GUEST EDITOR'S NOTE

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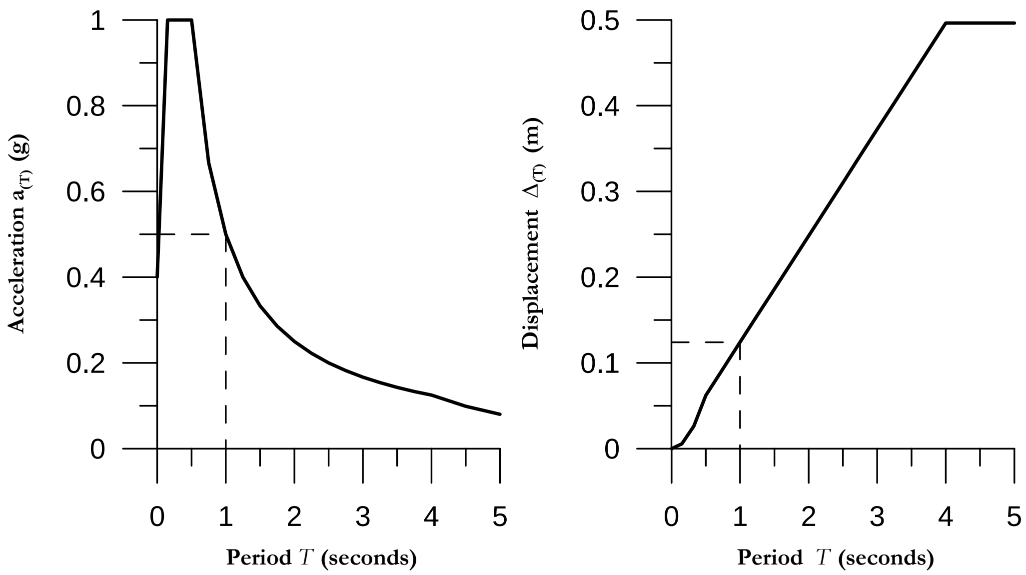
Seismic design has traditionally been based on considerations of seismic force. This can, to some extent, be explained by historical considerations — in the 1930's, when seismic response first became recognized as significant, the dynamics of building response was not well understood, and seismic actions were considered in terms of a constant fraction of the building weight (typically 10%) acting as a horizontal vector of force, distributed uniformly with height. Also, engineers have typically been more comfortable designing for strength, rather than displacement, since the latter is generally considered in rudimentary form in gravity load designs, if at all. Displacement capacity for gravity loads is often deemed to be satisfied if certain code-specified dimensional proportions are satisfied, and no specific calculations are required in such cases.

However, for seismic design, which generally assumes that inelastic response is used to limit seismic force levels, there is no demonstrable relationship between potential for damage and provided strength, despite the assumption that higher strength produces safer structures. On the other hand, it is very easy to demonstrate the direct relationship between damage potential and displacement demand. In structural elements, damage is related to material strain (e.g., yield of reinforcement or structural steel, cracking or crushing of concrete). Non-structural damage is typically related to drift. Both can be integrated to provide a direct relationship between damage and displacement.

For elastic systems, it is exactly equivalent to use either displacement or force as the fundamental design quantity. This is illustrated in Figure 1, where the design earthquake, for a typical firm ground site, is represented by both acceleration (Figure 1(a)) and displacement (Figure 1(b)) spectra.



(a) 5% Acceleration Spectrum **(d) 5% Displacement Spectrum**

Fig. 1 Acceleration and displacement response spectra for firm ground

Traditional seismic design has been based on the elastic acceleration spectrum. For an elastically responding single-degree-of-freedom (SDOF) structure, the response acceleration, $a_{(T)}$, corresponding to the fundamental period T is found, and the corresponding force, F and displacement $\Delta_{(T)}$ are given by

$$F = m \cdot a_{(T)} \cdot g\,; \qquad \Delta_{(T)} = \frac{F}{K} \tag{1}$$

where K is the system stiffness, m is the mass, and g is the acceleration due to gravity.

Alternatively, the displacement spectrum of Figure 1(b) could be used directly. In this case the response displacement $\Delta_{(T)}$ corresponding to the elastic period is directly read, and the corresponding force calculated as

$$F = K \cdot \Delta_{(T)} \tag{2}$$

In both cases the elastic period must first be calculated, but it is seen that working from the displacement spectrum requires one less step of calculation than working from the acceleration spectrum, since the mass is not needed once the period has been calculated. Although both approaches are directly equivalent, it would seem that using response displacement rather than response acceleration would be a more logical basis for design of elastic systems, as well as inelastic systems.

Design using force-based concepts results in non-uniform risk of damage, and a lack of appreciation of the factors that are important in reducing damage to acceptable levels. In the past ten years or so, researchers and designers recognizing this deficiency in force-based design have been developing seismic design procedures that more directly address the displacements, or deformations of structures. These procedures are collectively termed 'Performance-Based Seismic Design', and may be rather coarsely grouped into three categories as discussed below.

1. Force-Based/Displacement-Checked

This category is essentially a refinement to force-based design methodology. After determining the required strength from force-based considerations, a realistic assessment of displacement demand is carried out to check that these are within acceptable limits. If the check fails, the structure is redesigned to satisfy the displacement limits. Such methods include the adoption of more realistic member stiffnesses for deformation (if not for required strength) determination, and possibly use of inelastic time-history analysis, or pushover analysis, to determine peak deformation and drift demand. No attempt is made to achieve uniform risk of damage, or of collapse for structures designed to this approach.

2. Deformation Calculation-Based Design

A more refined version of the 'force-based/displacement-checked' approach relates the detailing of critical sections (in particular details of transverse reinforcement for reinforced concrete members) to the local deformation demand, and may hence be termed 'deformation calculation-based design'. Strength is related to a force-based design procedure, with specified force-reduction factors. Local deformation demands, typically in the form of member end rotations or curvatures, are determined by state-of-the-art analytical tools, such as inelastic pushover analyses or inelastic time-history analyses. Transverse reinforcement details are then determined from state-of-the-art relationships between transverse reinforcement details and local deformation capacity.

3. Deformation Specification-Based Design

Parallel to developments in the above two categories, a number of design approaches have been developed where the aim is to design structures so that they achieve a specified deformation state under the design-level earthquake, rather than achieve a displacement that is less than a specified displacement limit. These approaches appear more philosophically satisfying than the preceding two approaches. This is because damage can be directly related to deformation. Hence designing structures to achieve a specified displacement limit implies designing for a specified risk, which is compatible with the concept of uniform risk commonly applied to determining the design level of seismic excitation.

One of the 'deformation specification-based design' procedures referenced by several papers in this special issue on performance-based seismic design is 'direct displacement-based design (DDBD)' (Priestley, 1993, 2000). The basics of this simple procedure are outlined in Figure 2, which considers a SDOF representation of a frame building (Figure 2(a)), though the basic fundamentals apply to all structural types. The bilinear envelope of the lateral force-displacement response of the SDOF representation is shown in Figure 2(b). An initial elastic stiffness K_i is followed by a post-yield stiffness of rK_i.

While force-based seismic design characterizes a structure in terms of elastic (pre-yield) properties (initial stiffness K_i, elastic damping), DDBD characterizes the structure by secant stiffness K_e at maximum displacement Δ_d (Figure 2(b)), and a level of equivalent viscous damping ζ, representative of the combined elastic damping and the hysteretic energy absorbed during elastic response. Thus, as shown in Figure 2(c), for a given level of ductility demand, a structural steel frame building with compact members will be assigned a higher level of equivalent viscous damping than a reinforced concrete frame building designed for the same level of ductility demand, as a consequence of “fatter” hysteresis loops (see Figure 2).

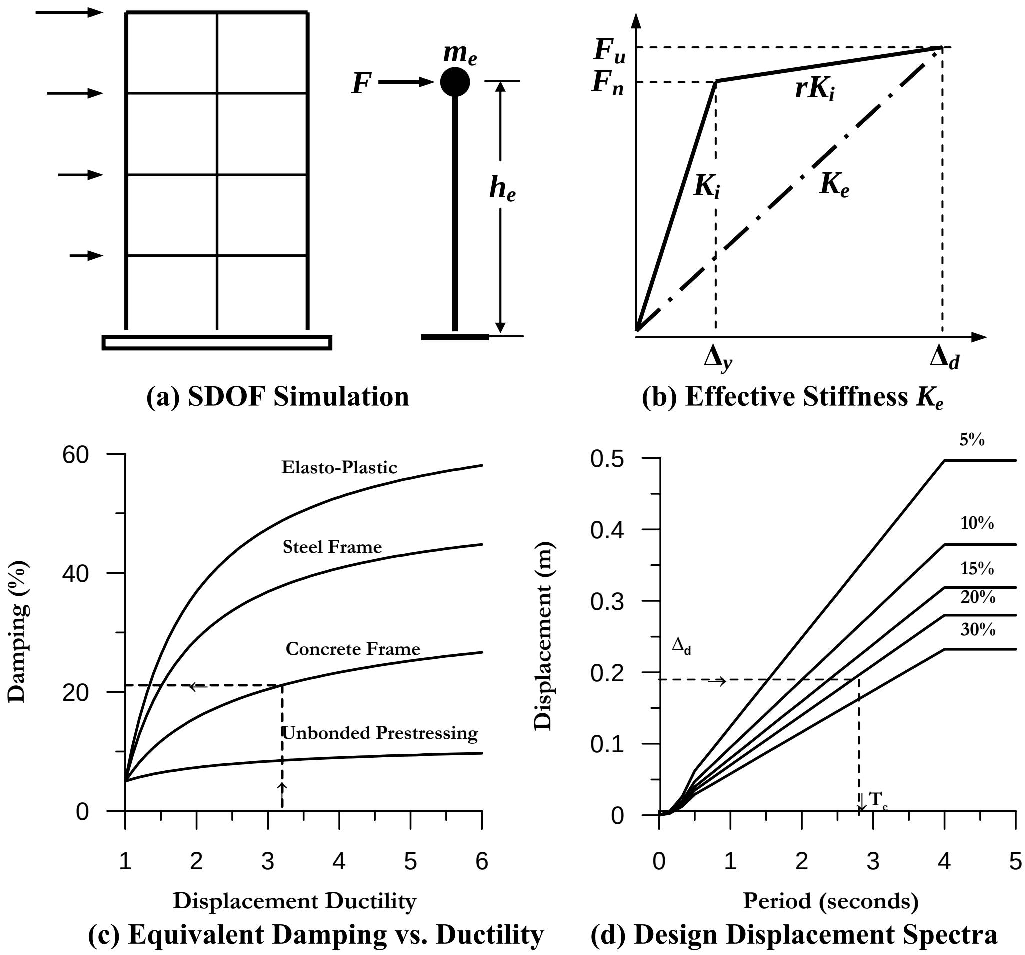


Fig. 2 Fundamentals of Direct Displacement-Based Design

With the design displacement at maximum response determined, and the corresponding damping estimated from the expected ductility demand, the effective period T_e at maximum displacement response can be read from a set of displacement spectra for different levels of damping, as shown in the example of Figure 2(d). The effective stiffness K_e of the equivalent SDOF system at maximum displacement can be found by inverting the normal equation for the period of a SDOF oscillator, to provide

$$K_e = 4\pi^2 m_e / T_e^2 \tag{3}$$

where m_e is the effective mass of the structure participating in the fundamental mode of vibration. From Figure 2(b), the design lateral force, which is also the design base shear force, is thus

$$F = V_B = K_e \Delta_d \tag{4}$$

The design concept is, thus, very simple. Such complexity that exists relates to determination of the “substitute structure” characteristics, the determination of the design displacement, and development of design displacement spectra (Priestley, 1993, 2000). It is emphasized, however, that this is just one of many displacement-specification procedures that have been developed.

The papers selected for publication in this special issue on performance-based seismic design cover a wide range of topics. Much of the current research on the topic relates more to analysis techniques and the response of specific structures, rather than to seismic design philosophy. It is the latter that is the focus of this issue. Most of the categories of design procedures outlined above are represented by papers in this issue, and though several papers relate to analysis, this generally is in support of required design information. Many, though not all, of the current unresolved design issues are addressed in these papers, including determination of displacement spectra, distribution of strength to provide the best distribution of deformation demand, the importance of residual drift, and the issue of cumulative damage.

The first paper, by Freeman, provides a review of the capacity spectrum approach, which while being primarily an evaluation tool has had an important role in the development of performance-based design, and is central to many design procedures.

The paper by Lam and Wilson outlines a global approach to determining displacement demand in intraplate regions (though the methodology is presumably also appropriate in interplate regions), based on integration of engineering seismology, soil dynamics, structural dynamics and structural engineering. This is an ambitious and controversial paper and deserves serious consideration. In particular, current estimates of appropriate displacement spectra are simplistic, and the methodology suggested by Lam and Wilson provides a means for improvement.

The paper by Christopoulos and Pampanin emphasizes the importance of residual deformation in performance-based design. This important aspect of performance has not received as much attention as it deserves. Modern, well-designed buildings should not have problems satisfying code maximum-displacement criteria, but if the residual displacement is excessive, the cost of reinstating serviceability may be excessive. The authors propose a performance-based matrix as a combination of maximum deformation and residual deformation within a direct displacement-based approach.

Wood structures have traditionally been the “poor relation” of seismic structural research. For this reason, the paper by Filiatrault and co-authors on displacement-based response of wood structures is extremely important. The pinched hysteretic force-displacement response of wood structures is very different from that of steel or concrete structures, making typical force-based assumptions of “equal-displacement” between elastic and inelastic response doubtful. Filiatrault and co-authors quantify the equivalent viscous damping of wood structures, and show they can be successfully incorporated within a direct displacement-based design philosophy.

Performance-based design approaches for multi-storey frames are normally based on single-degree-of-freedom approximations to determine the design base shear. The distribution of this base shear up the height of the building needs to be carried out in such a way that drift demands are as close to uniform as possible. This means accounting for the influence of higher mode response on drift at different heights of the building. This important problem is addressed by Medina, who reports on the relationship between strength distribution and drift demand, and makes design recommendations.

Aschheim and co-authors outline deficiencies in non-linear static (pushover) analyses, and suggest that for very little extra computational effort inelastic time-history analysis can be used instead of the pushover analysis, which has difficulty in including higher mode effects with any accuracy. They also provide information on appropriate scaling of earthquake records for this purpose.

Kappos and Panagopoulos also consider appropriate seismic input for inelastic time history analysis, and pushover analysis. Their approach, which is one of the most fully developed “deformation-calculation” procedures relates to detailing (confinement) of critical members based on plastic rotations obtained from the analyses.

The use of different methods of analysis for determining component plastic deformations is also addressed by Kunnath and Kalkan, who consider four levels of analysis technique complying with FEMA-2000 and examine the rationale for using component demands over storey and system demands.

Teran-Gilmore and Jirsa consider the influence of low-cycle fatigue in performance-based design. Many researchers have concluded that for well-designed structures with conservative deformation demands, low-cycle fatigue is not an issue, but should be considered in assessment of existing structures. The authors of this paper outline the methodology of incorporating low-cycle demand within a performance-based design environment, and comment on when it will be important.

Finally Prakash provides an extensive review of current Indian seismic design practice, as required by current Indian codes, and criticizes recent changes as potentially increasing risk of damage or collapse. He makes suggestions for incorporation of performance-based concepts, based on Californian proposals.

The ten papers in this issue cover a wide range of concepts and produce many interesting and controversial results. As all good research does, they deserve a thorough, but critical reading.

REFERENCES

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