Nonlinear Seismic Analysis and Design of Reinforced Concrete Buildings

Edited by

Peter Fajfar and Helmut Krawinkler

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NONLINEAR SEISMIC ANALYSIS AND DESIGN OF REINFORCED CONCRETE BUILDINGS

This volume consists of papers presented at the Workshop on Nonlinear Seismic Analysis of Reinforced Concrete Buildings, Bled, Slovenia, Yugoslavia, 13-16 July 1992.

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PREFACE

This monograph is a compendium of invited papers that focus on the following two topics of much relevance to the seismic protection of reinforced concrete structures:

(a) Energy concepts and damage models in seismic analysis and design
(b) Analysis and seismic behavior of buildings with structural walls.

The papers are intended to set the stage for an assessment of the state-of-the-knowledge and the identification of future research and implementation needs on these two topics. They form the basis for discussions to take place at a workshop scheduled for summer 1992 and for recommendations to be developed and communicated to the research and design communities in a follow-up publication. It is hoped that both this monograph and the workshop will make a contribution to the achievement of the aims of the International Decade for Natural Disaster Reduction (IDNDR).

The two topics were selected because of their importance in seismic design and the need for an evaluation and dissemination of recent advances in these areas. It has long been recognized that energy input, absorption, and dissipation are the most fundamental quantities controlling seismic performance. Already in late fifties G.W. Housner proposed "a limit design type of analysis to ensure that there was sufficient energy-absorbing capacity to give an adequate factor of safety against collapse in the event of extremely strong ground motion". In 1960 John A. Blume, in his classical paper on the Reserve Energy Technique (2WCEE), states that "with the procedures outlined, the anomalies of a great deal of apparently baffling earthquake history can be explained as can the gap between elastic spectral data and the capacity to resist earthquakes". However, to this day, energy concepts have been ignored in earthquake resistant design because of apparent complexities in the quantification of energy demands and capacities and their implementation in the design process. The papers presented in the first part of this monograph illustrate how energy terms together with cumulative damage models can be utilized to provide quantitative information useful for damage assessment and design. It is hoped that a study of these papers leaves the reader with the impression that energy-based design is a viable concept, but it is also recognized that much more work needs to be done in order to simplify energy-based design to a level that makes it useful for design practice.

In many countries extensive use is made of structural walls (shear walls) to increase the strength and stiffness of lateral load resisting systems. Recent earthquakes have often indicated better performance of multistory buildings containing structural walls compared to buildings whose structural system consists of frames alone. Clearly, this observation cannot be generalized since seismic performance is affected greatly by wall layout, strength, and detailing, as well as by the primary deformation mode (bending versus shear). Although the great importance of walls in seismic performance has long been recognized, mathematical modeling of the nonlinear static and dynamic response of structures containing walls is only in the development stage. The second part of this monograph addresses important design and modeling problems for structural walls and buildings that rely on the participation of walls in seismic resistance. The papers illustrate the complexity of the problems but also propose solution techniques intended to contribute to a more accurate prediction of the seismic behavior of buildings containing structural walls.

This monograph discusses selected issues of importance in the seismic design of reinforced concrete buildings. It lays no claim to providing final solutions to any of the problems investigated and probably raises more questions than it answers. Its purpose is to form a basis for discussion on the state-of-the-knowledge and research and implementation needs. Readers are encouraged to communicate their comments to the authors or the co-editors for consideration at the workshop for which these papers were written and which is scheduled for July 1992.

We are deeply indebted to the authors who have written original and thoughtful contributions to this monograph and have made commitments to participate in an international workshop in Bled near Ljubljana. This workshop was scheduled originally for June 1991 but has been postponed until summer of 1992. We are also much indebted to Elsevier Science Publishers Ltd who have generously agreed to make these publications available to the interested readers in a timely manner.

Sponsorship for the workshop for which these papers were written is provided by the U.S.-Yugoslav Joint Fund for Scientific and Technical Cooperation in conjunction with the U.S. National Science Foundation, the U.S. National Institute of Standards and Technology, the Ministry for Science and Technology of the Republic of Slovenia, and the Slovenian Academy for Sciences and Arts.

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ABSTRACT

This paper discusses the state-of-the-knowledge in the use of energy concepts in seismic-resistant design of structures emphasizing issues and future directions in the use of such concepts for proper establishment of design earthquakes. After a brief review of the nature of the earthquake problem, the need for improving the earthquake-resistant design of new structures and the proper upgrading of existing hazardous facilities is discussed. Emphasis is placed on the need and the difficulties of conducting nonlinear (inelastic) seismic design. The difference between design and analysis is pointed out, and the role of nonlinear analysis in the design process is discussed. The state-of-the-knowledge in the use of energy concepts in seismic-resistant design of new structures and particularly in the selection of proper (efficient) seismic upgrading of existing hazardous facilities is summarized. The importance of reliable estimation of the input energy of possible earthquake ground motions at the site of the structure in order to select the critical motion (i.e., to establish the proper design earthquake) is emphasized. The different engineering parameters that are needed for proper establishment of the design earthquake are discussed, concluding that while the input energy, E_I , is a reliable parameter for selecting the most demanding earthquake ground motion, it alone is not sufficient for proper design of the structure. For the sizing and detailing of a structure, it is necessary to specify the smoothed inelastic response spectra as well as the time history of the dissipated energy. Recommendations for research and development needs to improve the use of energy concepts in seismic-resistant construction are offered.

INTRODUCTION

STATEMENT OF THE ISSUES. It is well recognized that most human injury and economic loss due to moderate or severe earthquake ground motions are caused by the failure[1] of civil engineering facilities (particularly buildings), many of which were presumed to have been designed and constructed to provide protection against natural hazards. This has been dramatically confirmed during recent earthquakes around the world (the 1988 Armenia, 1989 Loma Prieta, 1990 Iran, and 1990 Philippines earthquakes). Therefore, one of the most effective ways to mitigate the destructive effects of earthquakes is to improve existing methods and/or develop new and better methods of designing, constructing and maintaining new structures and of repairing and upgrading (retrofitting) existing hazardous facilities, particularly buildings.

Although this paper will discuss only problems related to the seismic-resistant design of structures, it should be noted that, while a sound design is necessary, this is not sufficient to ensure a satisfactory earthquake-resistant structure. The seismic response of the structure depends on the state of the whole soil-foundation-superstructure and nonstructural components system when earthquake shaking occurs, i.e., response depends not only on how the structure has been designed and constructed, but on how it has been maintained up to the time that the earthquake strikes. A design can only be effective if the model used to engineer the design can be and is constructed and maintained. Although the importance of construction and maintenance in the seismic performance of structures has been recognized, insufficient effort has been made to improve these practices (e.g., supervision and inspection) [1].

In an attempt to realize the above mentioned improvements, the authors and their research associates have carried out a series of studies examining the problems encountered in improving earthquake-resistant design of new structures and the development of more reliable approaches to the seismic upgrading of existing hazardous facilities. Because the fundamental earthquake ground motion data required to conduct reliable vulnerability assessment of existing structures and facilities and then to develop efficient strategies for seismic upgrading of hazardous structures is the same as that required for earthquake-resistant design of new structures, only this last case will be discussed herein with special emphasis on building structures.

The state-of-the-art and the state-of-the-practice of earthquake-resistant design and construction of buildings have been reviewed in a series of recent publications by the author and his colleagues [Refs. 2-4]. The importance of a number of problems that have been under study and mentioned in these reviews has recently been confirmed by: the ground motions recorded during two major earthquakes in 1985 (March 3rd in Chile and September 19th in Mexico) and the 1989 Loma Prieta earthquake; the results obtained from the processing of these records; the performance of the structures, particularly buildings during the above and other recent earthquakes; and the results of integrated analytical and experimental studies that have recently been conducted. To recognize the importance as well as the difficulties involved in the solution of the general issues (problems) encountered in the seismic-resistant design of structures, it is convenient to briefly review these problems.

<u>Overview of Special Problems Encountered in the Design of Earthquake-Resistant Structures</u>. To conduct efficient earthquake-resistant design of a facility (for example, a building), it is necessary to predict reliably the mechanical (dynamic) behavior of the

[1]The term failure is used herein not only to represent physical collapse, but also any serious structural and nonstructural damage which can jeopardize human life and/or the function of the facility.

whole soil-foundation-superstructure and nonstructural components of the building system. The general problems involved in predicting the seismic response of a building are symbolically defined and schematically illustrated in Fig. 1.

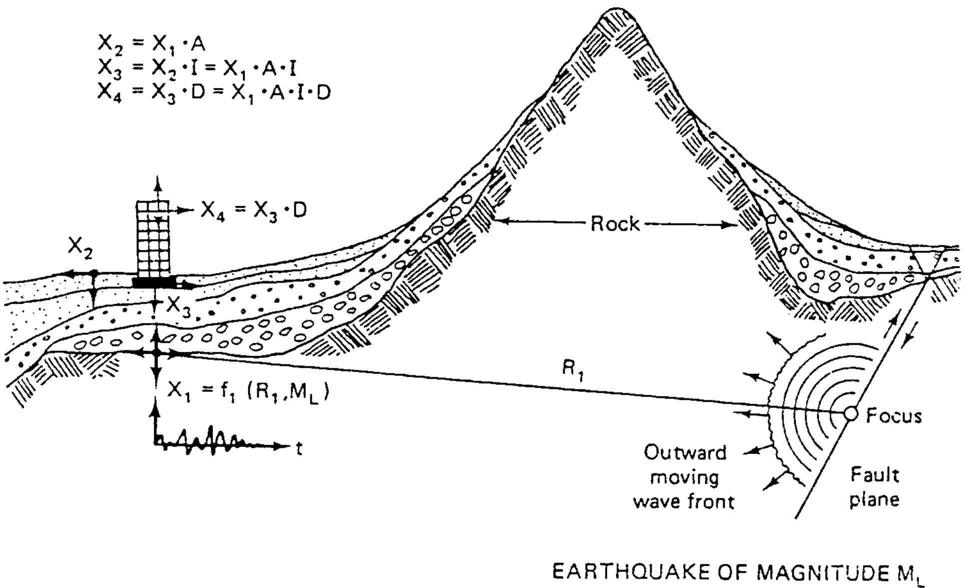


Fig. 1 Illustration of Problems and Factors Involved in Predicting the Seismic Response of a Building

The first problem is to estimate accurately the ground motion at the foundation of the building, X_3. For an earthquake of specified magnitude, M_L, and focal distance, R_1, it is analytically feasible to estimate the base rock motion at the given site of the building, X_1, if the fault type is known $[X_1 = f(R_1, M_L)]$. Prediction of X_3, however, must account for the effects of the soil layers underlying and/or surrounding a building. These effects can be classified in two groups: One is related to the influence of the dynamic characteristics of the different soil layers during the transmission of X_1 to the free ground surface, indicated in Fig.1 by an attenuation or amplification factor, A $[X_2 = A \cdot X_1]$; the other is related to the interaction between structure and soil foundation, symbolically represented by a factor I. There are presently large uncertainties regarding the realistic values of A and I, and major errors could be introduced by trying to quantify these two factors using available analytical techniques. Even if X_1 could be predicted with engineering accuracy, attempts to quantify the influence of soil conditions on X_1 to attain X_2 and X_3 would result in a wide range of predicted values. Soil behavior can be very sensitive to the intensity of the seismic waves, as well as to the rate of straining they could induce. Thus, the analyst or designer would not rely exclusively on results obtained from a single deterministic analysis. Bounds on the possible variations in A and I should also be considered.

The second problem is to predict the deformation, X_4, from shaking at the foundation, X_3 by a dynamic operator, D. Although this is a simple expression, the uncertainties involved in realistically estimating X_3 and D give rise to serious difficulties in obtaining an accurate numerical evaluation of X_4.

Even if it were possible to predict the mechanical characteristics of a building, there remain many uncertainties in establishing the six components of the critical X_3, and attempts to predict the response (strength and deformation) of the building should consider the complete range, or at least the bounds of the dynamic characteristics of the possible excitations, X_3. Owing to these uncertainties, the ideal solution would be a conservative one which would identify the critical excitation, X_3, for the given building. Although it is easy to define this critical X_3 as that which drives a structures to its maximum response, its specific quantification is more complicated. Quantification is feasible for elastic response, but is complicated for cases involving nonlinear response.

The precise evaluation of X_4 at any point in a structure requires that its three translational and three rotational components be established. Furthermore, the prediction of X_4 for a particular building to a specific ground motion depends on the combined effect and dynamic characteristics of all excitations acting on the building. Usually the main excitations on a structures during a severe earthquake are due to: (1) Gravity forces, G(t), with the associated effects of volumetric changes produced by creep of the structural material, especially in concrete; (2) changes in environmental conditions, E(t), such as stresses produced by variations in temperatures; and (3) at least the three translational components of the foundation shaking, $X_3(t)$.

As shown in eq. (1a), the dynamic characteristics of the whole system, which can change continuously as the structures is deformed into its inelastic range, can be summarized by denoting them as the instantaneous values of: (1) Mass, M(t); (2) damping coefficient, $\xi(t)$; and (3) resistance function, (R versus X_4)(t). They can also be represented as illustrated in eq.(1b) by the instantaneous values of: (1) Fundamental period, T(t); (2) damping coefficient, $\xi(t)$; (3) yielding strength, $R_y(t)$; and (4) energy absorption and dissipation capacity as denoted by instantaneous available ductility, $\mu(t)$, which is a function of $X_4(t)$.

$$X_4(t) = F\{[G(t),\Delta E(t),X_3(t)], \qquad [M(t),\xi(t),(R \text{ vs. } X_4)(t)]\} \tag{1a}$$

$$X_4(t) = F\{\underbrace{[G(t),\Delta E(t),X_3(t)]}_{\textbf{dynamic characteristics of excitations}}, \qquad \underbrace{[T(t),\xi(t),R_y(t),\mu(t)]}_{\textbf{dynamic characteristics of whole soil-building system}}\} \tag{1b}$$

Analysis of the parameters in eqs. (1a) and (1b) indicates the magnitude of the problems involved in predicting response to earthquake ground motions. The first problem is that to predict X_4, X_4 must be known. Another problem is that all such parameters are functions of time, although the gravity forces and environmental conditions tend to remain nearly constant for the duration of an earthquake. It should be noted that the value of $\Delta E(t)$ represents more than just the stresses induced by environmental changes that occur during the critical earthquake ground motion, X_3; it also accounts for stress and strain existing at the time of the earthquake due to (1) previous thermal changes or shrinkage, which cause residual stress or distress, and deterioration from aging and corrosion; (2) degradation in strength and stiffness caused by previous exposure to high winds, fires, or earthquakes; (3) strength and stiffness caused by alternation, repair or strengthening. Since any one of these conditions can significantly affect structural response, factors that must be considered in determining the strength and deformation capacities include the variations in loading and environmental histories during the service life of the building and their effects on the condition of the structure at the time of the occurrence of the extreme environment. To this end, it should be noted that E(t) also affects (R versus X_4)(t).

Another difficulty is that in the case of predicting the response, X4(t), to the extreme (safety) ground motions, this usually involves nonlinear (inelastic) response. Therefore, it is not possible to apply the principle of superposition and solve independently the problem for each of the different excitations and then superimpose their solution. This is one of the main reasons why in practice designers prefer to reduce (simplify) the prediction of the seismic response of a structure and, therefore, limit its design to the linear elastic range of the actual response.

Differences Between Analysis and Design, and Between Design and Construction. A preliminary structural design should be available to conduct linear elastic and nonlinear (inelastic) analyses of the soil-foundation-superstructure model(s). To recognize clearly the differences between analysis and design, and at the same time identify problems inherent in the design of earthquake-resistant structures, it is convenient to analyze the main steps involved in satisfying what can be called the **basic design equation**:

DEMAND	≤	**SUPPLY**
on		of
Stiffness **Strength** **Stability** **Energy absorption & energy dissipation capacities**		**Stiffness** **Strength** **Stability** **Energy absorption & energy dissipation capacities**

Evaluation of the **demand** and prediction of the **supply** are not straightforward, particularly for earthquake-resistant buildings. Determination of the **demand**, which usually is done by numerical analyses of mathematical models of the entire soil-foundation-building system, depends on the interaction of this system as a whole and the different excitations that originate from changes in the system environment and of the **intrinsic interrelation between the demand and supply itself.**

In the last three decades our ability to analyze mathematical models of buildings when subjected to earthquake ground shaking has improved dramatically. Sophisticated computer programs have been developed and used in the numerical analysis of the linear as well as nonlinear seismic response of three-dimensional mathematical models of the bare structure of a building to certain assumed earthquake ground motions (**earthquake input**). The opportunity is ripe to take advantage of these improvements in analysis in the seismic design of structures. In general, however, these analyses have failed to predict the behavior of real buildings, particularly at ultimate limit states. As a consequence of this and due to the lack of reliable models to predict **supplies to real structures**, there has not been a corresponding improvement in the design of earthquake-resistant structures. There is an urgent need to improve mathematical modeling of real facilities. This requires integrated analytical and experimental research.

The proportioning (sizing) and detailing of the structure elements of a building are usually done through equations derived from the theory of mechanics of continuous solids or using empirical formulae. Except in the case of pure flexure, a general theory with reliable equations that can accurately predict energy absorption and dissipation capacities of structural elements and of the so-called nonstructural elements, and therefore of real buildings, has not been developed. Improving this situation will require integrated analytical and experimental research in the field (through intensive instrumentation of buildings) and in the experimental laboratory through the use of pseudo-dynamic and/or earthquake simulator facilities.

The information needed to improve prediction of earthquake responses of structures, and therefore necessary to improve their design, can be grouped under the following three basic elements: **Earthquake input, demands on the structure, and supplied capacities of the structure.** The authors believe that a promising approach for improving the solution of the problems involved with these three elements is through the use of energy concepts [6]. To review the state-of-the-art in the use of these concepts is one of the main objectives of this paper. Because of space limitations, this paper will attempt to focus on the state-of-the-art in the use of such an energy approach only to solve the problem of proper selection of the earthquake input.

Earthquake Input: Specification of Design Earthquakes and Design Criteria. The design earthquake depends on the design criteria, i.e., **the limit state controlling the design.** Conceptually, the design earthquake should be that ground motion that will drive a structure to its critical response. In practice, the application of this simple concept meets with serious difficulties because, first, there are great uncertainties in predicting the main dynamic characteristics of ground motions that have yet to occur at the building site, and , secondly, even the critical response of a specific structural system will vary according to the various limit states that could control the design.

Until a few years ago seismic codes have specified design earthquakes 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 Elastic Design Response Spectra (SEDRS)** based on **Effective Peak Acceleration** (EPA) have been recommended [2-5]. While this has been a major improvement conceptually, great uncertainties regarding appropriate values for EPA and GMS, as well as other parameters that have been recommended to improve this situation, persist [5 & 7]. The authors believe that a promising engineering parameter for improving selection of proper design earthquakes is through the concept of **Energy Input, E_I, and associated parameters.** The use of this concept and associated parameters is the main subject of this paper which has the following objectives.

OBJECTIVES. The main objectives of this paper are: First, to discuss the state-of-the-knowledge in the use of energy concepts in seismic-resistant design of structures with emphasis on the proper establishment of the design earthquakes through the use of E_I and associated parameters; and, secondly, to point out the main issues and future directions in the use of such an energy approach.

STATE-OF-THE-KNOWLEDGE IN THE USE OF ENERGY CONCEPTS

GENERAL REMARKS. Traditionally, displacement ductility has been used as a criterion to establish **Inelastic Design Response Spectra (IDRS)** for earthquake-resistant design of buildings [8]. The minimum required **strength** (or capacity for lateral force) of a building is then based on the selected IDRS. As an alternative to this traditional design approach, an energy-based method was proposed by Housner [9]. Although estimates have been made of input energy to Single Degree of Freedom Systems, SDOFS, [10] and even to **Multi-Degree of Freedom Systems, MDOFS,** (steel structures designed in the 60's for some of the existing recorded ground motions) [11], it is only recently that this approach has gained extensive attention [12]. This design method is based on the premise that the **energy demand** during an earthquake (or an ensemble of earthquakes) can be predicted and that the **energy supply** of a structural element (or a structural system) can be established. A satisfactory design implies that the energy supply should be larger than the energy demand.

To develop reliable design methods based on an energy approach, it is necessary to derive the energy equations. Although real structures are usually **MDOFS**, to facilitate the analysis and understanding of the physical meaning of the energy approach, it is convenient to first derive the energy equations for **SDOFS** and then to derive these equations for **MDOFS.**

DERIVATION OF ENERGY EQUATIONS: **Linear Elastic-Perfectly Plastic SDOFS**. In Ref. 13 is a detailed discussion of the derivation of the following two basic energy equations starting directly from the eq. (2) for a given viscous damped SDOFS subjected to an earthquake ground motion

$$m\ddot{v}_t + c\dot{v} + f_s = 0 \qquad (2)$$

where: m = mass; c = viscous damping constant; f_s = restoring force (if k = stiffness, $f_s = kv$ for a linear elastic system); $v_t = v + v_g$ = absolute (or total) displacement of the mass; v = relative displacement of the mass with respect o the ground; and v_g = earthquake ground displacement.

Derivation of "Absolute" Energy Equation. Integrating Eq. 2 with respect to v from the time that the ground motion excitation starts and considering that $v = v_t - v_g$ it can be shown that

$$\frac{m(\dot{v}_t)^2}{2} + \int c\dot{v}dv + \int f_s dv = \int m\ddot{v}_t dv_g \qquad (3)$$

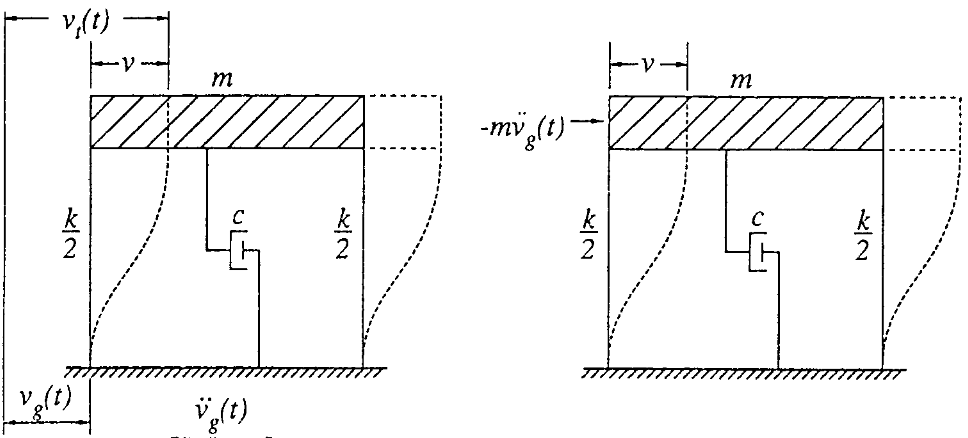
$$E_K + E_\xi + E_a = E_I \qquad (4)$$

"Absolute" Kinetic Energy	Damping Energy	Absorbed Energy	=	"Absolute" Input Energy

Considering that E_a is composed of the recoverable Elastic Strain Energy, E_s , and of the irrecoverable Hysteretic Energy, E_H, eq. (4) can be rewritten as

$$E_I = E_K + E_S + E_\xi + E_H \tag{5}$$

The E_I is defined as the **"Absolute Input Energy"** because it depends on the absolute acceleration, $\ddot{v}_t$. Physically, it represents the inertia force applied to the structure. This force, which is equal to the restoring force plus damping force [see eq. (2) and Fig. 2], is the same as the total force applied to the structure foundation. Therefore, E_I represents the work done by the total base shear at the foundation on the foundation displacement, v_g.



(a) Moving Base System (b) Equivalent Fixed-Base System

Fig. 2 Mathematical Model of a SDOFS subjected to an Earthquake Ground Motion

Derivation of "Relative" Energy Equation. Considering that Eq. (2) can be rewritten as

$$m\ddot{v}+c\dot{v}+f_s=-m\ddot{v}_g \tag{6}$$

and the structural system of Fig. 2(a) can be conveniently treated as the equivalent system in Fig. 2(b) with a fixed base and subjected to an effective horizontal dynamic force of magnitude, $m\ddot{v}_g$. Integrating Eq. (6) with respect to v, the following eq. can be obtained:

$$\frac{m(\dot{v})^2}{2} \quad + \quad \int c\dot{v}dv \quad + \quad \int f_s dv \quad = \quad -\int m\ddot{v}_g dv \qquad (7)$$

$$E_K' \quad + \quad E_\xi \quad + \quad E_a \quad = \quad E_I' \qquad (8)$$

"Relative" Kinetic Energy	Damping Energy	Absorbed Energy	"Relative" Input Energy

As $E_a = E_s + E_H$, Eq. (8) can be rewritten as

$$E_I' = E_K' + E_s + E_\xi + E_H \qquad (9)$$

The E_I' that is defined as the **"Relative" Input Energy** represents the work done by the static equivalent internal force ($-m\ddot{v}_g$) on the equivalent fixed-base system; that is, it neglects the effect of the rigid body translation of the structure.

Difference Between Input Energies from Different Definitions. Ref. 13 discusses in detail the differences between the values of the input energies E_I and E_I'. Although the profiles of the energy time histories calculated by the absolute energy equation (3) differ significantly from those calculated by the conventional relative equation, eq. 7, the maximum values of E_I and E_I' for a constant displacement ductility ratio are very close in the period range of practical interest for buildings which is 0.3 to 5.0 secs.

Comparison of E_I with the Maximum Input Energy that is Stored in a Linear Elastic SDOFS. For a linear elastic SDOFS the maximum input energy that is **stored** is given by

$$E_{IS} = \frac{1}{2} m (S_{pv})^2 \qquad (10)$$

where S_{pv} **is the linear elastic spectral pseudo-velocity.**

This E_{IS} has been used by some researchers as the energy demand for an inelastic system. In Ref. 13 it is shown that E_{IS} may significantly underestimate the E_I for an inelastic system. In this reference, it is also shown that, except for highly harmonic ground motions (like the recorded one at SCT in Mexico City during the 1985 earthquake), the E_I for a constant ductility ratio can be predicted reliably by the elastic input energy spectra using Iwan's procedure [14] which takes into consideration the effect of increasing damping ratio and natural period.

Input Energy to MDOFS. The E_I for an N-story building can be calculated as follows [13]:

$$E_I = \int \left(\sum_{i=1}^{N} m_i \ddot{v}_{ti} \right) dv_g \qquad (11)$$

Where: m_i is the lumped mass associated with the i-th floor, and $\ddot{v}_{ti}$ is the total acceleration at the i-th floor. In other words, E_I is the summation of the work done by the total inertia force ($m_i\ddot{v}_{ti}$) at each floor through the ground displacement v_g. Analysis of results obtained from experiments conducted on medium rise steel dual systems indicates that the E_I to a multi-story building can be estimated with sufficient practical accuracy by calculating the E_I of a SDOFS using the fundamental period of the multi-story structure.

ADVANTAGES OF USING ENERGY CONCEPTS IN SEISMIC DESIGN OF STRUCTURES. Equation (5) can be rewritten as

$$E_I = E_E + E_D \tag{12a}$$

$$E_I = \overbrace{E_K + E_S} + \overbrace{E_\xi + E_H} \tag{12b}$$

where E_E can be considered as the stored elastic energy and E_D the dissipated energy. Comparing this equation with the design equation, it becomes clear that E_I represents the **demands**, and the summation of E_E + E_D represents the **supplies**. This eq. (12a) 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 ground motion. Then the designer has to analyze if it is possible to balance this demand with just the elastic behavior of the structure to be designed or will it be convenient to attempt to **dissipate** as much as possible some of the E_I , i.e., using E_D. As revealed by eq. (12b), there are three ways of increasing E_D: One is to increase the linear viscous damping, E_ξ; another, is to increase the hysteretic energy, E_H; and the third is a combination of increasing E_ξ and E_H. At present it is common practice to just try to increase the E_H as much as possible through inelastic (plastic) behavior which implies damage of the structural members. Only recently it has been recognized that it is possible to increase significantly the E_H and control damage through the use of **Energy Dissipation Devices.**

If technically and/or economically it is not possible to balance the required E_I through either 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 seismic-resistant design and construction of new structures, but also for the seismic upgrading of existing hazardous structures [15]. To reliably use this energy approach, it is essential to be able to select the critical ground motion (design earthquake), i.e., that which controls the design; in other words, the ground motion that has the largest damage potential for the structure being designed. Although many parameters have been and are being used to establish design earthquakes, most of them are not reliable for assessing the damage potential of earthquake ground motions. As mentioned in the Introduction, a promising parameter for assessing damage potential of these motions is the E_I [6]. However, as it will be discussed below, this parameter alone is not sufficient to evaluate (visualize) the E_D (particularly E_H) that has to be supplied to balance the E_I for any specified acceptable damage. Additional information is needed.

INFORMATION NEEDED TO CONDUCT RELIABLE SEISMIC-RESISTANT DESIGN

GENERAL REMARKS. It has been pointed out previously that the first and fundamental step in seismic-resistant design of structures is the reliable establishment of the design earthquakes. This requires a reliable assessment of the damage potential of all the possible earthquake ground motions that can occur at the site of the structure. An evaluation of the different parameters that have been and are still used is offered in Ref. 6. Currently, for structures that can tolerate a certain degree of damage, the **Safety or Survival-Level Design Earthquake** 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 **SEDRS,** through the use of the **displacement ductility** ratio, **μ, 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 one standard deviation of the **Inelastic Response Spectra, IRS,** corresponding to all the different time histories of the severe ground motions that can be induced at the given site from earthquakes that can occur at all of the possible sources affecting the site [7].

While the above information **is necessary** to conduct reliable design for safety, i.e., to avoid collapse and/or serious damage that can jeopardize human life, **it is not sufficient.** Although the IRS takes into account the effects of duration of strong motion in the required strength, these spectra do not give an appropriate idea of the amount of energy that the whole facility system will dissipate through hysteretic behavior during the critical earthquake ground motion. They give only the value of maximum global ductility demand. In other words, **the maximum global ductility demand by itself does not give an appropriate definition of the damage potential of ground motions.** In Ref. 6 the authors have shown that a more reliable parameter than those presently used in assessing damage potential is the E_I. As is clearly shown by eqs. 3 and 4, 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 and the corresponding E_I of the critical ground motion give sufficient information to conduct a reliable seismic design for safety?

Although the use of E_I can identify the damage potential of a given ground motion and, therefore, permits selection, amongst all the possible motions at a given site, of that which will be the critical one for the response of the structure, it does not provide sufficient information to design for safety level. From recent studies [7 & 13] 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 earthquake-resistant design. This is particularly true when the ductility deformation ratio, say μ, is limited, because of the need to control damage of 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 (given by SIDRS), and the E_H (including **Accumulative Ductility Ratio, μ_a, and Number of Yielding Reversals, NYR)** are promising for defining rational earthquake-resistant design procedures. The need for considering all of these engineering parameters rather than just one will be justified below by a specific example. From the above discussion, it is clear that when significant damage can be tolerated, the search for a single parameter to characterize the ground motion or the design earthquake for safety is doomed to fail.

IMPORTANCE OF SIMULTANEOUSLY CONSIDERING THE E_I , IDRS, AND E_H (INCLUDING μ_a AND NYR) FOR DEFINING THE SAFETY-LEVEL DESIGN EARTHQUAKE. Figures 3-7 permit comparison of the values of these different engineering parameters for two recorded ground motions, San Salvador (SS) and Chile (CH); Table 1 summarizes approximate maximum values for these parameters corresponding to each of these two different recorded ground motions. The importance and, actually, the need for simultaneously considering all the above parameters in selecting the critical ground motions and, therefore, for defining the safety-level design earthquake, is well illustrated by analyzing the values of these parameters for these two records.

San Salvador (SS) vs. Chile (CH) Records. From analyses of the values of Peak **Ground Acceleration (PGA), Effective Peak Acceleration (EPA),** and **Effective Peak Velocity (EPV)** (given in Table 1) which are values presently used to define the seismic hazard zoning maps, it might be concluded that the damage potential of these ground motions is quite similar. One can arrive at a similar conclusion if the values of the required **Yielding Strength Coefficient, $C_y = V_y /W$** , for different values of μ are compared or, in other words, if the IRS for different μ are compared (Fig. 3). However, a completely different picture is obtained when the values of the E_I , E_H, μ_a, and NYR for different values of μ are compared. The E_I for the CH record can be as much as 5 times the E_I for the SS record (Fig. 4). The E_H [represented by the equivalent hysteretic velocity, $V_H = (2E_H /m)^{1/2}$, in Fig. 5] for the CH record is more than 3 times the E_H for the SS record when the period, T, is about 0.5 secs. and nearly 2 times when the T varies from 0.5 secs. up to 1.5 secs. The μ_a for the CH record are 2 to 4 times higher than those of the SS record (Fig. 6). The NYR for the CH record and for a $\mu = 6$ and $T < 0.5$ seconds are more than 10 times the NYR for the SS record (Fig. 7). For a $\mu = 4$ and $T \geq 0.5$, the NYR for the CH record are more than 5 times those of the SS record.

From the above comparison, it is clear that the damage potential of the CH recorded ground motion is significantly (at least 3 times) greater than that of the SS record in spite of the fact that PGA, EPA, EPV, ERS (IRS for $\mu = 1$) and even the IRS for different values of μ are very similar. Thus, the importance of evaluating the E_I and E_H (represented herein by V_H, μ_a and NYR spectra) which are functions of the duration of strong ground motions, t_d , becomes very clear. While the t_d for the CH records is 36 secs., the t_d for the SS record is only 4.3 secs.(see Table 1). The importance of t_d in judging damage control is discussed in Ref. 7. While the above spectra are very helpful in preliminary design, for the final design (detailing of members), the ideal would be to have the time history of the E_H, i.e., the time history of the load-deformation relationship of the designed structure.

Table 1. Parameters Corresponding to the Chile (CH) and San Salvador (SS) Earthquake Ground Motions

EQ GROUND MOTION PARAMETERS / EQ RECORD	PGA (g)	EPA (g)	EPV (in/s)	t_d (secs)	$\mu = 2$				$\mu = 4$				$\mu = 6$			
					C_y	E_I/m $\frac{in^2}{sec^2}$	μ_a	NYR	C_y	E_I/m $\frac{in^2}{sec^2}$	μ_a	NYR	C_y	E_I/m $\frac{in^2}{sec^2}$	μ_a	NYR
CHILE (CH)	0.67	0.57	16	35.8	0.95	11,200	11	28	0.70	9,600	33	53	0.67	8,800	133	122
SAN SALVADOR (SS)	0.69	0.54	17	4.3	1.04	2,400	5	6	0.69	1,900	12	9	0.69	1,700	28	9

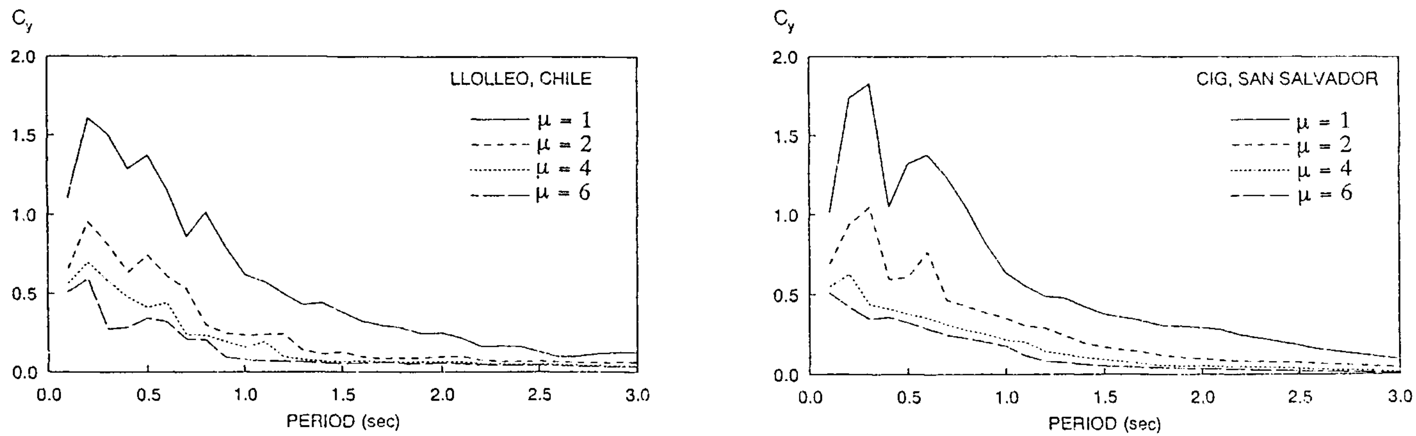


Fig. 3 Yielding Strength Spectra (C_y) for CH and SS Records (5% Damping)

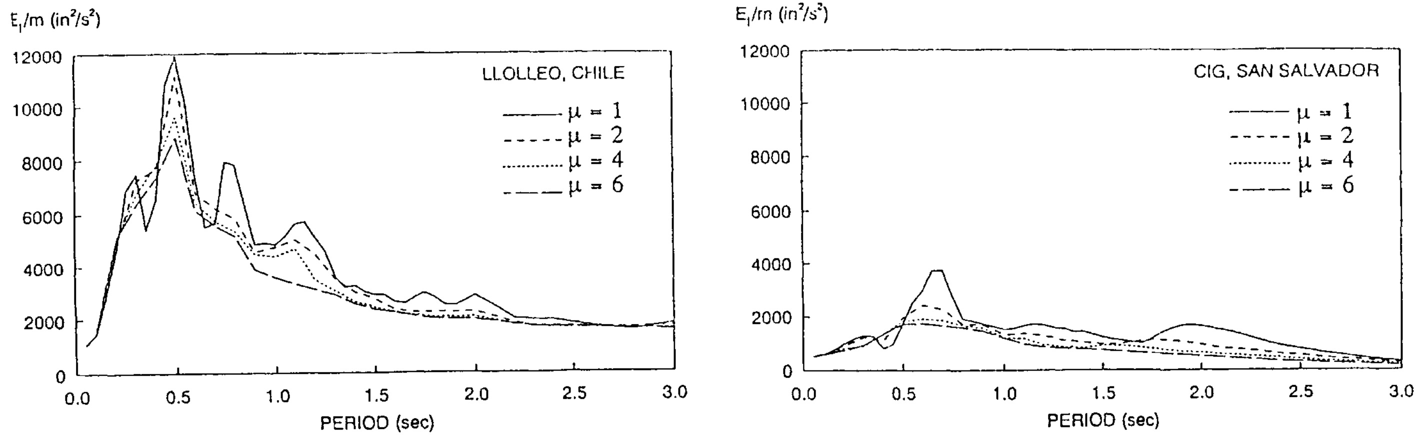


Fig.4. Input Energy (E_I /m) Spectra for CH and SS Records (5% Damping)

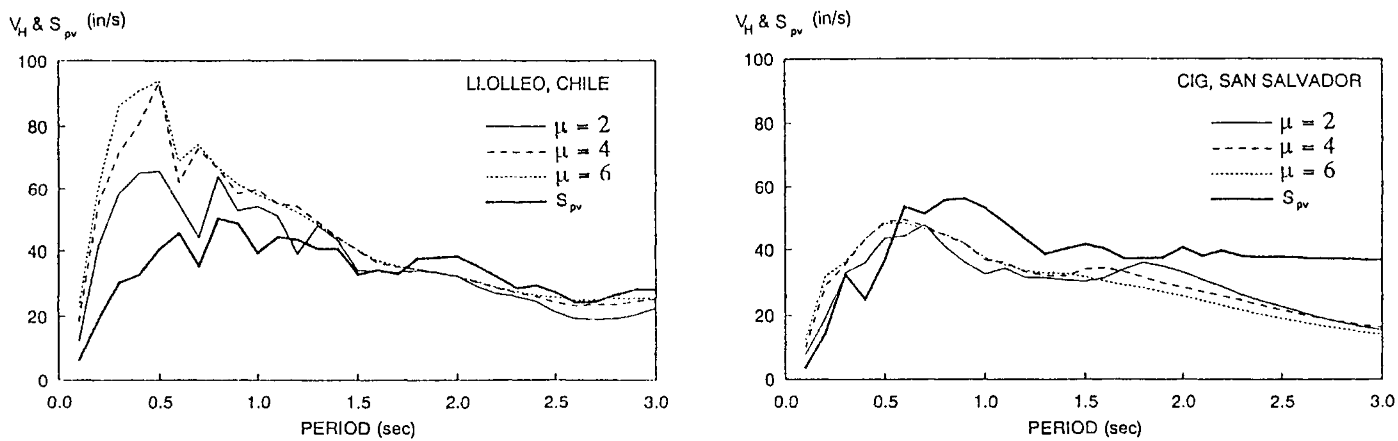


Fig.5. Hysteretic Energy Equivalent Velocity (V_H) Spectra for CH and SS Records (5% Damping)

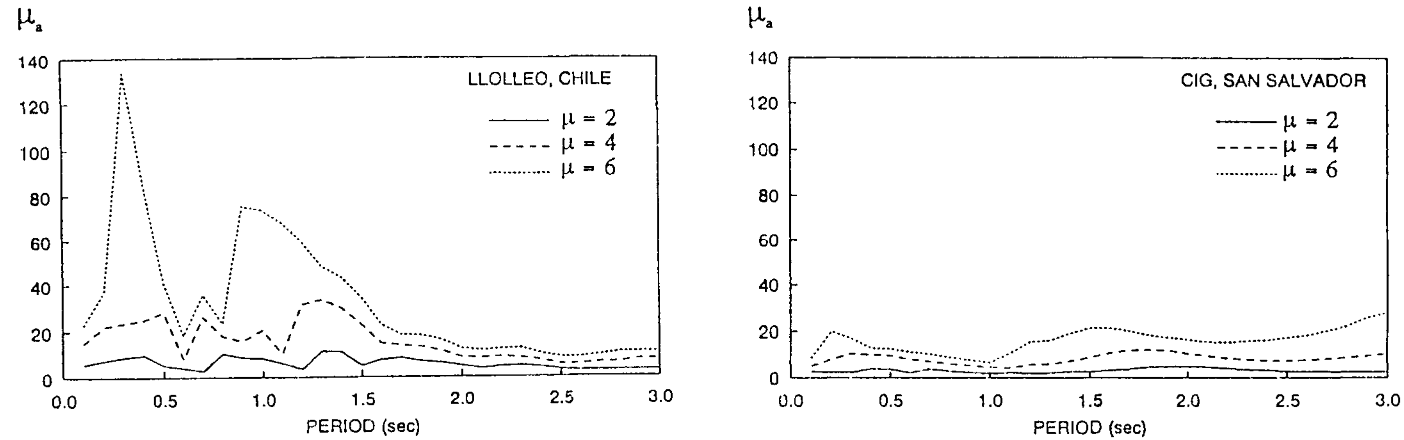


Fig. 6 Accumulative Displacement Ductility Ratio (μ_a) Spectra for CH and SS Records (5% Damping)

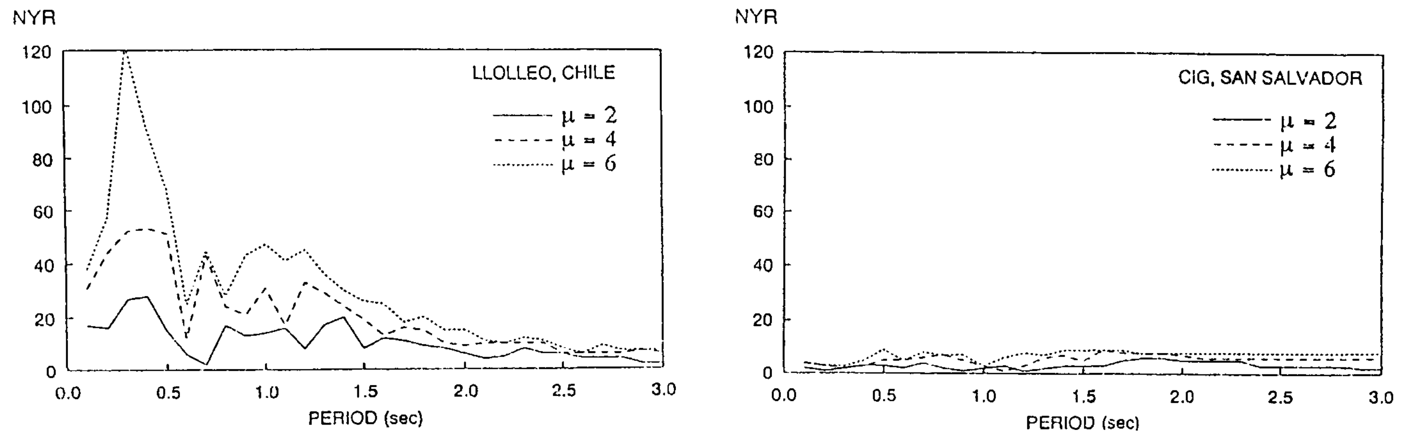


Fig. 7 Number of Yielding Reversal (NYR) Spectra for CH and SS Records (5% Damping)

The assembly of all the above spectra and time histories can be considered the **ideal information** for making reliable decisions regarding the critical earthquake ground motions and, therefore, for reliable establishment of design earthquake and design criteria. Thus, the gathering of this basic information should be pursued for research in order to improve seismic codes as well as for the design of important facilities. It should be noted that all of the above spectra can be computed by the engineer if he/she is provided with the time history of all possible ground motions than can occur at the site of the structure.

It has to be recognized that, for practical preliminary design of most standard facilities, it will be convenient to specify the minimum possible information to keep it simple. It is believed that, for a given structural site, this minimum could be the E_I and the SIDRS of all the possible ground motions as that site. The E_I would permit selection of the type of critical ground motion, i.e., the one that will induce the largest damage. The SIDRS, corresponding to the type of critical ground motion, can be used to conduct the preliminary design of the structure. Once a preliminary design is completed, it will be possible to obtain all the other information, i.e., the E_H, μ_a and NYR for different μ, from nonlinear, dynamic time history analyses, taking advantage of the significant advances achieved in the development of computer programs for such analysis. This will permit checking the adequacy of the preliminary design. While a nonlinear analysis of the preliminary design using a static approach (i.e., equivalent static lateral force) can give an idea of the strength and deformation capacities as well as a lower limit of the available E_H and therefore it should be used if no time history of the critical ground motions is possible, this type of analysis will not supply any information regarding the μ_a or NYR or the sequence of damage.

From the above discussion, it becomes clear that, 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.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS. Review of the state-of-the-knowledge in seismic-resistant design of structures reveals that among the several issues that exist the following two are very important: First, what are the earthquake effects, and in particular for any selected site of a structure, what are the ground motions against which the structure has to be designed? And secondly, how should the design be conducted to resist such earthquake effects? From the above discussions and the analyses of the results obtained in the studies published in the references cited in this paper regarding these two main issues, the following observations can be made:

(1) The application of energy concepts through the use of energy equations has the advantage that it guides (indicates) the designer through the different alternatives at his disposal to find an efficient (technical and economical) design. It encourages and guides the designer in the proper application of recent developments in the use of techniques

in base isolation and energy dissipation devices.

(2) Of the two energy equations derived from analysis of response of SDOFS, the use of the "**absolute**" energy equation rather than the "**relative**" energy equation has the advantage that the physical energy input is reflected.

(3) The absolute and relative input energies for a constant displacement ductility ratio are very close in the period range of practical interest, namely 0.3 to 5 secs.

(4) For certain types of earthquake ground motion, the absolute input energy spectra are sensitive to the variation of the ductility ration, μ.

(5) The use of the stored energy in a linear elastic SDOFS, $E_{IS} = m(S_{pv})^2/2$, as a measure of the energy demand for an inelastic system can significantly underestimate the E_I.

(6) The E_I for a constant ductility ratio can be predicted reliably based on the use of Elastic Input Energy Spectra provided that the increased damping ratio and natural period proposed by Iwan are used. An exception to this is when the ground motion is of the type (highly harmonic) recorded at the SCT station in Mexico City during the 1985 Mexico earthquake.

(7) For certain types of multi-story buildings (i.e., MDOFS), their E_I can be estimated with sufficient reliability from the E_I of the SDOF using the fundamental period of the MDOFS.

(8) For proper establishment of design earthquakes and design criteria, it is necessary to have a reliable assessment of the damage potential of each of the different ground motions that can occur at the site of the structure. The different parameters used currently in practice (codes) are inadequate in assessing the damage potential of an earthquake ground motion. The E_I is a reliable parameter in selecting the most demanding earthquake; however, it **alone** is not sufficient for conducting reliable design, sizing and detailing when damage can be tolerated.

(9) The conventional inelastic response spectra, based on a constant μ, cannot be used **alone** as a parameter for judging the damage potential of the earthquake ground motions and thus for establishing the design earthquakes. These spectra do not reflect the possibility of high energy dissipation demand for earthquakes with long duration of strong motion.

(10) For a given structure site, the best parameters for selecting critical earthquake ground motions at the safety or survivability level are the E_I and E_H spectra corresponding to all the possible earthquake ground motions that can occur (or have been recorded) at the selected site. While E_I represents the total energy demand, the E_H is directly related to the damage (inelastic deformations) that can be expected.

(11) The E_H spectra are generally in close agreement with the spectra for the energy stored in a linear elastic SDOFS, $m(S_{pv})^2/2$; however, this elastic stored energy may

underestimate significantly the E_H for structures subjected to long duration of strong motions as those recorded during the 1985 Chile and Mexico earthquakes.

(12) For proper selection of the structural system to be used and particularly for the sizing and detailing of the structural members, the use of the E_I , IRS and E_H spectra is not sufficient. The energy dissipation capacity of a structure is dependent on the deformation path (i.e., the deformation time history). Thus, it is necessary to have information about: The accumulative deformation ductility ratio, μ_a , and the number of yielding reversals, NYR. The μ_a and NYR spectra are not enough, however, by themselves; what is needed is the deformation time history of the critical regions of the selected structural system when subjected to the critical ground motions.

(13) It looks as if any attempt to base seismic design of structures on a design earthquake developed by only one engineering parameter is doomed to fail. But if the present building code philosophy of maintaining as simple a code as possible persists and it is also desired to base seismic design on the formulation of just a design response spectra, it is suggested that this be accomplished by specifying SIDRS for different levels of μ and for different types of site conditions rather than to specify SEDRS and R factors and site coefficients, S. This should be done together with very strict limitations on the type of structural systems to be used and very stringent requirements on the sizing and detailing of the structural components to achieve the largest possible ductility deformation ratio that can be economically attained so that the structure can economically supply a large E_H. Even if these restrictions are specified, it would be desirable that the codes require nonlinear (inelastic) analyses of the preliminarily design structure at least under static lateral forces. Ideally, it should be done using time history analyses.

RECOMMENDATIONS: To improve solutions of the existing issues in the use of energy concepts and their application in practice, the following needs are identified.

Research Needs. Most of the advances in the use of energy concepts for seismic-resistant design have been achieved through analytical studies conducted on SDOFS. Because real structures, and particularly building structures, are MDOFS, there is an urgent need to conduct integrated analytical and experimental studies on the validity of applying the results obtained from analysis of SDOFS to MDOFS. To achieve this, the following recommendations are proposed: **(1)** To develop more efficient and reliable computer programs for the 3D, nonlinear dynamic analysis of multi-degree of freedom building structures; **(2)** to properly instrument whole multi-story building systems (soil-foundation-superstructure and nonstructural components) having different structural systems; **(3)** to conduct integrated and experimental investigation on the energy dissipation capacities of the different building structural components as well as their basic subassemblages when these components and assemblies are subjected to excitations reliably simulating the effects of the response of the building system to critical ground motions; **(4)** to use earthquake simulator facilities to perform integrated analytical and experimental studies on the 3D seismic performance of different types of building systems.

Development Needs. It is necessary that the results of the research be used to develop practical methods for applying the energy concepts, as well as the derived energy equations, to the design of buildings. To facilitate this application, it will also be necessary to develop efficient base isolation and base dissipation devices that can be used to control in a reliable way the E_I and E_H as well as the E_ξ.

Education Needs. It is time that the use of the energy concepts be introduced into the education of our engineering students. Furthermore, the practitioners (professional engineers) in regions of seismic risk should also be educated or at least exposed to the use of energy concepts. This information may be disseminated through short courses.

Implementation Needs. Researchers should work with professional engineers and code officials to develop practical methods of design based on energy concepts that can be introduced into the seismic codes.

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SEISMIC DESIGN BASED ON DUCTILITY AND CUMULATIVE DAMAGE DEMANDS AND CAPACITIES

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ABSTRACT

This paper summarizes results of a continuing study on damage potential of ground motions and its implications for seismic design. A seismic design procedure that accounts explicitly for ductility and cumulative damage demands and capacities is proposed. The discussion focuses on the identification and determination of seismic demand parameters that are needed to implement the proposed design procedure. Emphasis is placed on strength, ductility, and energy demands. Results are presented for demands imposed by rock and stiff soil ground motions on single and multi degree of freedom systems. The objective of the paper is to demonstrate that ductility and cumulative damage considerations can and should be incorporated explicitly in the design process.

INTRODUCTION

Seismic design is an attempt to assure that strength and deformation capacities of structures exceed the demands imposed by severe earthquakes with an adequate margin of safety. This simple statement is difficult to implement because both demands and capacities are inherently uncertain and dependent on a great number of variables. A desirable long-range objective of research in earthquake engineering is to provide the basic knowledge needed to permit an explicit yet simple incorporation of relevant demand and capacity parameters in the design process. A demand parameter is defined here as a quantity that relates seismic input (ground motion) to structural response. Thus, it is a response quantity, obtained by filtering the ground motion through a linear or nonlinear structural filter. A simple example of a demand parameter is the acceleration response spectrum, which identifies the strength demand for elastic single degree of