DISPLACEMENT-BASED SEISMIC DESIGN CRITERIA

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ABSTRACT

Performance-based seismic design criteria, intended to produce structures that satisfy specific performance objectives, are under development by various individuals and organizations. Many of these are evolving around displacement-based design concepts, which use expected displacement response of a structure to gauge performance. Displacement-based seismic design criteria possess the benefit of being relatively simple and direct in their application in the design process. Limitations of these criteria should be recognized. Probabilistic approaches should be developed and applied to deal with the uncertainties in estimating demands and capacities.

KEYWORDS

displacement-based design, earthquake-resistant design, experimental data, performance-based seismic design, seismic response, reinforced concrete construction

INTRODUCTION

There are no simple, reliable, and fool-proof rules that will produce safe and economical structures all the time. Earthquakes, and earthquake responses, are complex phenomena depending on uncertain physical conditions, and gauged by social needs and expectations for which there is no universal standard. Earthquake occurrence, earthquake characteristics, and structural response characteristics are not deterministic, and need to be viewed as probabilistic or even chaotic phenomena. Designs are implemented by mere humans, and the design product may be altered by natural or human influences throughout the life of the structure. In the face of these formidable impediments, why, then, displacement-based seismic design?

There are, in fact, simple reasons why displacement-based seismic design is in many cases a useful and preferable approach to seismic design. Perhaps most importantly, displacement-based design is an intelligible tool for achieving a measure of performance in structures constructed at sites prone to earthquake shaking. Its concepts apply to a range of structure types, from single-story, single-element systems to multi-story, mixed-element systems. Of equal importance, displacement-based design can be viewed as a naked tool, one that is so simple and direct that its user can see all its beauties and its flaws.

The object of this paper is to define displacement-based seismic design, to illustrate how it relates to performance, and to describe its current limitations. Some examples of applications in current codes and design guidelines are described.

DEFINITION OF DISPLACEMENT-BASED DESIGN

Displacement-based seismic design means simply that the design takes into account the anticipated earthquake-induced displacements for the design event(s). Whereas conventional code design approaches focus on design forces, the focus of displacement-based design approaches is displacements. Furthermore, an emphasis is directed to achieving a realistic, and realistically-conservative, estimate of the displacements. Several interpretations of the approach have been put forward.

By one interpretation [Sozen; 1981], displacement-based seismic design recognizes that displacement amplitude, and especially interstory drift amplitude, relates directly to structural and non-structural damage in yielding systems. Therefore, the designer should use displacement information to select the structural system that economically will produce reduced displacements by comparison with other competing systems. This version of displacement-based design does not presume to provide adequately accurate information to enable the designer to directly relate the calculated displacements and the structural details. In light of the uncertainties involved, this limited version of displacement-based design may actually be the most realistic.

By another interpretation [Moehle; 1992], displacements are used first as an aid in selecting the basic structural system, and then the anticipated displacements are used directly as an aid in proportioning the structure and selecting details. Wallace and Moehle [1992] show one application of this approach to wall building design, where it is found that requirements for confined boundary elements relate directly to the quantity of walls provided in the structural system. In these approaches, the engineering either selects the details given the expected structural displacements, or selects the structural system to limit the required details. Priestley [1993] suggests that the engineer first select a target displacement and corresponding details, and then back-calculate structural characteristics required to achieve the target displacement. Obviously, these approaches are limited by the quality of information on ground motion and structural response.

The fact that displacements are the focal point of the design process does not excuse the designer from considering other aspects. For example, the design should attempt to control the yielding mechanism in a yielding structure, so amplitudes of local demands can be controlled, and so details can be apportioned to the critical regions. Therefore, elements of capacity are directly applicable in a displacement-based design approach.

DISPLACEMENTS AND PERFORMANCE

Performance of a structure following an earthquake typically is gauged by whether it posed a significant life-safety threat, and if it did not, by how much it will cost and how long it will take to return it to service. Because these parameters generally relate to specific levels of damage, a damage indicator is a critical component of performance based design. For seismic design, implemented by engineers with limited resources, the indicator should be simply defined. Obvious choices are force or displacement amplitude.

Damage in a yielding structure usually can be related more directly to displacement (distortion) than to force or stress. An obvious example on the material level is a steel coupon subjected to direct tension. During a tension test, fracture occurs when the engineering tension strain reaches a characteristic value. Although there exists a corresponding engineering stress level to which failure can be related, the fact that the material is yielding means that strain is a more discerning measure. Similar relations exist for structural components. Practical examples relating damage to deformation include failure of confined concrete at large strain limits, cracking of masonry panels under in-plane loading, and damage to non-structural components under in-plane racking.

Degradation of component strength, and consequent failure modes, also may be related to deformations. An example is provided by the relations in Figure 1 [ATC-6-2; 1983], where it is suggested that shear strength of a reinforced concrete column is directly related to the component deformation demand. Lehman, et al. [1996] present experimental data in support of the relation shown in Figure 1.

Design approaches based on anticipated ductility demands, rather than actual deformations, have been proposed [e.g., Park; 1986]. These approaches have many advantages. However, they ail in some important aspects. Importantly, it has been reported that displacement at first yield cannot be accurately determined for actual structural components, with typical errors being on the order of plus or minus 50% [e.g., Sozen, et al.; 1992]. It follows that deformation ductility capacity (equal to the ratio of deformation capacity to yield deformation) as a measure of performance is problematic.
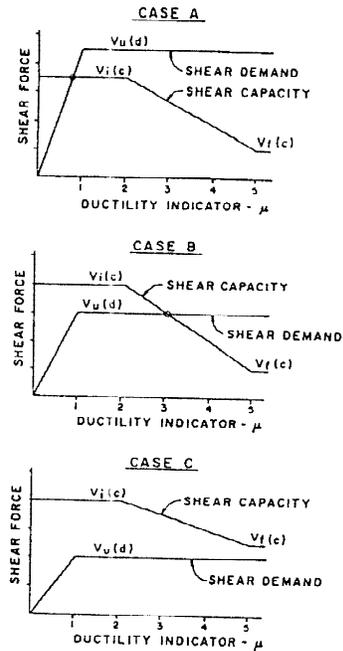

Figure 1 - Relation between shear strength and displacement ductility demand. Case A indicates shear failure without flexural ductility. Case B indicates shear failure after flexural ductility. Case C indicates flexural ductility without shear failure.

Displacement-based approaches hold some distinct advantages for seismic evaluation and rehabilitation of older existing construction where there may exist a mixture of old and new components having widely different stiffness, strength, and deformation capacity. Figure 2 illustrates an idealized problem, where it is determined that an existing structure (Figure 2a) has inadequate deformation capacity (Figure 2c) for the design deformation demands (Figure 2d). By introducing a new bracing system of high stiffness and deformation capacity (Figure 2b), it is possible to improve the overall performance of the system (see Figures 2c and 2d). By viewing the problem through a displacement perspective, the solution is plainly visible. If a traditional strength based approach was used, the designer would be faced with the circuitous path of determining the required strength to limit ductility demands in a mixed system, and deformation compatibility would have to be checked to ensure that the existing components were not deformed beyond their capacities. In cases such as these, a displacement-based approach is more simple, more direct, and more effective.
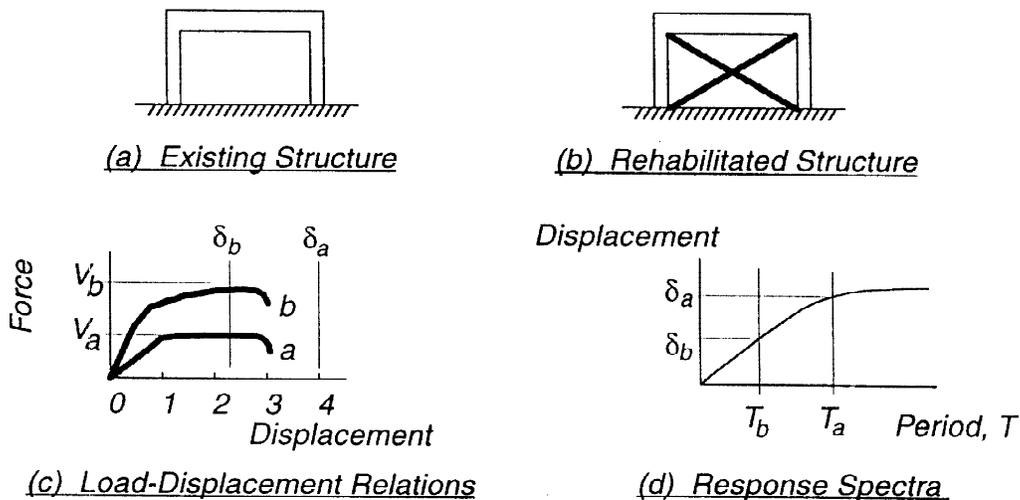

Figure 2 - Illustration of displacement concepts applied to seismic rehabilitation of an existing frame

In promoting displacement-based design, one must not deny its limitations. For some components, including building contents, damage can be more directly related to inertial forces (that is, the products of mass and acceleration). In design for low-intensity earthquakes, it may be more practical to keep a structure essentially elastic, in which case strength becomes a more discerning parameter for design. In any structure, it is well-established that damage is a cumulative process; therefore, a structure that sustains a given maximum drift is likely to be more damaged by a long duration event than by a short one. Some of these basic limitations are characterized in the following section.

LIMITATIONS OF DISPLACEMENT-BASED DESIGN

Performance-based seismic design has as one of its goals to produce structures of more predictable performance. The approach can be organized around the theme of performance objectives, which can be defined as the combination of a performance level (e.g., immediate occupancy, life safety, collapse prevention) and an earthquake demand with a specified probability of exceedance (or return period) [ATC-33; 1995]. Limitations exist with regard to estimating earthquake displacement demands (including ground motions and displacement estimations) and performance levels.

Displacement Demand Estimation

To estimate displacement demands, one must define the design ground motion(s) and the effects on the subject structure.

Design Ground Motion. Design motions should be consistent with the expected performance levels. For new building design, it may well be inappropriate to pair a ground motion having 10 percent probability of exceedance in 50 years with a deformation measure corresponding to structural collapse. Similarly, it may be uneconomical to pair a 2%-in-50-yr ground motion with a deformation measure corresponding to partition cracking.

It is easy to lose sight of the conspicuous statements of the preceding paragraph when attempting to implement displacement-based design concepts in existing design codes. A tangible example is found in the provisions for shear wall confined boundary elements of the 1994 Uniform Building Code [UBC; 1994]. According to these provisions, confined boundary elements are required only if compression strains, calculated for the code loading, exceed the strain corresponding to crushing strain of concrete. For many sites in California, the event represented by this code loading has a probability of exceedance of around 10% in 50 years. Other reasonably credible events have spectral ordinates significantly larger than this code loading. For example, response spectra for the 1994 Northridge earthquake, a moderate event by most measures, exceeded the UBC code loading by a considerable margin (Figure 3) [EERI; 1995]. Because loss of a confined boundary element may represent a serious threat to life safety, a lower probability event than that represented by the code loading might be more appropriate.
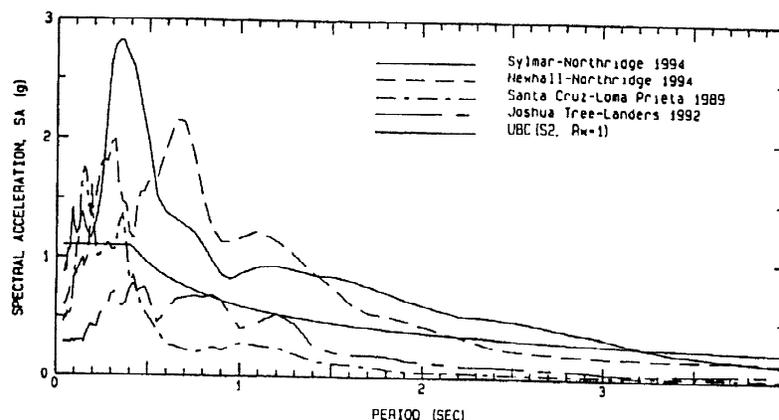

Figure 3 - Spectral acceleration (5% damped) for the UBC design spectrum and various California earthquakes.

An alternate approach to dealing with uncertainty in the seismic loading has recently been adopted in provisions of the 1995 ACI Building Code [ACI; 1995]. According to these provisions, gravity columns (those columns not considered in design to be part of the lateral force resisting system) are to be checked to determine if they are likely to develop strength for the design response spectrum (which may be assumed to be equivalent of the UBC loading). Those that are calculated to reach strength are recognized as requiring significant ductility capacity, and are required to be detailed as if they were part of a ductile moment resisting frame. Those that according to calculations do not reach strength for the code loading are allowed to contain less stringent details, but the details still must allow for some ductility capacity (e.g., shear failure must be avoided for loads corresponding to flexural plastic hinging). Implicit in this provision is the understanding that life-threatening demands well in excess of the code loading are reasonably credible.

Other proposals are available. For example, the ATC-32 report [1996] recommends to use mean response spectra for ordinary structures, and 1.5 times the mean spectra (effectively mean-plus-one-standard-deviation spectra) for important structures, and for all structures an implicit margin is provided between calculated demands and expected capacities. As another example, the draft ATC-33 report [1995] recommends to use 10%-in-50-yrs ground motions for the life safety performance objective, and 2%-in-50-yrs ground motions for the collapse prevention objective (some aspects of near-field effects in western California are as yet unresolved). These procedures provide simple ways of dealing with the general uncertainty surrounding future ground motions.

Estimation of SDOF Displacements. Numerical procedures are required that estimate structural response amplitude to ground motions. For design, simplified procedures usually are appropriate. Since the 1950's, effects have been made to relate response of structures responding non-linearly to that of structures responding linearly. For example, the equal displacement rule, which states that maximum displacement amplitudes are equal for nonlinear and linear response of an oscillator with given damping and initial stiffness, was the product of analog and digital computer studies of the 1960's [Moehle; 1992]. This expedient has formed the basis of many design procedures.

Later studies demonstrated that the equal displacement rule was not valid for a range of structural systems. For example, Sozen and Shimazaki [1984] and others noted that the relation between displacement amplitude for nonlinear and linear response depended on characteristics of the ground motion, initial period of the oscillator, strength of the oscillator, and hysteretic characteristics of the load resistance function. Statistical studies by Miranda [1996] of bilinear oscillators have clarified the significant scatter associated with relations between nonlinear and linear response amplitude. These results, coupled with the basic uncertainty in the loading function, emphasize the need to consider uncertainty as a part of the overall analysis problem.

These studies do not consider the effects of gravity loads acting through lateral displacements. P-delta effects can induce extreme results in otherwise stable systems.

Few codes or design guidelines take full advantage of the available technical information on nonlinear response. For example, the Uniform Building Code [1994] continues to define the design displacement as three-eighths of the displacement calculated for elastic response. On the other hand, recommendations from the ATC-32 project for bridge design [ATC; 1996] and from the draft ATC-33 project for building rehabilitation [ATC; 1995] contain a more realistic representation of expected displacement response; Figure 4 is based on recommendations from the ATC-32 report.

Estimation of Local Displacements. Beyond estimation of SDOF displacement amplitude, as described previously, it is important to obtain a good estimate of the local displacements within the structure. For structures responding nonlinearly, it in general is not adequate to estimate internal displacements using a linear model. As an example, consider a simple, soil-supported, single-column bridge pier, where inelastic action is restricted to column flexure near the base. The total lateral displacement is equal to the sum of the contributions from the foundation, δ_f, elastic deformations of the column, δ_{ce}, and inelastic deformations of the column, δ_{ci}. If we assume that the elastic displacement contributions from all three components are

equal, and if we assume that the maximum displacement is equal to twice the yield displacement, then the total displacement of the yielding plastic hinge must be $\delta_y/3 + \delta_y = 4/3\delta_y$, where δ_y = the yield displacement. Therefore, the flexural hinge must accommodate two-thirds of the total displacement, rather than one-third as would be determined from elastic analysis. (Note that the flexural hinge displacement ductility is equal to 4 whereas the system displacement ductility is equal to 2.)

The result of the preceding paragraph is well known, but is not always applied in displacement-based design methods because of uncertainties in how inelastic deformations are distributed. Nonlinear static analysis has been recommended in some design methodologies [ATC-32, 1996; ATC-33, 1995]. However, even these do not adequately address multi-degree-of-freedom structures where apparent higher mode contributions add to the uncertainties. General and rigorous procedures for taking these effects into account are not currently available. Some discussion is provided in [Krawinkler; 1996].

Displacement Capacity Estimation

Experimental and analytical research continue to add to our understanding of the deformation capacities of structural components. Still, the available knowledge is incomplete. The user of displacement-based design concepts should understand the limitations imposed by our incomplete knowledge of displacement capacity.

Figure 4 - Displacement amplification factors to account for nonlinear response. T/T* is the ratio of structure period to characteristic ground motion period. Z is a strength reduction factor.

Figure 5 - Displacement capacity of flat-plate construction as a function of the intensity of the gravity shear loading.

Direct observation of deformation capacities is one common means of establishing design criteria. An example is provided by data for deformation capacity of slab-column connections, as shown in Figure 5 [Moehle; 1996]. Although a basic relation between deformation capacity and shear (acting transverse to the plane of the slab) is identified, no fundamental mechanical model is inferred. To be of general use, relations of this type must report results for representative connections subjected to representative loading histories.

More general, but still limited, approaches are available for some structural components. For example, for flexurally-dominated reinforced concrete construction one may invoke empirical models based on cross-sectional analysis to obtain curvature capacities, combined with procedures for distributing curvature along the component length. Figure 6 shows the familiar plastic hinge model for a reinforced concrete beam, column, or wall. This model enables the engineer to calculate deformation capacity for a range of geometries. Figure 7 compares measured and calculated deformation capacities for spirally-reinforced bridge columns, satisfying modern design provisions, tested at the University of California at San Diego [ATC 32; 1996]. Even though the test specimens satisfied basic conditions for which the predictive model
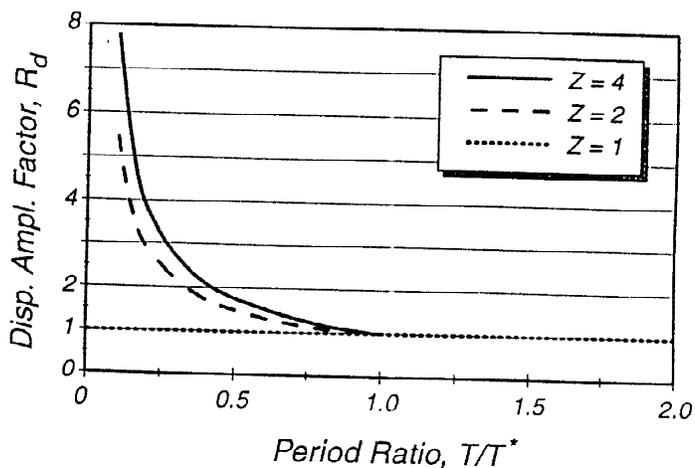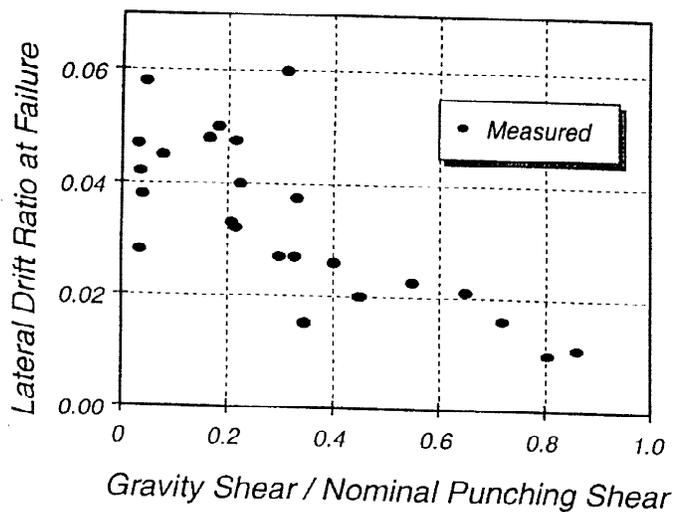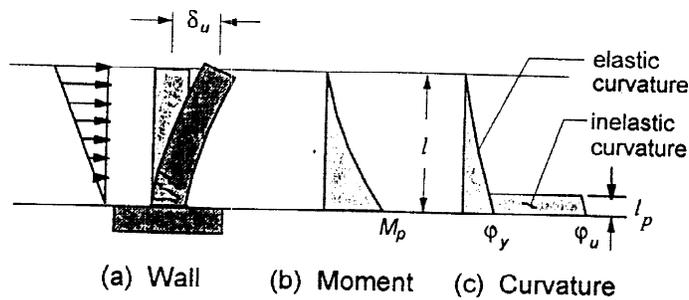
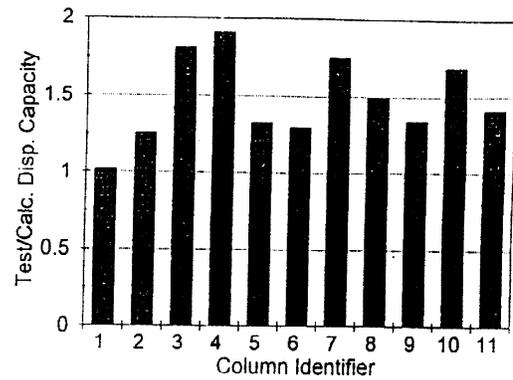Figure 6 - Plastic hinge model for a flexural member.

Figure 7 - Comparison of measured and calculated column displacement capacities

was designed, and even though the loading histories all followed a standard routine, there is considerable scatter in the comparison between theory and test. Variations from this testing theme would certainly introduce more scatter. Probabilistic approaches seem unavoidable if reasonable measures of performance are to be obtained.

CONCLUSION

Displacement-based seismic design criteria are simple and direct in representing design parameters that relate to performance. Approaches are available to estimate both displacement demands and capacities, although additional developments are needed. The inherent uncertainty in the design problem is apparent. Therefore, whereas a stated goal of performance-based seismic design is to produce structures of predictable performance, only the probabilities associated with achieving a given performance can be stated.

ACKNOWLEDGMENT

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