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A FEW BASIC CONCEPTS FOR PERFORMANCE BASED SEISMIC DESIGN

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ABSTRACT

Performance based seismic design needs to be based on fundamental concepts that can be derived from first principles and make the design process transparent and accessible to an objective evaluation process. This goal can be achieved with a demand/capacity based design process that consists of a conceptual design phase in which global strength and stiffness requirements are estimated and satisfied approximately, and a design evaluation and modification phase in which strength and deformation demands are predicted analytically, detailed acceptability criteria are established, acceptability is evaluated, and the design is modified as needed to fulfill all performance objectives in a structurally and economically effective manner. This paper outlines some basic concepts and provides quantitative information that is believed to be useful for this purpose.

KEYWORDS

Performance based design; seismic design criteria; ductility ratio; strength demands; deformation demands; conceptual design; strength reduction factor; inelastic spectra.

INTRODUCTION

In many countries seismic design is undergoing drastic changes triggered by a variety of reasons. Improved knowledge about earthquake occurrences and ground motion and structural response characteristics is certainly one of them. The realization from recent earthquakes in the U.S. and Japan that monetary damage can surpass expectations by a large amount is another one. Perhaps most important is the realization that present code design procedures often cannot be rationalized sufficiently by first principles to satisfy (a) the designer's desire for a logical explanation of the rules of the game, (b) the owner's desire for sound judgment on the costs and benefits of earthquake protection, and (c) society's needs for informed decision making in the face of uncertain (and often unknown) seismic demands and equally uncertain (and often unknown) seismic capacities of existing and even new man-made construction.

By now it is widely acknowledged that seismic design is not a one-step process with a single set of criteria targeted for a "universal" level of protection. There is a minimum level of protection demanded by society in order to safeguard against partial collapse that endangers human lives. But society has responsibilities in addition to life safety, including continuing operation of critical facilities, protection against the discharge of hazardous materials, and protection against excessive damage that may have far-reaching consequences for society on a local, regional, national, or international level. Moreover, educated owners want options for maximizing the return on their investment or for providing life safety protection to the inhabitants of their facilities beyond the minimum required by society. These options differ between developers and, for instance, corporate owners whose livelihood may depend on the resumption of operation soon after an earthquake. In the past, most of these considerations were lumped into judgmental scaling factors in the base shear equation. [In the 1994 U.S. Uniform Building Code the term I/R_w (I = importance factor, R_w = system dependent strength reduction factor) accounts for many of these considerations]. It is becoming widely recognized that a simple elastic design based on a single seismic load level that is difficult to relate to seismic input and structural performance will not fulfill the needs of society and owners in the future.

The need to consider different objectives associated with various levels of performance has led to a recent emphasis on, and some developments in, performance based seismic design. There is increasing agreement that future seismic design will have to be performance based, but there are widely divergent viewpoints of the meaning of performance based design and its methods of implementation. In concept, performance based design provides the opportunity to society and owners to chose performance goals, and it compels the designer to formulate and implement a design process that fulfills the stated goals. This paper cannot address the many issues associated with performance based design. The reader is referred to recent development efforts on this topic (e.g., SEAOC, 1995; ATC, 1995) and to several papers presented in the Special Theme Session on Seismic Design Criteria (e.g., Bertero, 1996; Cornell, 1996; Hamburger, 1996; Moehle, 1996; Otani, 1996). Few things are clear about performance based design except that it will change the way structures will be designed, and that much research and development is needed before it can be implemented in a consistent fashion.

Different performance levels and objectives will require different design criteria to be applied to different design parameters. In general, performance may be concerned with structural and nonstructural systems as well as facility contents, and with various levels of behavior, ranging from cosmetic damage to partial or complete collapse. There is no single design parameter that will control all performance objectives at all performance levels. Ground shaking will impose demands on different design parameters, and satisfactory performance implies that the imposed demands do not exceed the capacities associated with the specified performance objectives. For instance, structural damage threshold is controlled by element strength capacities, but strength demands are greatly affected by element deformations that make up the structure stiffness, which in turn controls the inertia forces generated in the structure. Nonstructural damage is controlled mostly by interstory drift limitations, which demand large stiffness. Content damage, on the other hand, is often proportional to floor accelerations, which can be limited by reducing the stiffness and/or strength of the structure. At the other extreme, life safety and collapse prevention are controlled by the inelastic deformation capacity of ductile elements and the strength capacity of brittle ones.

This discussion shows that different performance objectives may impose conflicting demands on strength and stiffness, and that seismic design is likely to become an iterative process in which different performance objectives may lead to a trade-off between strength and stiffness requirements, but in which no compromises can be made on issues of life safety and collapse prevention. This iterative process can be accomplished in two phases; a conceptual design phase in which a suitable structural system is configured and rough-sized, and an evaluation and modification phase in which the system is analyzed, evaluated, and modified to fulfill all performance objectives. The conceptual design phase needs rough targets for strength, stiffness, and ductility demands, and the evaluation and modification phase needs acceptability criteria based on capacities of the selected structural, nonstructural, and content systems.

This paper addresses concepts that are intended to assist in the conceptual design phase and the design evaluation/modification phase of a performance based design.

DEFORMATION BASED DESIGN CONCEPTS

The designer has at least six basic features available to configure and tune a structure so that it performs in accordance with chosen performance objectives. These features are strength, stiffness, ductility, base isolation, passive energy dissipation, and active control. The last three are not discussed in this paper. It is argued here that the first three are deformation driven, implying that deformations are the properties most appropriate for tuning structures to fulfill performance objectives. This is the case for high performance levels concerned with damage control, where the structure stiffness (i.e., natural periods) controls the strength demand for the structural system and the interstory drift demand for nonstructural elements. It is also the case for low performance levels concerned with life safety or collapse prevention, where the inelastic deformation capacity of ductile elements controls the strength demands needed to provide structural stability.

The conclusion is that strength demands are derived quantities, and that their magnitudes can be controlled by manipulating deformation quantities. For high performance levels this implies manipulation of the global stiffness and of story stiffnesses. Interstory drift limitations due to nonstructural performance requirements can be used to estimate an acceptable roof displacement. Considering that the global roof displacement is rather insensitive to higher mode effects, elastic displacement spectra (together with an estimate of the first mode participation factor) can be used to estimate an upper limit on the fundamental period and corresponding stiffness values. The corresponding strength demands (for elastic behavior) can be deduced from acceleration response spectra and appropriate modal properties.

For low performance levels, in which significant inelastic deformations have to be tolerated, limits on the global roof displacement (e.g., for pounding) and interstory drift (e.g., for P-delta control), and the ductility (or plastic deformation) capacity of the ductile elements in the structure become basic design parameters. How strong the structure and its elements have to be depends on the limits of tolerable deformations. Presuming that the ductility capacity of structural elements is known (an issue to be discussed later), story and global structure ductility capacities can be estimated and inelastic strength demand spectra can be utilized to estimate the required strength for the structure.

This conceptual procedure requires answers to many questions, ranging from probabilistic aspects of earthquake occurrences (needed to define demands at different performance levels) to quantification of performance objectives. This paper focuses on low performance levels (e.g., collapse prevention) and will comment only on the following three issues:

- Acceptability criteria for structural elements
- Strength and stiffness requirements for conceptual design
- Design evaluation

In the latter two issues it is assumed that earthquake severity levels have been established and ground motion descriptions at the site are available in the form of spectra and/or time history records.

ACCEPTABILITY CRITERIA FOR STRUCTURAL ELEMENTS

At the collapse prevention level acceptable performance implies that the structural system must have sufficient integrity to prevent partial or complete collapse and to provide adequate gravity load resistance (global stability) at the deformations associated with the design earthquake. In the design process, acceptable performance is achieved if in all elements of the structure the predicted demands are less than or at most equal to the available capacities. Capacity takes on a different meaning for different performance levels and different actions. A component may experience a brittle failure mode, in which case the strength capacity is the critical quantity (for instance, axial force in a column that is part of the gravity load system). The same component may experience a ductile deformation mode in a different action (for instance, bending moments applied to the same column), in which case the deformation capacity needs to be defined. For the collapse prevention level the deformation capacity may be associated with the onset of significant deterioration if the integrity of the element is critical to the stability of the structural system, or it may be larger if significant deterioration has acceptable consequences. For new construction there is no good reason to permit significant deterioration even at a low performance level, but it may be acceptable for existing structures (for instance, loss of beam bending resistance at a welded steel beam-to-column connection, provided that shear capacity can be maintained and sufficient redundancy exists in the structural system).

General element behavior may be described - in concept - by a multi-linear force-deformation relationship of the type illustrated in Fig. 1. It appears that δ_m is a critical deformation quantity for acceptability at low performance levels. The problem is that this deformation is a moving target that cannot, at this time, be determined with accuracy or confidence. Real cyclic behavior is represented by hysteresis diagrams of the kind shown in Fig. 2. Stiffness and strength degradation, which sooner or later will occur in every element, take on different forms depending on the type of element, material, and loading history. In particular, the loading history has a significant effect on deterioration. Every cycle the element experiences in an earthquake causes damage, and the state of deterioration at a given time depends on the cumulative damage caused by previous cycles. Many cumulative damage models have been developed (e.g., Park et al., 1984; Krawinkler and Zohrei, 1983), but none of them are sufficiently general to model deterioration with due regard to all the phenomena controlling the time history response of a structural element (cycle amplitudes, sequence effects, strong motion duration effects, etc.).

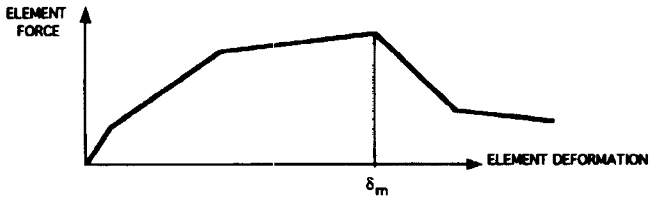


Fig. 1 Conceptual Load-Deformation Response

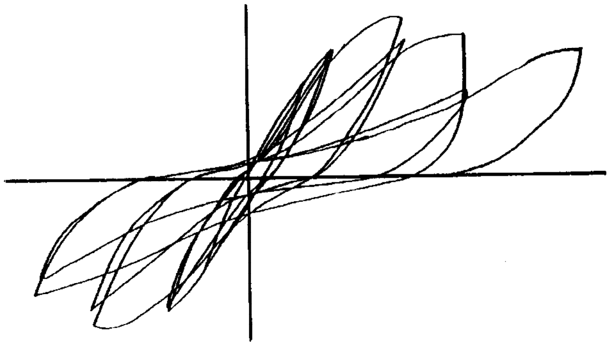


Fig. 2 Typical Cyclic Load-Deformation Response

The upshot of this brief discussion is that much more research is needed to provide the knowledge required to predict element deformation capacities with confidence. At this time rough and often judgmental rules have to suffice (e.g., ATC, 1995). This may not be a major drawback since deformation demands cannot be predicted accurately either, and since accurate predictions of deformation demands and capacities are desirable but likely not critical, particularly for components that deteriorate in a gradual manner. What is likely more important is the realization that collapse and life safety hazards are caused primarily by brittle failure modes in components and connections that are important parts of the gravity and lateral load paths.

What is needed in the design evaluation phase is capacity information in a format that facilitates interpretation of the analysis results. Whenever possible, capacity information should be given in terms of parameters that are directly obtained from the analysis. At the element level such parameters are absolute deformation values (e.g., plastic hinge rotations) and not ductility ratios. There is too much ambiguity in expressing acceptability criteria in terms of a ductility ratios since the latter depend on the definition of a yield deformation and since acceptable ductility ratios depend on the geometric configuration of the element.

What is needed in the conceptual design phase is an estimate of the global ductility capacity of the structural system, which can be used to estimate global strength and stiffness requirements. In this phase the details of the structural system are not known, but a global target ductility ratio can be estimated based on knowledge about the deformation capacity of the elements that make up the system. There is no contradiction between the estimation of a global target ductility ratio for conceptual design and the statement made earlier that design evaluation should be based on absolute deformation quantities. Conceptual design serves to configure a structural system, and estimate member sizes. Fine tuning of final member sizes and details is to be done during the design evaluation phase. In concept it is feasible - although difficult to implement because of inadequate knowledge - to weigh the target ductility ratio for expected cumulative damage based on the number of inelastic cycles the structure is expected to experience in the design earthquake.

TARGET STRENGTH AND STIFFNESS REQUIREMENTS FOR CONCEPTUAL DESIGN

Explicit and direct design for deformation capacities is difficult to implement in engineering practice. Strength and elastic stiffnesses (or deflections) are the design parameters with which designers are familiar. Thus, the need exists to establish target values for these parameters, which can be utilized to select and evaluate suitable structural systems and to perform a preliminary design for final evaluation. In order to avoid excessive modifications during the design evaluation phase, it is prudent to consider all performance levels at this stage. High performance levels concerned with control of damage lead to requirements on the elastic strength and stiffness as has been stated earlier. This section is concerned only with target strength and stiffness requirements for low performance levels at which significant inelastic deformations have to be tolerated.

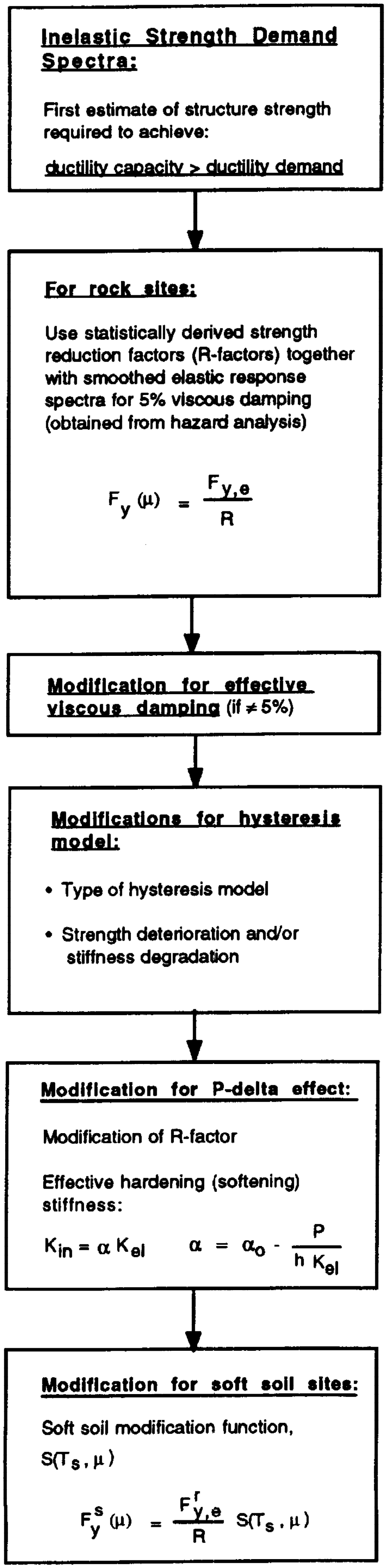
Much research has been performed on this subject by many investigators, which cannot be summarized in this short paper. The following discussion presents concepts on which the derivation of strength and stiffness requirements can be based, and representative results obtained by the author and his students are used to illustrate the significance of some of these concepts. It is assumed that a global target ductility ratio for the structural system has been established based on the deformation capacities of the critical elements of the system. Given this target ductility ratio, the issue is to estimate strength and stiffness requirements so that a good preliminary design will result in behavior that is close to fulfilling strength, deformation, and deflection based performance criteria under the design earthquake.

Fundamental information on inelastic strength demands (see Fig. 3) and displacement demands (see Fig. 4) can be derived from statistical information on nonlinear SDOF systems, using bilinear nondegrading hysteresis models and ground motions on rock sites as baselines. Inelastic strength demand spectra for a target ductility ratio μ can be obtained from elastic ground motion spectra and statistically derived strength reduction factors (R-factors), whose definition is illustrated at the top of Fig. 3. Many expressions for period and ductility dependent R-factors are reported in the literature (e.g., Miranda and Bertero, 1994; Nassar and Krawinkler, 1991). These R-factors (or the corresponding inelastic spectra) need to be modified to account for non-baseline conditions as shown in Fig. 3. Studies by Nassar and Krawinkler (1991) and Rahnama and Krawinkler (1993) have shown that stiffness degradation has little effect on R-factors but that strength degradation may have a significant effect. P-delta effect decreases the R-factor considerably if it results in an effective negative post-yield stiffness (negative strain "hardening" ratio α). Most important is the modification of basic inelastic spectra if a structure is located at a soft soil site. Rahnama and Krawinkler (1993) proposed the use of a soil modification function $S(T_S, \mu)$ as shown at the bottom of Fig. 3. The period T_S is the predominant soil period.

Inelastic displacement demand spectra for a target ductility μ can be obtained by multiplying the corresponding elastic displacement demand spectrum with μ/R. Figure 4 illustrates this process for ground motions at rock sites and soft soil sites. It also shows typical examples of the period dependent ratio of inelastic to elastic displacement demands. For rock motions this ratio is insensitive to μ and smaller than unity for all but short period systems, but depends strongly on μ and increases rapidly for short period systems. For soft soil motions this ratio depends strongly on the period ratio T/T_S; it is much smaller than unity around $T/T_S = 1.0$, but exceeds unity and is strongly dependent on μ for $T/T_S < 0.75$.

Demand information obtained from studies on SDOF systems provide baseline data but need to be modified for MDOF effects in order to be applicable to real structures. Modifications for higher mode effects for frame and wall structures are discussed elsewhere in these proceedings (Seneviratna and Krawinkler, 1996). Much more research is needed to assess the effects of design overstrength, vertical strength and stiffness irregularities, torsion, and soil-structure interaction.

Presuming that all important MDOF modifications can be evaluated, the global strength and stiffness requirements for the structural system are established. Since the information is obtained from bilinear SDOF systems, the reference for preliminary strength design is the mechanism strength of the structure. Thus, plastic design is the direct approach to strength design. Alternatively, elastic design at the member strength level may be used, which requires estimation of the difference between the structure's elastic strength and mechanism strength, and may involve re-sizing of members in the evaluation and modification process summarized next. There is much more to preliminary design than can be discussed here since the objective is not only to provide the structure with sufficient global strength and stiffness, but also to balance relative member strengths so that inelastic behavior occurs in those elements that can be detailed for ductility and so that overloads on "brittle" elements (no or unreliable ductility capacity) are avoided when the structure is subjected to a collapse level design earthquake. The latter can be achieved with rather well established capacity design concepts.



Inelastic Strength Demand Spectra:

First estimate of structure strength required to achieve:

ductility capacity > ductility demand

For rock sites:

Use statistically derived strength reduction factors (R-factors) together with smoothed elastic response spectra for 5% viscous damping (obtained from hazard analysis)

$$F_y(\mu) = \frac{F_{y,e}}{R}$$

Modification for effective viscous damping (if ≠ 5%)

Modifications for hysteresis model:

- Type of hysteresis model
- Strength deterioration and/or stiffness degradation

Modification for P-delta effect:

Modification of R-factor

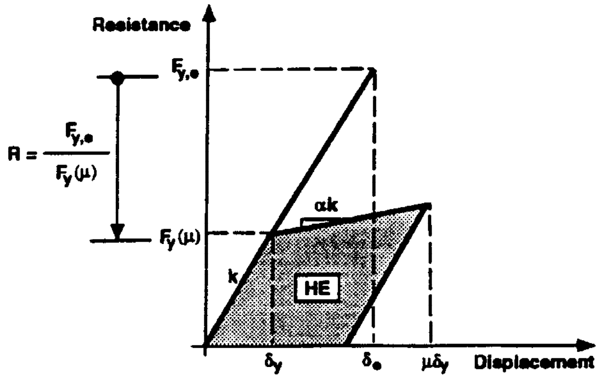
Effective hardening (softening) stiffness:

$$K_{in} = \alpha K_{el} \qquad \alpha = \alpha_o - \frac{P}{h K_{el}}$$

Modification for soft soil sites:

Soft soil modification function, $S(T_s, \mu)$

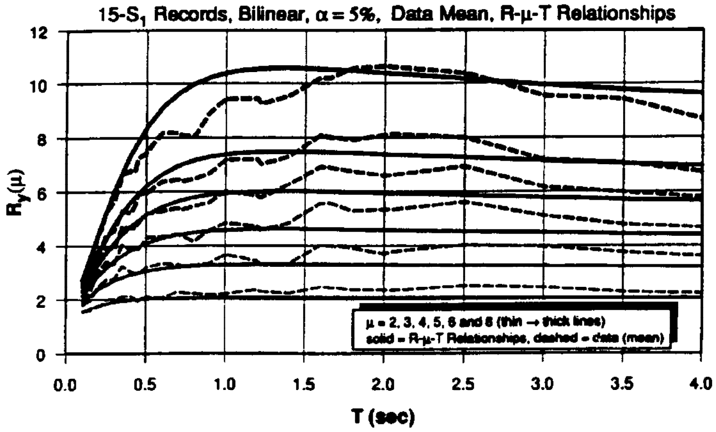
$$F_y^s(\mu) = \frac{F^r_{y,e}}{R} S(T_s, \mu)$$



BASIC SEISMIC DEMAND PARAMETERS

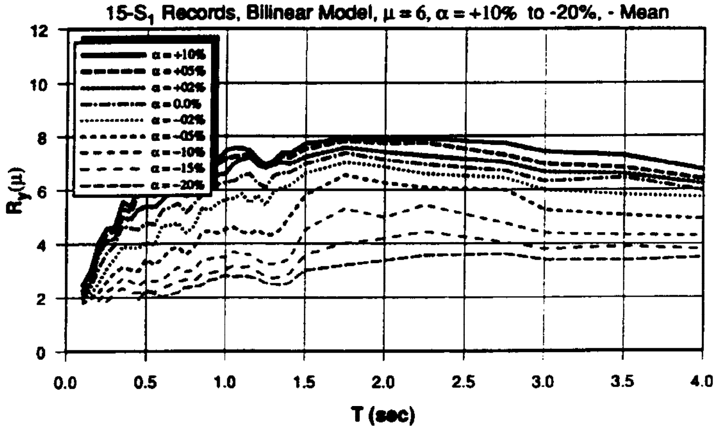
STRENGTH REDUCTION FACTORS, $R_y(\mu)$-(15s.bi-05)

15-S_1 Records, Bilinear, α = 5%, Data Mean, R-μ-T Relationships



EFFECT OF STRAIN HARDENING/SOFTENING ON $R_y(\mu)$

15-S_1 Records, Bilinear Model, μ = 6, α = +10% to -20%, - Mean



MODIFIED STRENGTH DEMAND SPECTRUM FOR SOFT SOILS

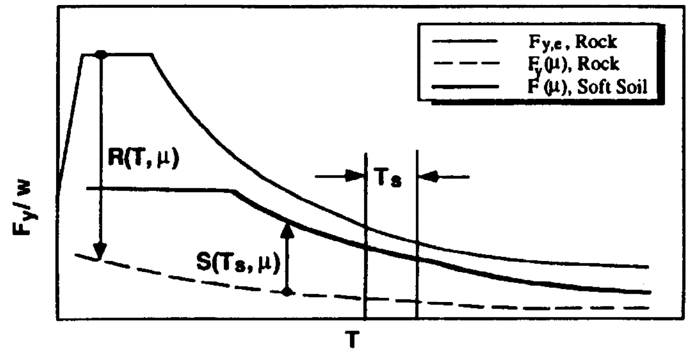


Fig. 3 Tools for development of inelastic strength demand spectra

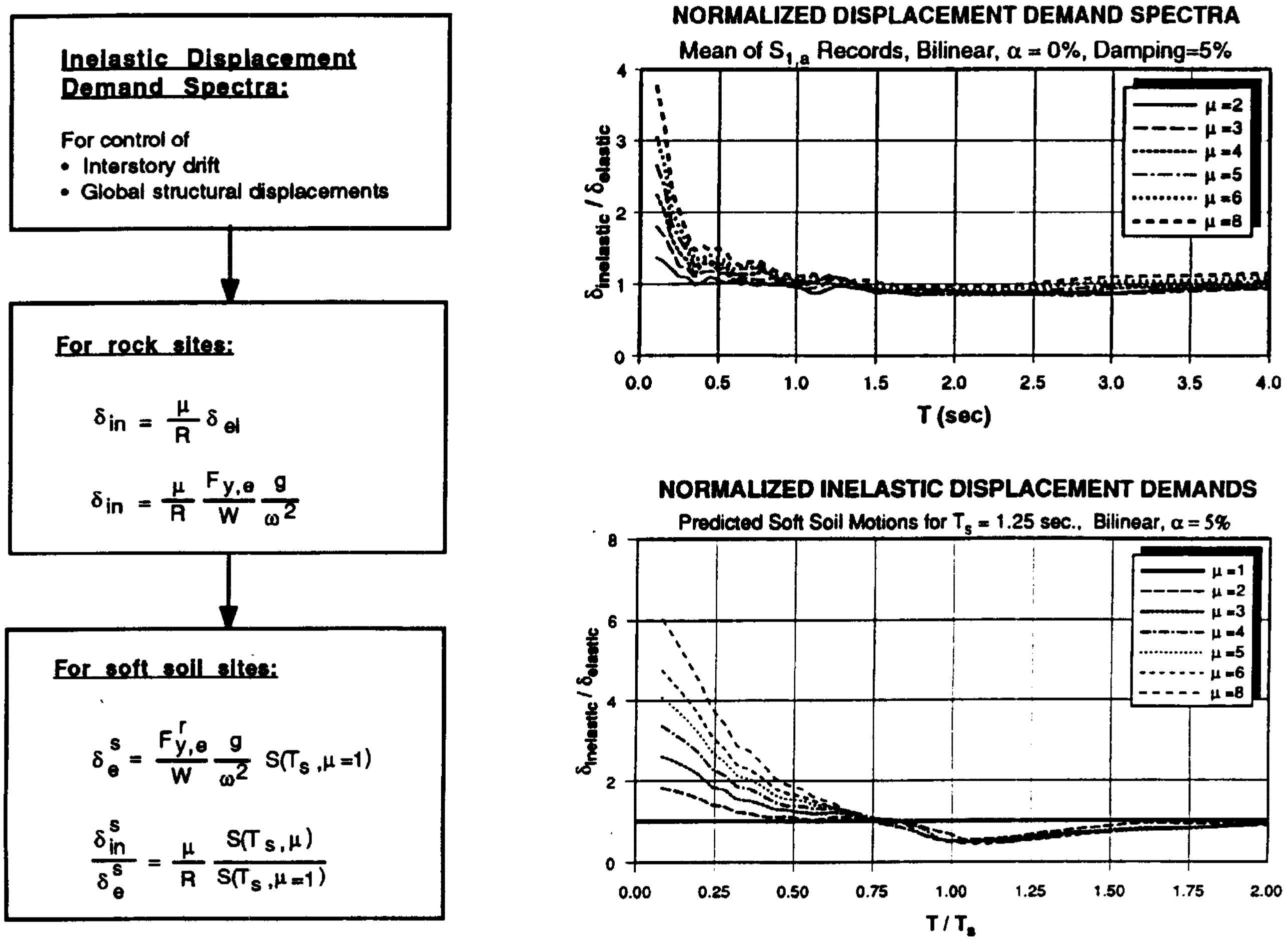


Fig. 4 Tools for development of inelastic displacement demand spectra

DESIGN EVALUATION AND MODIFICATION

Considering that a conceptual design for target strength and ductility does not assure acceptable performance at any or all performance levels, an evaluation and modification process needs to form an essential part of the design procedure. Evaluation implies that demands and capacities are assessed under the design earthquake actions. At low performance levels the evaluation process will require an inelastic analysis that provides reasonable estimates of deformation demands in ductile elements and conservative estimates of force demands in brittle elements that must be protected from overloads. If the demands are found to be excessive, the design needs to be modified to fulfill the stated performance objectives.

Much of the needed information can be obtained - within limitations - from a static incremental pushover analysis. In a pushover analysis the structure is loaded with a predetermined or adaptive lateral load pattern and is pushed statically to target displacements at which the performance of important elements and of the structure is evaluated. The target displacements are estimates of global displacements expected in the design earthquakes corresponding to the chosen performance levels. This method works reasonably well if higher mode effects are not very important and if the many limitations and shortcomings of the pushover analysis are recognized and accounted for (ATC, 1995).

It is fair to say that the pushover method is an improvement over existing elastic analysis methods but is an unsatisfactory long-range solution for important structures. The most realistic verification process is the prediction of deformations and forces from nonlinear time history analyses, utilizing a series of representative ground motions that bracket the range of frequency contents and amplitudes expected in a design earthquake. The general use of such a verification procedure requires that (a) representative ground motions can be generated with confidence, (b) the structure can be modeled realistically for nonlinear time history analysis, (c) the cyclic inelastic load-deformation characteristics of each element can be modeled realistically, and (d) reliable analysis and interpretation tools are readily available to the practicing engineers. The state of the art and practice on these issues is not at a level that permits widespread usage, but it should be a target for researchers to provide the knowledge and tools, and for the practitioners to implement them.

CONCLUSIONS

Performance based seismic design needs to be based on fundamental concepts that can be derived from first principles and make the design process transparent and accessible to an objective evaluation process. This goal can be achieved with a demand/capacity based design process that consists of a conceptual design phase in which global strength and stiffness requirements are estimated and satisfied approximately, and a design evaluation and modification phase in which strength and deformation demands are predicted analytically, detailed acceptability criteria are established, acceptability is evaluated, and the design is modified as needed to fulfill all performance objectives in a structurally and economically effective manner. This paper outlines some basic concepts and provides quantitative information that is believed to be useful for this purpose, but it is recognized that much fundamental and applied research is needed before a performance based design process can be implemented in engineering practice.

ACKNOWLEDGEMENTS

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