APPRECIATION

It is an immense pleasure for the senior author to be able to participate in this international symposium to honor the 70th birthday of Prof. Tom Paulay. He met Prof. Paulay for the first time in 1969 at the Fourth World Conference on Earthquake Engineering in Santiago, Chile, where Prof. Paulay presented a paper on "the Coupling of Reinforced Concrete Shear Walls." Since that opportunity, the senior author has been following Prof. Paulay's publications very closely and has had not only the pleasure of listening to many of his inspiring presentations of papers and lectures on earthquake-resistant design of RC structural walls and RC ductile frames, but also the privilege of having valuable personal discussions in these important areas of earthquake-resistant construction. Professor Paulay has been the leading researcher in these areas and his work has opened the way to improving the design procedure, construction details and building codes around the world. In congratulations, we wish him the very best in his future activities.

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INTRODUCTION

A recent statistical study [1] shows that seismic risks in our urban areas are increasing with the years. Most human and economic losses due to moderate and severe EQ Ground Motions (EQGMs) are caused by the failures of human-made facilities, which presumably are designed and constructed to protect their occupants against expected natural hazards. In practice, the design and construction of any facility located in a region of seismic risk follows code design procedures and regulations. Analysis shows that current seismic code design methodologies fail to realize the goals and objectives of the worldwide-accepted philosophy of Earthquake-Resistant Design (EQ-RD). Also, present seismic codes are not transparent, i.e., their regulations do not present in a visible way the basic concepts that govern EQ performance of structures. Thus, there is a need to improve EQ-RD by identifying the basic problems created by EQs and finding out how these problems can be solved and how the solutions can be codified in a transparent way. From analysis of the various approaches and methodologies suggested for such an improvement, it has been concluded that in the end the best solution is a new transparent format for seismic codes, covering in logical sequence all aspects that a seismic code should regulate, whose regulations will invoke basic concepts rather than empirical rules. For reliable application of these regulations in practice, the code regulations must remain simple and in accordance with the education in EQ Engineering of the practitioners. Therefore a three-step approach is proposed for the final formulation of the simple seismic code regulations.

First Step -- Based on the state of the art in EQ Engineering, a *conceptual seismic code* should be developed, covering all aspects that a seismic code should regulate. Given the different groups of aspects and problems involved in EQ-RD and EQ-RC [1, 2], the conceptual seismic code will consist of regulations that can be grouped as follows.

Group 1. *Guidelines for assessing seismic activity and sources of potential seismic hazards (damage); restrictions for land use and guidelines for the selection of building sites and corresponding siting restrictions; and procedures for site suitability analysis.*

Group 2. *For a selected site and function of a building, conceptual establishment of the EQ-RD criteria, design EQGMs, and design methodology.*

Group 3. *Conceptual overall design of the entire building system, covering restrictions and/or guidelines regarding: selection of building configuration or form (size and shape), foundation, structural layout, structural system, structural materials, and nonstructural components (potential unintentional structural components) and their materials.*

Group 4. *Conceptual preliminary numerical design of the whole facility system, which requires prediction of the mechanical behavior of such a system and involves: proper modelling of the entire system; estimation of the demand on the structure and its contents (structural and stress analysis) at the different levels of design EQGMs; preliminary sizing and detailing through estimation of the capacities to be supplied to the structure.*

Group 5. *Reliable analysis of the performance of the preliminarily designed facility when subjected to the expected critical EQGMs at each of the limit states contemplated in the design criteria.*

Group 6. *Final design (detailing).*

Group 7. *Monitoring of field construction, function (use) and maintenance (alterations, repair, and/or upgrading) of the constructed structure.*

Group 8. *Conceptual methodology for the upgrading of hazardous facilities.*

<u>Second Step</u> -- The conceptual code regulations will be applied to the design of building facilities with different regular and irregular configurations, structural layouts and structural systems, and to the upgrading of different types of existing hazardous facilities. In order to judge current or modern code procedures, the deigned buildings will preferably be selected from among those that have been designed and constructed according to current or modern seismic codes and have available records or predictions of the response to EQGMs, and the existing hazardous facilities preferably will be selected from among those that have been recently upgraded.

<u>Third Step</u> -- From analysis of the results obtained in the second step, a simplified conceptual code that can be applied properly by the practitioners should be developed. It should state clearly all restrictions in siting and in selection of configuration (or form), foundation systems and structural systems for which such simplified code regulations could be used. For complex buildings, a peer review process should be required in which the conceptual code to be developed in the first step could be used.

Importance and Advantages of Formulating a Conceptual Seismic Code.

The importance and advantages of developing conceptual seismic code provisions are discussed in Refs. 1-3. The importance of a conceptual "overall design" (i.e., an overall conception of the configuration or form of a building and its foundation; and selection of the structural layout, structural systems and material and nonstructural components that could become unintentional structural components) is discussed in detail in Refs. 4-8. The importance of formulating a conceptual methodology for numerical preliminary EQ-RD of structures based on well-established fundamental principles of structural dynamics, mechanical behavior of the entire facility system and comprehensive design, and in compliance with the worldwide-accepted EQ-RC philosophy, is discussed in Refs. 1-3. Its main advantages are: (1) it leads to a transparent numerical design procedure that considers and checks the selected or desired performance objectives; and (2) in spite of the great uncertainties in the quantification of some of the concepts involved in its codification, such quantifications can be improved as new or more reliable data become available without changing the philosophy and particularly the format of this codified methodology. Another important advantage is that such a formulation can be used as a basis for improving the education of architects and engineers, as well as for the establishment of the much-needed prioritization and program of the focussed research needed to improve EQ-RC.

Objectives and Scope of Paper.

The main objective of this paper is to summarize the development of a "conceptual seismic code," with particular emphasis on a framework for what can be called a ***conceptual methodology for numerical EQ-RD***. The basic ideas of the proposed conceptual methodology and some of the main observations and results obtained in its application to a 30-story RC frame building are presented. These results are compared to results obtained in the analysis of the performance of the same building designed according to the 1991 UBC. Main conclusions and recommendations for research needed to improve the quantification of the developed conceptual methodology are offered.

FORMULATION OF A CONCEPTUAL METHODOLOGY FOR THE EQ-RD OF BUILDING STRUCTURES

Among the different groups of aspects or problems that the conceptual seismic code should regulate, as listed in the introduction, the following groups must be considered in order to formulate a conceptual methodology and the corresponding code provisions for the EQ-RD of a building facility.

Group 2. *(a) Conceptual establishment of the design criteria according to the desired function (occupancy) or performance of the building. (b) According to the selected site, conceptual establishment of the design EQGMs, as well as any other*

source of potential hazard that needs to be considered in the design. (c) Selection of the design method.
Group 3. *Conceptual overall design (conception) of the entire building system.*
Group 4. *Conceptual preliminary numerical design of the whole facility system.*
Group 5. *Reliable analysis of the performance of the preliminarily designed building when subjected to the established critical EQGMs.*
Group 6. *Final design (detailing).*

All of the above groups, with the exception of **Group 3**, can be considered under the umbrella of ***conceptual methodology for numerical EQ-RD***. Therefore, the conceptual methodology for EQ-RD can be considered to consist of two main parts: *the conceptual overall design (conception) of the facility system*; and *the conceptual methodology for numerical EQ-RD*. Although these two main parts are discussed separately below, they are actually intimately interrelated.

Conceptual Overall Design.

Conceptual overall design is the avoidance or minimization of problems created by effects of seismic excitations, using understanding of behavior rather than numerical computations [7].

Conceptual overall design of the facility system involves not only the choice of overall shape and size of the building, but also the selection of the structural layout, the structural system, the structural material, type of nonstructural components (particularly those that could become unintentional structural components), and the foundation system. Both the architect and the engineer have to understand how design decisions regarding building layout may have serious seismic effects on the structure. The inertial forces depend on the mass (amount and distribution), the damping, and the structural characteristics (stiffness, yielding strength, maximum strength and energy absorption and energy dissipation capacities). In 1979, Arnold [6] reported that 65% to 80% of buildings designed within the last 15 years were of irregular form. This percentage does not agree with the conceptual basis upon which the UBC specifications were then based. Although there is no universal ideal building configuration, certain basic principles of EQ-RD can be used as guidelines to select adequate building and structural configuration [4-8].

CONCEPTUAL METHODOLOGY FOR NUMERICAL EQ-RD

The conceptual methodology for numerical EQ-RD of new structures covers problem groups 2 and 4-6. A detailed discussion of the conceptual methodology, which is based on energy concepts, and its solution of the problems in group 2 and some of the problems in groups 4-6, is offered in Refs. 3 and 9. In the following formulation of the problem of EQ-RD of building structures, it is assumed that the conceptual overall design part of the overall EQ-RD (group 3) has already been solved [9].

GIVEN: • Function of building; site of building; and general configuration of building (structural layout, structural system, structural material and nonstructural components and their materials).
REQUIRED: • An efficient (optimum) EQ-RD of the building.
SOLUTION: • A technically efficient and economical solution requires an iterative procedure, starting with an efficient preliminary EQ-RD and ending with a final design.

The procedure for achieving efficient EQ-RD of a structure should be rational, transparent and reliable. It is convenient to divide the preliminary EQ-RD procedures into two main phases: *the establishment of design EQs (design EQGMs)* and the *design procedure* for the building against them (Fig. 1).

First Phase: Establishment of Design EQGMs.

This phase covers acquisition and processing of data for establishment of design EQGMs (Figs. 1 and 2).

Acquisition of Data -- The needed data and the problems involved in acquiring them can be summarized as follows.

GIVEN: • The site of the building (soil profile and topography).
REQUIRED: • Return periods of different levels of possible EQGMs at the site and their damage potential to the entire building system for at least its service and safety limit states.
SOLUTION: • Conduct a reliable analysis of the site; identify all of the sources of EQGMs that could affect the building; define the seismic activity at the site due to all possible EQ sources in the form of time histories and recurrence periods (T_r) of EQGMs; select T_r for at least two limit states of EQGMs considered in the general philosophy of EQ-RD (the service or functional level and the safety level).

Ideally, acquisition of the needed data should be based on EQGM records from the site. If there are not enough records, the data can be obtained either from EQGMs recorded at sites with similar soil profile and topography, or by using numerical synthesis [10] to generate several probable EQGM time histories.

Processing of Data -- In this key step, the available data about probable future EQGMs at the site are processed to facilitate reliable selection of the design EQs. Conceptually, a design EQ should be ***the critical EQGM*** for the limit state under consideration, i.e., the EQGM that drives the structure to its critical (maximum) response for the failure stage under study. However, the application of this simple concept in practice meets with serious difficulties, and it has been shown that the reliability of the design EQs recommended by current seismic codes is highly questionable. According to recent studies [1-3, 9, 11, 12], the problems involved in this step, and their solutions, can be summarized as follows.

GIVEN: • Time histories of probable EQGMs for at least service and safety limit states.
REQUIRED: • *For serviceability limit state:* Smoothed Linear Elastic Design Response Spectra (SLEDRS) for strength (C_s) and displacement (S_d) for different damping (ξ). • *For safety limit state:* the SLEDRS and Smoothed Inelastic Design Response Spectra (SIDRS) (for different values of the displacement ductility ratio, μ, and ξ) for C_s and S_d, and for the parameters needed for evaluation of the cumulative damage caused by cyclic load reversals [input energy (E_I), damping energy (E_ξ), plastic hysteretic energy ($E_{H\mu}$), cumulative ductility ratio (μ_a), Number of Yielding Reversals (NYR), and Number of Equivalent Yielding Cycles at μ_{max} (NEYCμ_{max})].
SOLUTION: • Computation of the Linear Elastic Response Spectra (LERS) and the Inelastic Response Spectra (IRS) (for different values of μ and ξ) for C_s and S_d for each possible EQGM that can be generated at the site from the EQ sources. From statistical studies of LERS and IRS find SLEDRS and SIDRS. In smoothing the LERS and IRS, close consideration should be given to the standard deviation, σ, as well as to uncertainties in the estimation of the dynamic characteristics of future EQGMs and of the entire building system. To obtain the critical EQGMs to be considered for safety level, where some damage is tolerated (i.e., μ>1), it is necessary to compute for each EQGM the following spectra: E_I, E_ξ, $E_{H\mu}$, μ_a, NYR, and NEYCμ_{max}, and hysteretic behavior history. Selection of critical EQGMs can be simplified using recently proposed damage indices and by introduction of the γ factor, as discussed in Refs. 3, 9 and 13.

In current practice, design for the safety limit state is done on the basis of only strength, C_s, Smoothed Inelastic Design Spectra (SIDS) and in some cases a displacement, S_d, SIDS derived directly from the C_s SIDS. As these spectra do not reflect the effect of the duration of the strong motions on inelastic demands (E_I, E_ξ, and particularly $E_{H\mu}$, μ_a, NYR and NEYCμ_{max}), which can have significant effects on the damage potential of an EQGM, it is necessary to compute the spectra of these new parameters or to use the simplifications discussed in Refs. 2, 3 and 9.

Second Phase: Design Procedure.

This second phase of the proposed conceptual methodology for numerical EQ-RD is devoted to the design (sizing and detailing of the members and their connections and supports) of the entire building system against the critical combinations of the established design EQs with other excitations that can act simultaneously on the building according to its location and site. As illustrated in Fig. 1, in order to arrive at the desired final design it is necessary to start with a preliminary design procedure.

Preliminary Design Procedure -- The main objective of this phase is a design which is as close as possible to the desired final design. As illustrated in Fig. 1, the preliminary design phase consists of three main steps: (i) preliminary analysis, (ii) preliminary design, and (iii) analysis of preliminary design.

1. Preliminary Analysis. The objective of this first group of steps is to establish the design criteria and estimate the acceptable maximum fundamental period (T) and the design forces (critical combinations among all of the forces that can be induced). In the conceptual methodology, preliminary analysis of the design problem can be formulated as follows.

GIVEN: • Function of building; • general configuration of the building, structural layout, structural system, structural materials and nonstructural components and contents; • gravity, wind, snow and other possible loads or excitations; and • SLEDRS and SIDRS for expected service and safety EQGMs. The SIDRS should be based on the selected acceptable value of the damage index (alternatively, the spectra of the γ factor must be given [3, 9, 13]).
REQUIRED: • Establishment of the design criteria, the minimum stiffness (or maximum T) capable of controlling the damage (maximum deformation and deformation rates of the building), the design seismic forces, and the critical load combinations.
SOLUTION: • Based on a transparent approach that takes into account from the beginning that: the structure is a Multi-Degree-of-Freedom System (MDOFS); there can be important torsional effects even under service EQGMs (i.e., in the linear elastic response) and that for safety EQGMs these effects can be different; and it is necessary to consider the desired value of the damage index (control of damage) for selecting the appropriate μ that can be used, as well as the expected overstrength.

Figure 3 shows a flow chart of the steps involved in the preliminary analysis for estimating the design seismic forces. Note that although the main purpose of this step is analysis of the problem (i.e., what is given, what is known, and what is needed), it is clear that preliminary design of member sizes is in fact necessary in order to control the maximum deformation and deformation rates and to obtain the T_1 to be used for estimating the design forces.

2. Preliminary Design. This step (assuming that preliminary sizing for stiffness was done in the preliminary analysis) can be stated as follows for a RC building:

GIVEN: • Gravity, wind, snow and seismic design loads for service and safety limit states; critical load combinations; and mechanical characteristics of the structural and nonstructural materials.
REQUIRED: • Preliminary sizing and detailing of both the structural elements

[beam and columns sizes and their flexural reinforcement (in the case of moment-resisting space frames)], and the unintentional structural (sometimes called nonstructural) components, which can affect the seismic response of the building.
SOLUTION: • Based on an application of linear optimization theory, the design of beams and columns in each story minimizes the volume of flexural reinforcement (in the case of RC), using practical requirements and service forces and moments as constraints so that the preliminary design simultaneously considers the demands for serviceability and safety.

3. Analysis of Preliminary Design.
GIVEN: • General configuration of building, structural layout, structural system, structural material and its mechanical characteristics, and nonstructural components and their materials and mechanical characteristics; • sizes and reinforcement of intentional and unintentional structural components; and • design EQs, critical load combinations and possible critical EQGMs for service and safety limit states.
REQUIRED: • Determine the acceptability of the preliminary design, i.e., check if it satisfies the desired performance according to the established design criteria.
SOLUTION: • Check interstory drift index (IDI); floor velocity and acceleration; stress-ratios; axial, flexural, and shear stresses in members and joints; adequacy of foundation; and local damage index (DMI) under critical EQGMs at each limit state using static and dynamic load analyses.

Because of the importance of an efficient preliminary EQ-RD that is as close as possible to the desired final design, a discussion of the main aspects and problems involved in the preliminary design procedure is presented below.

Discussion of 1. Preliminary Analysis. One of the most important data for attaining a reliable numerical design is the reliable quantification of the excitations against which the structure is to be designed. Thus, proper selection of the design EQs is an important and very difficult task in efficient preliminary EQ-RD of a structure. As summarized above under "Establishment of Design EQs" and discussed in detail in Refs. 3 and 9, it is necessary to compute a series of spectra. At present most of these spectra are computed just for SDOFS, but because a real building generally is a MDOFS, it is necessary to modify the obtained SDOFS spectra.

Modifications of SDOFS Spectra to Account for MDOFS -- In selecting the design global displacement ductility ratio, $\mu_g = \mu_{SDOF}$, to be used to find the SIDRS for the design of the equivalent SDOFS, it must be considered that for an MDOFS the demanded story ductility ratio, μ_s, will not usually be uniform along the height of the structure, i.e., there will always be a story whose μ_s will be larger than the global μ_g. Therefore, the μ_g selected for the design of the SDOFS equivalent to the MDOFS should be somewhat smaller than that selected for the design of a real SDOFS. The taller the building and the larger the structural irregularities along its height, the smaller this equivalent μ_g should be [14]. As indicated in Fig. 3, the SIDRS developed for the SDOFS considering a μ_g modified to consider that the real structure is a MDOFS still needs some additional modifications, depending on the type of design to be conducted and the possible effects of torsion. These modifications, which are discussed below, are needed to obtain a preliminary design as close as possible to the desired final design.

Modifications of the SIDRS to Account for Design Method -- Because in EQ-RD the critical regions of the members, and therefore the members themselves, are usually provided with a larger strength than is required, and particularly because critical regions are usually provided with a large local μ, μ_l, elastic design methods usually result in buildings with strength higher than their design strength, resulting in designed and usually constructed structures with significant lateral overstrength over code-required strength. This overstrength varies with the fundamental period, T_1, of the structure. The taller the building (the larger the T_1) and the fewer structural bays, the smaller the overstrength will be. It should be noted that if the designer tailors the main reinforcement so that all of the critical regions of each of the members reach their demanded strength simultaneously, the resulting structure's overstrength will be reduced. Thus it is not only difficult, but even dangerous, to attempt to codify just one constant value for such overstrength. Similarly, if the designer uses the ACI code [15] strength method with the redistribution due to plastic deformation allowed by this code, the overstrength will also be reduced. Use of an inelastic design method that accounts for plastic redistribution of the internal forces that are demanded elastically from the structure will result in a decrease in overstrength. However, the degree of decrease depends on how the design is conducted. For a design based on an optimization, such as that suggested in Ref. 9, the overstrength will be reduced to a minimum, but can still be significant. The actual dynamic overstrength during the dynamic response to recorded EQGMs is even higher than that estimated under equivalent static load (pushover test) [16].

In specifying the possible reduction in the ordinates of the SIDRS for C_s due to overstrength, it is necessary to consider both the possible overstrength and its effect on maximum IDI. An increase in IDI beyond the acceptable limit can control the reduction. Thus, the final design will generally have a maximum yielding strength larger than that required by the adopted yielding strength spectra, C_s, and therefore the response ordinates of such SIDRS can be reduced by a factor R_{OVS}. *The problem is, how much can the value of R_{OVS} be*? Because this value depends on many variables (design method, dynamic effects, T_1 and T_1/T_i, etc.), at present its selection requires seasoned judgement and should be done conservatively, until needed research produces the calibration data for its proper selection. Detailed discussion of potential overstrength sources is given in Refs. 9, 14 and 17.

Modifications due to Torsional Effects -- Because of torsion, the demanded strength and IDI at certain parts of the structure increase over those required by just translational deformation. The larger the eccentricity between the center of rigidity and the center of mass, the larger the torsional effects. These effects differ under service and safety EQGMs. At the safety level involving inelastic behavior, they can increase significantly, depending on the initial location of the center of torsional resistance and how this center and the resulting yielding resistance eccentricity are