

In the ATC 33-03 project, significant efforts were devoted to the development of simplified procedures, including some empirical equations using just linear elastic analysis to determine component acceptability (Shapiro *et al.*, 1996). While the author recognizes the need for such development and applauds efforts to develop such simplified procedures, usually these simplifications use empirical equations that are based on assumptions that limit their applications to real situations. In the determination of the component acceptability, ATC 33-03 proposed that the component actions be classified as being either ***force-controlled*** or ***deformation-controlled***, which are defined as follows: ***Deformation-controlled action*** (an action for which deformation can exceed yield, and the maximum permissible deformation is limited by ductility); and ***Force-controlled action*** (an action for which force cannot exceed yield, and the maximum permissible force is limited by strength).

Recommended Procedure for Determination of Component Acceptability. ***For deformation-controlled actions*** on primary and secondary components, the demanded internal forces shall satisfy the following equations.

$$Q_G \pm Q_E \leq m\, Q_C \quad (2) \qquad \text{and} \qquad Q_G \leq Q_C \quad (3)$$

where: Q_G = internal force due to gravity forces acting on component; Q_E = component force action due to earthquake loads determined from the linear elastic structural analysis model subjected to the seismic force V; Q_C = the strength capacity of the structural component action represented by the *expected* strength at the demand deformation level; and m = a component demand modifier to account for the expected ductile response capacity of the component. The m factor represents the ratio of permissible component deformation to yield deformation. It is related to ductility and is obtained from hysteretic data from laboratory cyclic tests and engineering judgment considering Performance Levels (i.e., acceptable levels of damage).

For force-controlled actions:

$$Q_G \pm Q_{EF} \leq Q_{CF} \qquad (4)$$

where: Q_{EF} = an estimate of the maximum force that can be delivered to the component; and Q_{CF} = the strength capacity of the structural component represented by a *lower bound* strength. In order to emphasize the importance of avoiding blind application of the demands resulting from the static linear elastic pushover analysis or even from the dynamic linear elastic modal spectra response analysis, some of the unexpected and undesirable inelastic behavior (performance) that can occur is illustrated with results presented in the following discussion of a simple one-story, one-bay special moment-resistant frame.

Statement of Problem. Consider a MRF building on a site in ***a region of low seismicity and very heavy environmental gravity loads (Live and Snow)***. Assume that: (1) the columns are very strong and stiff compared to the strength and stiffness of the beam, but that the flexibility of the columns is enough to allow that the moment diagram under the gravity loads, P_G, to be the same as the one shown in Fig. 2a, i.e., the moments at the ends of the girder (i.e., at B and D) when compared to the plastic moment capacity, M_P, of the girder are:

$$|(M_B)|_G = |(M_D)|_G = \frac{1}{2}|M_p| \qquad (5)$$

and the moment at midspan of the girder, i.e., at M $(M_M)_G$ is

$$|(M_M)_G| = \frac{3}{2}|(M_B)_G| = \frac{3}{2}|(M_D)_G| = \frac{3}{4}|M_p| \qquad (6)$$

The moments induced by the statically equivalent seismic lateral force, $(V_E)_{el}$ are those shown in Fig. 2b, i.e.,

$$|(M_B)_E| = |(M_D)_E| = \frac{3}{2}|M_P| \qquad (7)$$

From examination of the linear elastic analyses of the MRF under P_G and $(V_E)_{el}$ shown in Figs. 2a and 2b, respectively, and their superimposed effects, shown in Fig. 2c, it is clear that the critical section of the girder appears to be either the end D or the end B, depending on the selected direction of the $(V_E)_{el}$. For the direction adopted in the plots of Fig. 2, the critical section is D, and a check of the deformations at this section, blindly applying Eqs. 2 and 3, leads to the following results.

Eq. 2 requires that:

$$(M_D)_G + (M_D)_E \leq m\,(M_D)_C \qquad (8)$$

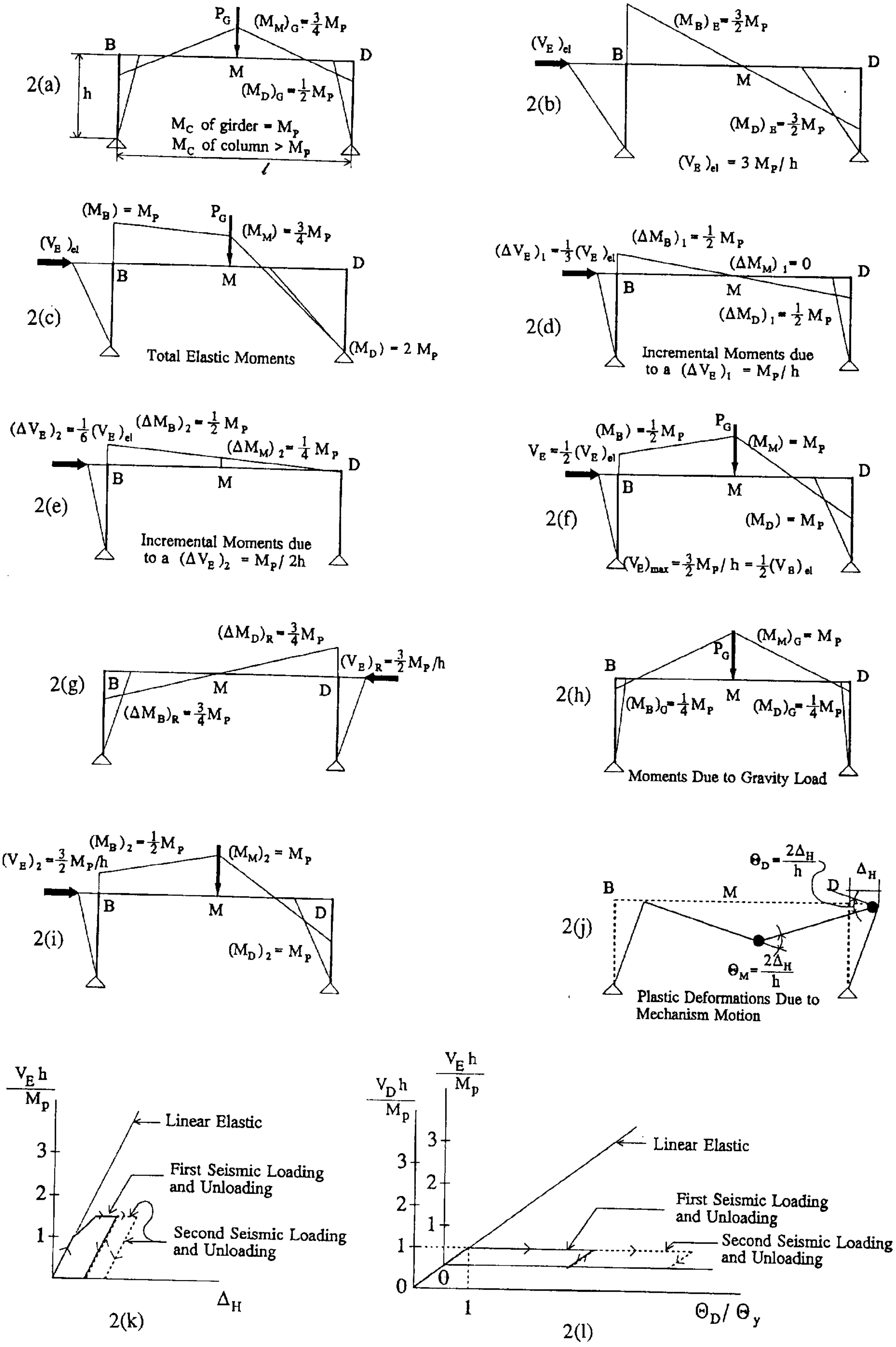

Fig. 2 Linear elastic vs. elastic/plastic demands for a MRF

Using the above values and assuming $m = 2$: $\frac{1}{2}M_P + \frac{3}{2}M_P = 2M_P$ **(9)**

I.e., Eq. 2 is satisfied. Eq. 3 requires that: $(M_D)_G \leq (M_D)_C$ **(10)**

As: $(M_D)_G = \frac{3}{4}M_P$ and $(M_D)_C = M_P$ **(11)** $\therefore \frac{3}{4}M_P < M_P$ **(12)**

Thus Eq. 3 is also satisfied. Therefore, it can be concluded that the existing MRF is adequate to resist the estimated effects of the EQGMs.

Fallacy of the Conclusions That Have Been Drawn. The fallaciousness of the above conclusions from linear elastic analysis can be demonstrated by estimating the expected inelastic behavior of the MRF when subjected to the given P_G and the expected V_E.

■ ***Nonlinear (Inelastic) Behavior.*** For the sake of simplicity, consider that the moment rotation (M vs. θ) relationships for the critical regions of the MRF are linear-elastic/perfectly-plastic. Then it is clear that as soon as the gravity load MRF is subjected to the effects of the EQGMs (Fig. 2b), the moment at D will increase and reach the M_p capacity of this section D, when $(\Delta V_E)_1 = (1/3)(V_E)_{el}$, as can be seen by adding the moments of the diagrams shown in Fig. 2a and 2d. After this, a plastic hinge (PH) will be developed at the end of the girder. Because of the development of this plastic hinge (PH) at D, the moments induced by an increased $(\Delta V_E)_2$ due to the EQGM excitation will be those shown in Fig. 2e. Thus, in this case it appears that as soon as $(V_E) > (1/3)(V_E)_{el}$ the lateral stiffness of the MRF when subjected to the EQ lateral force will be significantly smaller than that of the original linear elastic MRF and for which the expected linear elastic lateral deformations and consequently the inelastic deformations have been estimated.

The Moment Diagrams shown in Figs. 2a, 2d and 2e show that the maximum lateral EQ resistance, i.e.. $(V_E)_{max}$, is controlled by the formation of a new PH at M and which led to the formation of a type of sidesway mechanism with PHs at D and M that could not have been anticipated just from the linear elastic analysis. ***The linear elastic analysis does not give any hint that a PH can be developed at the midspan of the girder, and consequently no need for special detailing for ductility of the girder at this section would have been required.*** The resulting $(V_E)_{max}$ as given in Fig. 2f is shown to be equal to half of the equivalent linear elastic base shear that was estimated using the ATC guidelines (Shapiro *et al*., 1996). Other important observations regarding the danger of blind use of the results obtained just from linear elastic analyses for judging the expected nonlinear (inelastic) behavior can be drawn by analyzing ***what could happen after the effects of the first severe EQGMs cease and then the MRF is subjected to any one of the following new loading conditions: (a) An increase in gravity load; (b) A new impulsive EQGM inducing deformations and therefore a V_E in the same direction as the original pulse; and (c) A reversal of EQGM, and consequently a reversal of the V_E.***

Earthquake Unloading of the MRF. If the EQGM is just a pulse represented by the statically equivalent lateral force, $(V_E)_{max}$, when this EQGM ceases the MRF will unload and during this unloading will respond with a linear elastic behavior. The changes in the moments throughout the frame are illustrated in Fig. 2g, and the final moment diagram under gravity alone is illustrated in Fig. 2h. Analysis of this moment diagram shows that the critical section of the beam under gravity load alone is at M, i.e., at the midspan of the girder, rather than at the ends of the girders. This change in the moment diagram indicates that the girder will end with an increase in its vertical deflection at the center. Furthermore, because the moment at M is equal to the plastic moment capacity, M_p , of the girder, a small increase in gravity load can induce significant plastic deformations at this midspan region of the girder, which could not be predicted using just linear elastic analysis as is discussed below in some detail.

(a) An increase in gravity loads. *Can this realistically be expected?* Yes, it can if one uses the load combinations in the NEHRP (1994) recommendations (which are based on probabilistic studies). From analysis of the moment diagram shown in Fig. 2h, it is clear that any increase in P_G will lead to the development of a PH at section M, i.e., at the center of the girder span, ***with an extra significant increase in the vertical deflection, which is very undesirable and would not have been suspected from the linear elastic analysis alone.***

(b) A new impulsive EQGM inducing deformations and therefore a V_E in the same direction as the original pulse. In this case, the MRF will behave linear-elastically, with a lateral stiffness equal to the original linear elastic stiffness and the change in moments are given in Fig. 2i. When the V_E reaches a value of

$(V_E)_2 = (3/2)(M_p/h)$, the moment at D reaches again its plastic capacity, M_p, and therefore a PH will be developed at this section and the MRF cannot resist any extra significant lateral resistance under the V_E in this direction because an extra PH will also develop at M and a sidesway mechanism, as shown in Fig. 2j, is formed. Due to this mechanism, significant inelastic (plastic) rotations will be developed at sections D and M, as is illustrated in Fig. 2j. It should be noted that for any given mechanism lateral deformation, the corresponding mechanism rotations will be twice those that would have been developed if the PHs had developed at the ends of the girder. Thus, significant plastic rotations will accumulate at D (Fig. 2l), as well as at M with the application of a new EQGM pulse having the same direction and also significant increase in lateral deformation, Δ_H, will take place as illustrated in Fig. 2k. This performance cannot be predicted using just linear elastic analysis; nor, therefore, with Eq. 2.

(c) A reversal EQGM and consequent reversal of V_E. In this scenario, once again the MRF will perform in its linear elastic range with a lateral stiffness equal to that of the original MRF until the moment at B reaches its plastic moment capacity, M_p, which will occur under a $(V_E)_2 = (3/2)(M_p/h)$. This $(V_E)_2$ is also the maximum seismic lateral resistance for the MRF under this reversal of seismic loading, and the frame will start deforming as a sway mechanism with large plastic rotations at sections B and M.

The above results and discussion make it clear that under a time-history EQGM containing several severe acceleration pulses capable of demanding the inelastic (plastic) behavior of the frame, there will be a severe accumulation of plastic rotations, particularly at the midspan of the girder, i.e., at section M, ***which linear elastic analysis alone would not be able to predict.***

NEED FOR THE DEVELOPMENT OF EQ-RD PROCEDURES AND FORMATS BASED ON MULTI-LEVEL PROBABILISTIC STRUCTURAL PERFORMANCE CRITERIA

As discussed in the Introduction, it has long been recognized by practitioners and researchers that there is large variability in the type and degree of seismic hazards (particularly EQGMs) that can develop during an EQ, as well as in the response of entire facility systems to these hazards. The variability of the response of the entire facility system is due to the variability of mechanical characteristics of these systems. In spite of this awareness, these variabilities are not fully accounted for in current EQ-RD code procedures. Thus, it is not surprising that since the 1989 Loma Prieta and the 1994 Northridge EQs, a strong sentiment has developed among researchers and practitioners that there is a need to develop EQ-RD formats with explicit treatment of the variables and uncertainties. Based on this need, Wen (1995) evaluated the reliability of current code provisions and developed and calibrated reliability design procedures. Furthermore, he proposed a bi-level reliability and performance-based design procedure in which satisfactory performance of the building is enforced at both the serviceability and life safety levels.

Wood *et al.* (1995) proposed and applied a dual-level design procedure in which a building structure is designed for both an ultimate and a serviceability level force. This procedure is applied to the design of a seven-story RC MRF, which is also designed according to the 1991 NEHRP provisions. The reliability of the two designs at different response levels is evaluated. The dual-level design procedure resulted in better drift and damage control for severe EQGMs. Collins *et al.* (1995) developed a reliability-based dual-level seismic design procedure to address some of the shortcomings of current seismic design procedures. The proposed procedure attempts to enable designers to achieve code-specified target performance objectives for moderate and severe EQGMs. Although the procedure is more complicated than current ones, it should help designers to appreciate the consequences of various design assumptions and to identify critical regions of the structure that require careful design and detailing. The procedure was developed for steel building structures, but it should be applicable (appropriately modified) to other types of building structures as well. The procedure requires the designer to consider two levels of EQGMs. An equivalent system methodology and uniform hazard spectra are used to evaluate the performance of building structures. Performance is quantified in terms of the probability of exceeding displacement-based limit state criteria.

CONCLUSIONS AND RECOMMENDATIONS

In formulating the main conclusions of the discussion of the state of the art in EQ-RD criteria, as well as in formulating recommendations for improving it, it is convenient to distinguish the following two different purposes for establishing such criteria: one includes the design of very important and/or complex structures, as well as investigations in the search for reliable and simplified EQ-RD that can be codified; and the other purpose is to provide, in an unambiguous and simplified form, reliable rules and guidelines that the average designer can use in practice, i.e., that can be codified.

Conclusions. In the state of the art in the EQ-RD criteria for conducting research or for the practical design of important and complex structures, significant progress has been made in the last five years in the development of EQ-RD procedures that follow the sophisticated EQ-RD criteria that were discussed and proposed in the 1970s and 1980s. The main accomplishments have been: (1) the development of the ***conceptual framework for performance-based seismic engineering whose performance design objective matrix is based on multi-level design EQGMs and performance levels design criteria***; (2) the development of a ***comprehensive EQ-RD approach*** whose preliminary design phase is based on satisfying simultaneously the requirements for at least two performance design objective levels and attempting to produce optimum building structures using energy concepts; and (3) the development of a ***reliability-based dual-level seismic design procedure*** that uses uniform hazard spectra and an equivalent SDOF system to account for the variability and uncertainties in the EQGMs and inelastic response of the structures.

In the state of the art in the EQ-RD criteria that can be codified for use in practice by average designers, although code format, at least in the U.S., has not changed significantly in the 1980s and 1990s, there have been some attractive proposals for improvement such as: (1) the Department of Energy (DOE) guidelines (Kennedy *et al.*, 1994), which specify building performance goals in terms of probability of exceedance of some measure of damage; (2) attractive displacement-based EQ-RD approaches; and (3) simple codified EQ-RD procedures based on application of elastic ELF.

Recommendations. Many unresolved problems need to be addressed before the recently developed EQ-RD criteria and approaches can be implemented in practice, which is what is needed to reduce in the short run the seismic risk in our urban and rural areas. Recommendations for research, development and implementation of the EQ-RD criteria involved in performance-based EQ-RD are given by the SEAOC Vision 2000 Committee (SEAOC, 1995). Suggestions and recommendations for future research for improving the basic framework for reliability-based dual seismic design procedures are given by Collins *et al.* (1995), Elwood *et al.* (1995) and Wen (1995). Because of length restrictions on this paper, the reader is referred to these publications.

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