Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SG-R2

State-of-the Art Report
DUCTILITY BASED STRUCTURAL DESIGN

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SUMMARY

After discussing the differences in the concepts of **deformability, ductility and ductility ratio**, the importance of the proper use of these concepts is emphasized. The state-of-the-practice and particularly of-the-art in the use of the concept of ductility ratio for attaining efficient earthquake-resistant design is reviewed, and the various methodologies are discussed. The implications of lessons learned during recent earthquakes and research for improving earthquake-resistant design is assessed and used to identify further research, development and educational needs. Short and long-term solutions are formulated for the proper use of the concept of ductility.

INTRODUCTION

Introductory Remarks One of the most promising approaches for developing efficient methods for improving earthquake (EQ)-resistant construction is by approaching the solution of predicting the response of structures to EQ ground motions through an energy approach. In this approach, it is recognized that the total Energy Input, E_I, can be resisted by the sum of the Kinetic Energy, E_K, the Elastic Strain Energy, E_{ES}, and the Energy Dissipated, E_D, through Plastic Deformations (Hysteretic Damping), E_H; and the equivalent viscous damping, E_ξ. The energy equation for a single-mass oscillatory system can be written as:

$$E_I = E_K + E_{ES} + E_H + E_\xi \quad (1)$$

The sum of kinetic energy and the linear elastic strain energy constitutes the elastic vibrational energy. If it is assumed that for a given structure the E_I has a constant value, it is clear from the above equation that to achieve economical EQ-resistant construction it will be necessary to dissipate part of the total input energy E_I by nonlinear behavior, i.e., by either E_H or E_ξ or a combination of both. Although the advantages of controlling the seismic response of civil engineering structures by increasing damping has long been recognized, the concept of using plastic deformation of the structural material to dissipate part of the input energy does not appear in the U.S. literature until the 1950s. In 1956 Housner discussed the use of limit design for EQ-resistant design [Ref. 1]. Although the advantage of using ductile material and ductile type structures in seismic-resistant design was demonstrated early in the 1950s, the use of the concept of ductility and ductility ratio in EQ-resistant design of reinforced concrete (RC) structures was introduced in the U.S. for the first time in 1961 with the publication of the Portland Cement Association (PCA) Manual "Design of

Multistory Reinforced Concrete Buildings for Earthquake Motions" [Ref. 2].

Since the publication of the PCA Manual, significant experimental and analytical research efforts have been devoted to the development of reliable methods of EQ-resistant design based on economic combination of strength and ductility. Even though as early as 1977, computer programs for earthquake-resistant inelastic design of RC, ductile moment-resistant space frames (DMRSF) based on the use of the concept of ductility, had been developed and proposed for its use in practice [Ref. 3], the practical application of EQ-resistant inelastic design in the U.S. today is more an exception than a rule. This also seems to be the case worldwide, except for countries like Mexico and New Zealand, where their building codes have introduced explicitly the use of ductility ratio, μ, in the estimation of seismic design forces and allowed the use of limit design method. In New Zealand, the seismic code is based on a "capacity design" procedure.

The slow progress in the use of limit design or capacity design procedure for EQ-resistant design of RC structures (or in general for any kind of structural material) it is not surprising. The definition of ductility ratio, μ, and its evaluation is only precise for the case of ideal linear elastic-perfectly plastic behavior. In reality, such behavior is more an exception than a rule. Furthermore, even though the advantages of providing the EQ-resistant design of a structure with the largest ductility that is economically feasible are generally recognized, the term ductility is used very loosely to express the deformability of the structure or the ductility ratio. Although the deformability, ductility and ductility ratio are parameters that are interrelated, their values and significance in the real behavior of structures can be quite different. There is an urgent need to get a worldwide agreement regarding the proper use of these technical terms, and of their evaluation and application to EQ-resistant design of structures.

Objectives The ultimate goal of this paper is to review the states-of-the-practice and, particularly, of-the-art in the use of the concepts of ductility and ductility ratio for attaining efficient EQ-resistant construction, and to identify the research, development and educational needs to improve the proper use of these ductility concepts.

Scope To achieve this goal, the needs for ductility and its proper use are discussed first, emphasizing the importance of recognizing the differences between deformability, ductility, and ductility ratio, as well as their interrelationship, and of unifying the ways in which the different types of ductility ratios are estimated from the real seismic response of structures. Then it is shown that to achieve high energy dissipation capacity and overall effective seismic performance, it is advantageous to select highly redundant combined (hybrid) structural systems (several structural defense lines) and to provide their critical elements (i.e. those controlling the inelastic behavior of these systems) with the highest ductility ratio that is economically feasible. After a brief statement of the EQ-resistant design and construction problems, the states-of-the-practice and of-the-art are reviewed showing that there is a dangerous tendency in reducing the yielding strength required on the basis of linear elastic response to critical ground shaking, by means of using higher and higher values of ductility ratios, and to try to provide the constructed structure with just the minimum code required yielding strength. Finally, the implications of lessons learned during recent earthquakes and research for improving EQ-resistant design and construction are assessed and used to identify further research, development and educational needs. Short- and long-term solutions are formulated for the proper use of the concept of ductility and of energy dissipation capacity.

NEEDS FOR DUCTILITY AND ITS PROPER USE IN EQ-RESISTANT DESIGN

General Remarks It is well recognized and accepted that in EQ-resistant design, all structural members and their connections and supports should be designed (sized and detailed) with large ductility and stable hysteretic behavior so that the entire structure will also be ductile and display stable hysteretic behavior. There are two main reasons for this requirement: first, it allows the structure as a whole to develop its maximum potential strength which is given by the summation of the maximum strength of each component; and secondly, large structural ductility allows the structure to move as a mechanism under its maximum potential strength and this will result in dissipation of large amounts of energy. While these reasons have been recognized in the past, only the second has been emphasized because the large dissipation of energy was used to justify the reduction of the design strength that would be required if only linear elastic behavior were permitted. Although this reduction is justifiable in certain cases, the author has previously expressed his concerns about too large reductions of the required elastic strength or the linear elastic design response spectra (LEDRS) through the indiscriminate use of large values for the structural ductility ratio. For clarity and convenience in discussing the reasons for this concern, a glossary of the terms to be used in the discussion is given below.

Deformability: Capability of a material, structural component, or entire structure to deform before rupture.

Ductility: The ability of a material, structural component, or entire structure to undergo deformation after its initial yield without any significant reduction in yield strength.

Ductility Ratio or Ductility Factor, μ: The ratio of the **maximum deformation** that a structure or element can undergo without a significant loss of initial yielding resistance **to the initial yield deformation.**

The above definitions are illustrated in Fig. 1 for the case of DMRSF.

Needs to Recognize the Differences Between Deformability, Ductility and Ductility Ratio Although the ductility ratio depends on the ductility and the ductility depends on the plastic deformability (in other words, the three terms are interrelated), there are essential differences in their quantification that need to be recognized.

Deformability vs Ductility: While one structure can have significantly greater deformability than another, its ductility (particularly its usable ductility) can be smaller. For example, this can be the case of **a very flexible RC-DMRSF vs a stiff but very ductile shear wall.** It is clear from analysis of Fig. 2 that if the DMRSF is too flexible, i.e. the Δ_{Fy} is very large, and the maximum lateral deformation, Δ_{Fult}, that can be accepted or tolerated is limited, then the DMRSF ductility that can be used could be smaller than the available and usable shear wall ductility.

Ductility vs Ductility Ratio: The difference between these two terms is clearly illustrated in Fig. 2. While the shear wall usually has smaller ductility than a DMRSF, it can have a ductility ratio significantly higher.

Advantages of Providing Structural Components and Their Connections with the Largest Ductility Economically Feasible The minimum ductility desirable for each component should be that required to provide the structure the opportunity to develop its maximum potential strength according to the maximum strength of its components. The need for this is illustrated in Fig. 3 where the strengths of a simple structure composed of a ductile moment-resisting frame and two coupled walls are depicted as the sum of the resistance functions of each of their components. This figure illustrates that in order for a structure to develop its maximum potential strength R_T as determined by the sum of the maximum strength of each component ($R_T = R_{W1} + R_{W2} + R_F$), it is necessary that $\mu_{W1} \geq 4.3$, $\mu_{W2} \geq 2.8$, and $\mu_F \geq 1.0$. To allow the structure to move as a mechanism under its maximum potential strength, the ductility ratio of the walls, particularly wall w_1 must be significantly higher. This figure also illustrates the difference between ductility ratio and deformability. While the ductile moment-resisting frame has a larger deformability than the walls, its ductility ratio can be smaller than that of the individual walls and this frame ductility ratio cannot be used effectively because of its significantly larger deformability (flexibility) than the wall components, resulting in a relatively earlier failure of the wall components.

It should be noted that by providing large ductility and due to three-dimensional (3-D) interaction between DMRF and walls, it is possible that the maximum strength of the entire structure will exceed the summation of the components if the strength of each is determined considering it as acting independently. This is illustrated in the schematic representation (Fig. 4) of the behavior observed in the experiments conducted on the 7-story RC DMRSF-wall structures of the US-Japan Cooperative Research Program. Results of these experiments are discussed in detail in Ref. 4. The beneficial 3-D interaction was identified to be a consequence of the effects of outrigging action of frames on the wall, as illustrated in the isometric view of Fig. 5. The wall rocking around the compressive edge during its ductile axial-flexural behavior tends to lift up the surrounding girders of the DMRSF that frame into the walls. These girders resist this movement and in doing so, act as prestressing cables, which by increasing the axial compression in the wall, increase its axial-flexural capacity. Thus, this outrigging action results in a significant enhancement of the lateral strength of the whole structure.

Quantification of the Ductility Ratio Though the use of the concept of ductility ratio for the EQ-resistant design of structures was introduced in the U.S. EQ Engineering literature in the early part of the 1950s and its application to R.C. structures was presented in 1961 in the PCA Manual "Design of Multistory Reinforced Concrete Buildings for Earthquake Motions" [2], and that tremendous experimental and analytical research efforts have since been devoted to its evaluation and application, even today it continues to be an ambiguous parameter. In a workshop conducted in 1977 [5] a group of experts, including professors, researchers and practicing engineers, after recognizing the need to survey, analyze, and evaluate the main parameters (as well as their definitions) that are presently used in research (analytical and experimental) and in practice to describe the inelastic mechanical characteristics of reinforced concrete materials, sections, regions, members, subassemblages, structures and whole soil-building systems, made the following statement:

"One parameter of particular concern is ductility. While ductility is a useful concept, it has a precise definition and quantitative meaning only for the idealized case of monotonic, linear elasto-perfectly plastic behavior. Its use in real cases where behavior significantly differs from this idealized case leads to much ambiguity and confusion. It is thus difficult to make valid comparisons of "available" ductility values reported by different researchers because they are often based on different response parameters or on yielding values determined using different and/or unexplained definitions. These experimentally obtained "available" ductility values are also often misused in analytical studies of the "demand" or "required" ductility due to the difficulty of establishing realistic values for the "linear-elastic stiffness and yielding strength." Attempts should be made to integrate the definitions of response parameters that are used in experimental test programs and in analytical investigations. Furthermore, it is highly questionable whether the performance of different building systems can be properly described and evaluated on the sole basis of elastic stiffness, yielding strength, and ductility. Consequently, there is a need to introduce additional parameters for describing the total hysteretic energy dissipation, number of cycles of reversed deformations, and the degradation in stiffness and strength that has been observed under seismic conditions."

The needs stated above are still valid today.

Concluding Remarks While in discussing the **Philosophy** of ductility based design it is possible to use the concept of ductility and/or ductility ratio in a vague manner when such philosophy has to be applied in the EQ-resistant design of real structures, the philosophy has to be quantified, and therefore, it is necessary to use unambiguous parameters that can be reliably evaluated numerically. Such parameters are usually the displacement ductility ratio, μ_δ, and/or rotation ductility ratio, μ_θ. Preliminary designs are usually based on a selected maximum μ_δ which is determined based on the maximum values of μ_θ, that can be developed or that can be accepted at the critical regions of the structural members.

Assuming that the values of μ_δ can be selected and reliably evaluated, the problem that remains is to correctly use this ratio or parameter in the design process of a structure. To discuss the solution of this problem it is advisable to review briefly the states-of-the-practice and of-the-art in EQ-resistant design of RC structures.

STATES-OF-THE-PRACTICE AND OF-THE-ART OF EQ-RESISTANT DESIGN OF RC STRUCTURES

Problems in Design and Construction of EQ-Resistant Structures The problem areas have been identified and discussed in detail by the author in a series of publications [6-8]. Because of the length limitation of this paper, the main problems that have been identified are simply enumerated: The first problematical area in EQ-resistant design is in establishing the critical earthquake input (**Design Earthquakes**). The second includes problems involved in determining the **demands** on the entire soil-foundation-building (superstructure and nonstructural components) systems by the critical earthquake. The third involves the visualization (for preliminary design) and prediction of the real **supplies** to the building at the moment that an earthquake strikes.

The supplies and demands, in general, involve the mechanical characteristics of stiffness, strength, stability, and energy absorption and dissipation capacities. Evaluation of the **demands** and prediction of the **supplies** are not straightforward. Determination of the **demands**, usually by numerical analysis using mathematical models of the entire soil-foundation-building system, depends on the interaction of this system as a whole with the excitations that originate from changes in the system environment and on the **intimate interrelation between the demand and supply itself**. Specific problems encountered in the three problematical areas of the earthquake-resistant design of structures -- **critical earthquake input, demands on the building, and supply capacities to the building** -- are discussed in Refs. 6-8.

While a sound preliminary structural design and reliable analyses of this design are necessary, they do not ensure an efficient EQ-resistant structure. The seismic response of a structure depends on the state of the entire soil-foundation and superstructure system at the time that earthquake shaking occurs, i.e., response depends not only on construction, but on maintenance as well. A design will only be effective if the model used can be 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 through, for example, supervision and inspection.

State-of-the-Practice This review will focus on just the state-of-the-practice of EQ-resistant design of buildings as reflected by present building seismic codes and emphasize how the concept of μ is used and/or how it could be used to improve the state-of-the-practice according to present knowledge.

Estimation of Demands in Present Seismic Codes: Although the review has been focused on U.S. seismic codes, the problems identified below are common to most codes in the world. There are several sources of uncertainty in code-specified procedures for the estimation of demands, uncertainties that can be grouped in two categories: (1) specified seismic forces; and (2) methods used to estimate response to these seismic forces.

For regular buildings, statically equivalent lateral seismic forces can be derived as follows. **For base shear:** $\mathbf{V = C_s W = (C_{sp}/R)W}$ [Eq. (2)] where V is base shear, C_s is defined as the design seismic coefficient, W is the weight of the reactive mass (i.e., the mass that can induce inertial forces), C_{sp} is the seismic coefficient equivalent to a linear elastic response spectral (LERS) acceleration, S_a, ($C_{sp} = C_s R = S_a/g$), and R is the reduction factor. Although in most of the codes the values of R are given without any explicit relation to μ_δ, these values implicitly depend on μ_δ.

Structural response is usually estimated using linear elastic analyses of the effects induced directly by the above statically equivalent lateral forces or by these forces multiplied by load factors depending on whether the design will be performed using allowable (service) stress or the strength method. There are only very few countries in which their codes recommend or encourage the use of limit analysis and limit design methods.

Code Procedure to Estimate Supplies Provided to the Structure Stiffness: **Stiffness** Most of the RC codes give only empirical expressions to estimate the so-called "initial" or "linear elastic stiffness."

Strength Most of the RC EQ-resistant design codes require that the provided supplied strength be estimated using a strength method in which nominal strength of critical sections are evaluated in function of just the minimum specified strength of the materials, and then it is reduced by a strength reduction factor. There are few codes, like the New Zealand Code, in which the design and detailing of the critical regions of the structure is based on the probable supplied strength capacity to the members. Although most of the present RC EQ-resistant design codes specify minimum size and reinforcement detailing according to the ductility ratio that is expected to be developed, this is done in an implicit way. Thus, it can be concluded that the state-of-the-practice, as reflected by most of present EQ-resistant design codes for RC buildings, do not appear to have included in a rational and reliable way the use of the concept of energy dissipation capacity through the use of the ductility ratio.

State-of-the-Art in Ductility Based EQ-Resistant Design The state-of-the-art, with respect to each of the problem areas identified above, is discussed in detail in Refs. 7-8. Here only the state-of-knowledge regarding the proper use of the concept of ductility ration in the EQ-resistant design process will be discussed. It is well recognized that EQ-resistant design requires an iterative procedure in which a preliminary design is improved through a series of analysis. The importance of a proper preliminary design should be overemphasized, because, if the design procedure is started with a poor preliminary design, the only thing that will be achieved at the end through its repeated analyses will be an improved bad design.

State-of-the-Art in Using Ductility Ratio μ_δ, in Preliminary EQ-Resistant Design
The first question that arises is where μ_δ should be used, i.e. in what steps of the whole design procedure? According to previous discussion, the answer is

obvious: Throughout the whole procedure, particularly in the final step, i.e. in the final designing and detailing of the critical regions of the structures. However as the importance of this last step is the main theme of the first part of this special session of the Conference, only the use of in estimating the demands will be discussed herein, specifically in (1) establishing the design EQs, and (2) in the preliminary design of the structure.

Use of μ_δ in Establishing the Design of EQs The following two main different methods are being used:

A. REDUCTION OF THE LINEAR ELASTIC DESIGN RESPONSE SPECTRA, (LEDRS) THROUGH THE DIRECT USE OF THE VALUE OF μ_δ (NEWMARK AND HALL PROCEDURE [9]), OR THROUGH THE USE OF R (ATC-3 PROCEDURE) R is a function of not only μ_δ but also of the provided overstrength, OVS, and increase in damping, ξ, due to plastic deformations.

B. DERIVATION OF IDRS THROUGH STATISTICAL STUDIES OF THE INELASTIC RESPONSE SPECTRA (IRS) OF STRUCTURES TO AVAILABLE RECORDED OR EXPECTED (PREDICTED) CRITICAL GROUND MOTIONS. These IRS are obtained through time history nonlinear dynamic analysis of structures with different yielding strengths (C_y), (or different degrees of μ_δ) and of ξ [10]. This method can be considered as a part of the overall energy approach to the design of EQ-resistant design [11].

Method A which is very simple, is already widely used and has been included in codes of several countries. However, as the proposers of this method pointed out, the method is only valid for very limited types of structures. The application of this method to the design of most real buildings is highly questionable [10-12].

Method B can be considered as the method of the future. Although it has already been applied to simple cases, its general application in practice will require extensive integrated analytical and experimental studies on real 3-D soil-foundation superstructure and nonstructural component systems. Once a reliable IDRS has been attained, the next problem is how to use μ_δ in the preliminary design of the structure.

Use of μ_δ in Preliminary Design For the purposes of this discussion, the different ways of conducting the preliminary design of EQ-resistant structures as far as the use of the ductility concept in the sizing of the structural members can be classified in the following three groups: **(a) μ_δ is not used at all.** The critical internal forces in the members are obtained through linear elastic distribution (LED) of forces. **(b) Implicit and Partial Use of μ_δ.** Usually this is done by allowing a limited amount of redistribution of the internal moments that have been obtained through a LED of forces. **(c) Use of Limit Design Approach.** Different methods, varying from the one based on simple plastic theory, which assumes infinity ductility, to those based on a more general plastic theory which consider "linear elastic serviceability conditions," as well as realistic limitation of μ_θ and μ_δ, incorporating also stability considerations. These methods are usually classified as **compatibility** and **serviceability** methods, with serviceability methods being the most promising of the two. This group also covers methods that include the possible occurrence of shakedown phenomena, which are, at present, being developed.

Concluding Remarks In summary, the author believe that the future of EQ-resistant design is on an energy approach in which the concept of ductility is used by combining the methods B and c, i.e., Bc, with proper consideration of the possibility of shakedown phenomena. However, this is considered a long-term approach. In present practice, most of the methods that are used can be classified as under the combination Aa. Although methods that can be classified as combined Ab are being used and have been investigated recently [13-15], the results of these investigations indicate the need for further studies regarding the: (1) proper limits in the amount of redistribution; and (2) the adequate redistribution pattern through the height of the structures.

In view of the above remarks, and the fact that it is very difficult to change radically the state-of-the-practice, the author would like to formulate for the immediate or very near future the following compromise solution: To conduct the preliminary design using improved Ab or Ac (or even Aa) methods; but, this should be complemented with time history nonlinear dynamic analyses of the response of the preliminary designed structure to the predicted probable maximum credible earthquake (MCEQ) ground shakings that can occur at the site of the structure during its service life. Before this compromise solution can be applied in practice, it is necessary to first identify the improvements that are needed, and then to carry out the studies required to achieve such improvements.

RESEARCH, DEVELOPMENT AND EDUCATIONAL NEEDS TO IMPROVE EQ-RESISTANT DESIGN

Improvement of Methods Based on the Use of LEDRS The compromise solution formulated above, i.e. the use of Aa, Ab, or Ac methods for preliminary design involves the combination of the use of an IDRS which is derived from a selected LEDRS through the use of μ_δ or R. Thus, there is a need to look at how each of these two ingredients can be improved.

Seismic Code Procedures to Determine LEDRS Because reliable, measured data on earthquake ground motions are scarce, design spectra are currently formulated using inadequate statistical information. Data from records of the severe ground motions of earthquakes that have occurred during the last seventeen years has altered the previous statistical base so dramatically that drastic changes in the LEDRS and, therefore, in the code-specified C_s have been required. Examples of such ground motions are: the 1971 San Fernando earthquake; the 1979 Imperial Valley earthquake; the recent 1985 Chilean and Mexican earthquakes, the latter being perhaps the most dramatic, and the 1986 San Salvador earthquake. Until 1971, the recorded NS component of the 1940 El Centro earthquake was considered the most extreme earthquake ground motion. The records obtained during the 1971 San Fernando Valley earthquake demonstrated, however, that the damage potential of this El Centro component was very low compared with that of some of the recorded San Fernando motions.

The author and his research associates have recently conducted a series of studies regarding the implications of recorded ground motions regarding the rationality and reliability of code LEDRS [7, 8, 11]. These studies clearly demonstrated that EQs like the 1940 El Centro (which is usually used as a MCEQ to check the safety of designed structures) have a damage potential to structures (as measured by its energy input, E_I) that are significantly smaller than that of recently recorded motions. This is illustrated in Fig. 6. Furthermore, as illustrated in Fig. 7 and 8, the LEDRS assumed by the 1985 SEAOC (which is the one used in the 1988 UBC) and ATC-3 are significantly smaller than the LERS corresponding to the recorded ground motions during the 1985 earthquakes in Mexico and in Chile, and in other earthquakes such as the 1986 San Salvador and the 1971 San Fernando earthquakes. Thus, if such ground motions were to occur in the U.S. in the future, the values of the LEDRS adopted by present U.S. code requirements will underestimate significantly the response that could occur.

Improvement of the Values of R. **Rationale for R Code Values** The author has recently analyzed the values of R that ATC-3 and the values of R_w that the 1985 SEAOC (1988 UBC) have recommended for reducing the LEDRS to the recommended IDRS. As discussed in more detail in Refs. 7 and 8, it is very difficult to judge the rationale for the values recommended for these R and R_w factors due to a lack of discussion or even any indication of how these values have been derived and what they are meant physically to represent. In Chapter 4 of the ATC-3 Commentary, it is stated that R "is an empirical response reduction factor intended to account for both damping and the ductility inherent in the structural system at displacements great enough to surpass initial yield and approach the ultimate load displacement of the structural system." In evaluating this statement, it should be noted that the LEDRS selected by ATC is already based on a 5% damped LEDRS. Therefore, the equivalent viscous damping expected in clean structures should not be significantly greater. If the values of R and R_w will depend only on μ_δ then the studies reported in Refs. 6-9 clearly demonstrate that for any selected resistance function, damping ratio, and ductility, the reduction factor varies with the period of the structure, decreasing as T decreases. It therefore appears that the recommendation of a constant value for R (or R_w), i.e., that the value be independent of T for the structure, cannot be justified solely on the basis of the ductility built up in a structure. The values recommended for R (or R_w) appear too high, particularly for short period structures (say, T less than 0.5 seconds) if the designer attempts to provide the structure with only the strength required by the code. Fortunately, as shown in previous publications [7, 8], the resulting code design generally produces a significant overstrength.

A better explanation of R is given in Chapter 3 of the ATC-3 Commentary. "The response modification factor, R, and ... have been established considering that structures generally have additional overstrength capacity, above that whereby the design loads cause significant yield." The author believes that this overstrength, OVS, together with built-in toughness is a "blessing" because of which structures designed according to presently specified design seismic forces (UBC or recommended ATC values) are able or would be able to withstand MCEQ shaking safely. The first "significant effective yielding" of properly designed (sized), detailed, constructed and maintained structures is not only considerably higher than that on which the code design is based, but such structures also have a significant overstrength beyond their first effective yielding. The resulting overstrength usually totals 2 to 3 times the minimum code-specified effective yield strength.

Implications of Recent Research Results with Respect to Rationale for R Code Values In Refs. 7 and 8 the author has analyzed the implications of the results obtained in shaking-table experiments on a seven-story RC frame-wall test structure, and after comparing ATC minimum required design strengths, the design strength used, ATC 5% damped LEDRS, 5% damped LERS for shaking table motion and measured strengths (Fig. 9), the actual value of R, termed R_a, could not have been larger than 2.7. Therefore, it was also concluded that "It is very difficult to rationalize (justify) quantitatively the values recommended by ATC and R. If the value of R alone is used in the design of reinforced concrete frame-wall dual systems, i.e., **without any other requirements**, the resulting design will not be reliable. The use of a specific value for R should be tied to other requirements. In the present ATC recommendations, the value of R is tied to stringent requirements for detailing reinforced concrete ductile moment-resisting space frame members and structural walls. The author believes that this is not enough, and suggests that the preliminary design using ATC-recommended approach (or that of the UBC) be subjected to a limit analysis to obtain an estimate of the **actual maximum resistance** of the structure as it will be constructed, and that a value approximately 3 to 5 (depending on the structural type and fundamental period T) times the minimum yielding strength required by ATC be ensured. Furthermore, the design of the wall (sizing and detailing) against shear (as well as against shear of members of ductile moment-resisting space frames) should be based on this maximum resistance.

Figure 10 [11] clearly shows that structures with $T \leq 1.5$ sec. which have been designed according to ATC-3 ($\mu_\delta = 5.5$ and $\xi = 5\%$) will be required to have a yielding strength (represented by C_y) significantly higher than that required by

ATC (represented by C_s) or a strength capacity (defined in the figure as Overstrength Factor OVF (req'd) = required C_y / ATC's C_s) significantly higher than that required by the ATC-3 provisions. Reference 11 shows that a structure with $T \leq 1.0$ sec. that has been designed and constructed to just satisfy the minimum required resistance (C_s) by the ATC-3 provisions will be required to develop ductility displacement ratios, μ, well beyond the value usually considered as acceptable ($\mu = 5$). Lessons learned from analysis of performance of buildings during recent destructive EQs and results from recent research clearly indicate that low-rise buildings (less than 4 stories) usually have large overstrength with respect to that required by code. Thus, it appears that in U.S. cities the buildings with between 4 and 12 stories are the ones that have to be suspected of becoming a serious threat to life and/or of incurring large economic losses in the case of a major EQ.

Research Development and Educational Needs The assessment presented above clearly indicates that there are gaps in the knowledge necessary for reliable use of the concept of ductility in EQ-resistant design of structures. In particular, the following further research, development, and education are needed.

1. To develop practical methods of EQ-resistant design based on an energy approach.

2. More reliable engineering parameters than are presently used to define the damage potential of recorded ground motions are needed. The E_I is a promising parameter that should be investigated further.

3. To improve quantification of ductility ratios.

4. To attain more reliable LEDRS, it will be necessary to install appropriate instruments, networks and array to record strong motions in the free field and at the foundation of structures. Research should be carried to improve processing and probabilistic methods of analyzing strong motion data and quantifying seismic hazard.

5. To develop more reliable methods for estimating the values of R. This requires a more precise definition of R. The definition illustrated in Fig. 11 is proposed as a basis for improving the evaluation of R. For the proper use of this definition in evaluating reliable values of R, there is an urgent need for calibration of the real strength of structures that have been designed according to present code.

6. The lag time for research and development to be reflected in codes should be reduced. This will require a broad educational effort. Efforts should be made to synthesize research results in EQ hazards and EQ-resistant design and construction of structures and to put them in an easily understandable, simplified form that can be applied in practice.

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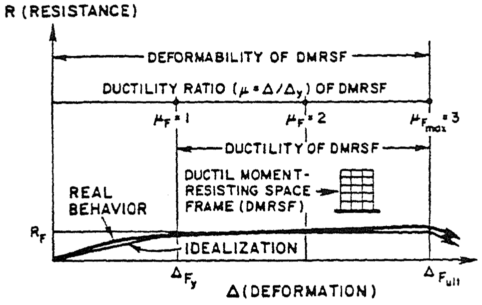

Fig. 1 Definitions of Deformability, Ductility and Ductility Ratio

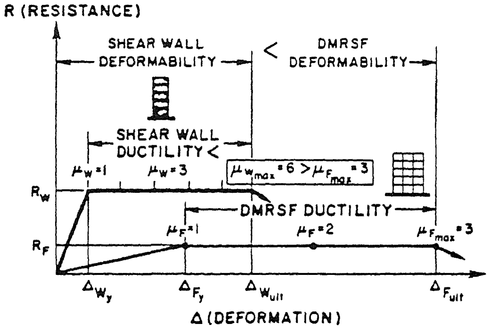

Fig. 2 Deformability and Ductility of an RC Wall and an RC DMRSF

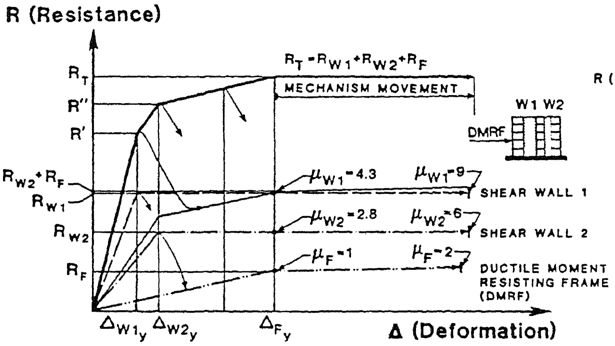

Fig. 3 Ductility Requirements for both Walls and Frames in an RC Frame-Wall System

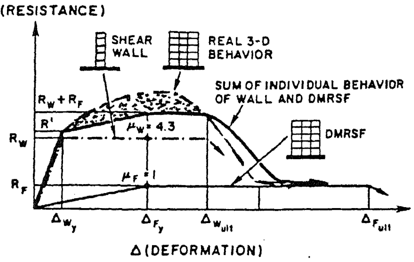

Fig. 4 The Effects of 3-D Interaction on the Strength of an RC Frame-Wall System

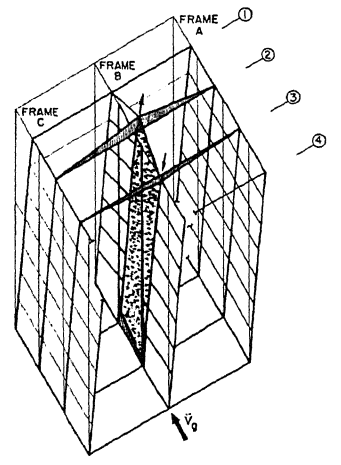

Fig. 5 Isometric View of Wall Rotation illustrating 3-D Outriggering Effect

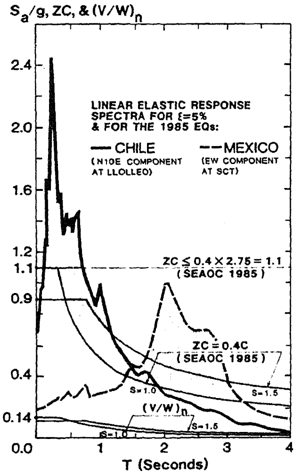

Fig. 7 Comparison of 5% Damped LERS and LEDRS

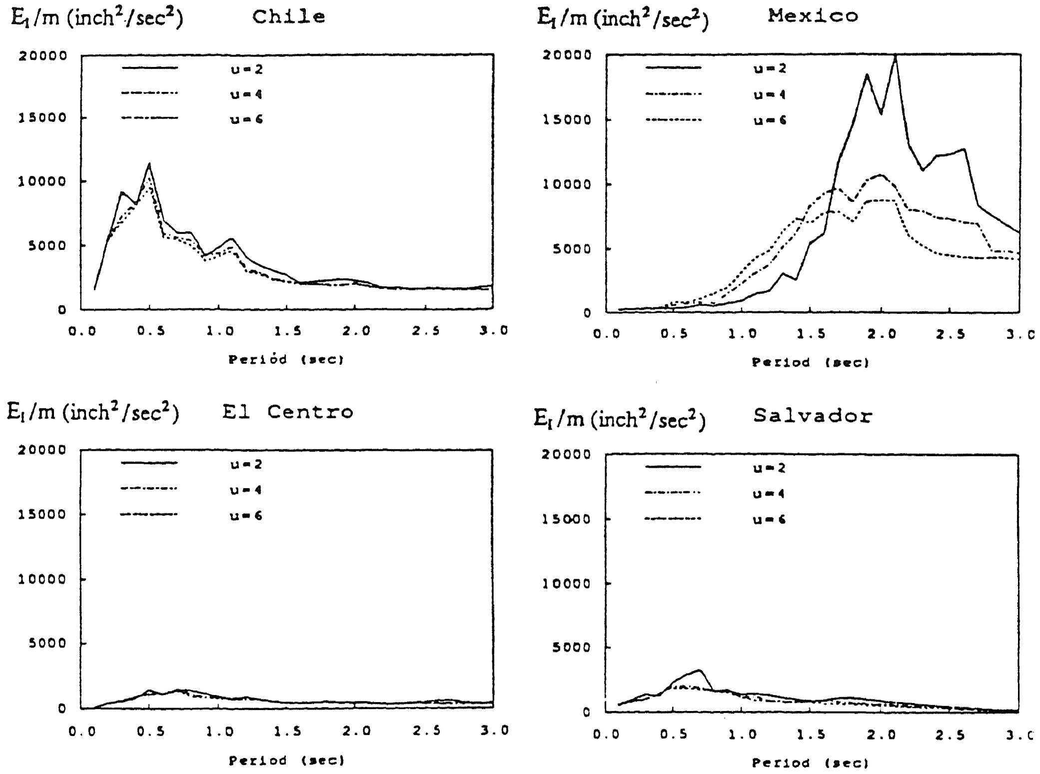

Fig. 6 Input Energy Spectra

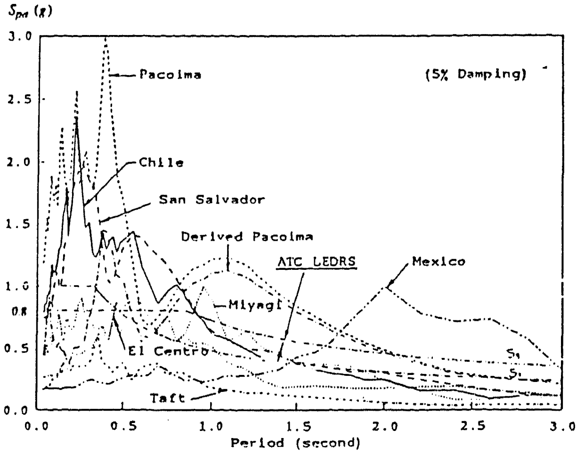

Fig. 8 Comparison of Pseudo-Acceleration Spectra, S_{pa}

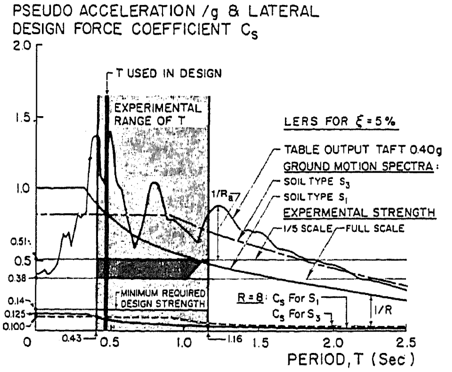

Fig. 9 Strength and Spectral Comparisons - ATC and Experimental

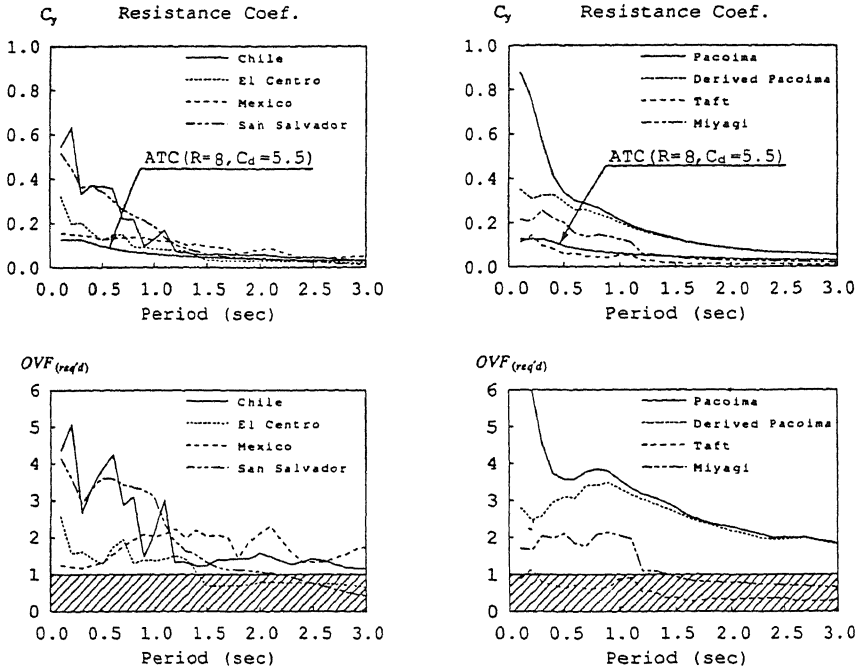

Fig. 10 Required Seismic Resistance Coefficient (C_y), and Over-strength Factor (OVF), for SDOFS designed in accordance with ATC for S_1 and assuming μ=5.5 and ξ=5%

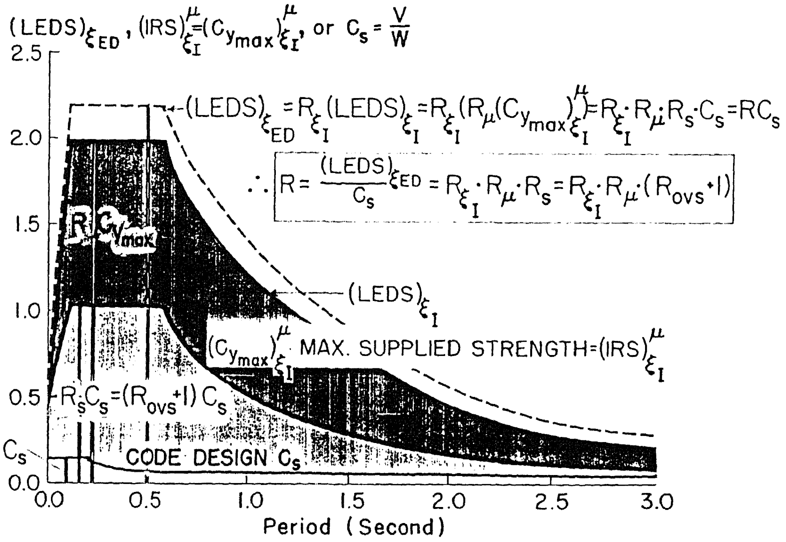

Fig. 11 Definition of the Response Modification Factor ($R = R_\mu \times R_\xi \times R_S$)