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Seismic Demand Analysis

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Overview

Implementation of performance-based earthquake engineering necessitates the probabilistic evaluation of engineering demand parameters (EDPs) that can be related to decision variables (DVs), such as dollar losses and structural instability (collapse), on which quantitative seismic performance assessment can be based. The scope of the presentation, which is summarized here, is to identify relevant EDPs, illustrate quantification of these EDPs for regular frame structures, and demonstrate how statistically representative relationships between these EDPs and ground motion intensity measures (IMs) can be established. Emphasis is on the development of such relationships for ordinary ground motions (with pointers towards issues that have to be addressed in order to incorporate near-fault ground motion effects) and considering the performance targets of damage control (monetary losses) and global structural collapse.

Relevant EDPs and Their Dependence on Structural Models and Ground Motions

The present focus within PEER is on the performance targets of life safety (which incorporates global and local collapse modes), direct monetary losses, and downtime. In each case, EDPs are intermittent variables whose central value and measure of dispersion have to be computed as a function of ground motion IMs (such as the spectral acceleration at the first mode period, $S_a(T_1)$) whose uncertainties are accounted for in the hazard analysis. The EDPs and their associated uncertainties are then used, often in conjunction with fragility curves (expressing the probability of exceeding a defined limit state, given the EDP), to evaluate DVs (such as existence of collapse, or dollar losses) whose probabilistic realizations are utilized to assess performance.

In the context of this performance assessment framework it is apparent that the choice of EDPs depends on the performance target. As recent earthquakes have shown, monetary losses and downtime are controlled by a combination of structural, nonstructural, and contents damage. The EDPs of primary interest are, therefore, parameters that correlate best with the various types of damage. For structural damage, local parameters such as shear distortions in joints and rotations at plastic hinges may be most relevant. In most cases, these local parameters can be deduced from story drifts. This indicates that the maximum drifts in each story (and not the maximum drift over the height of the structure) are relevant EDPs. The same parameters also are relevant for damage assessment of many deformation sensitive nonstructural components and subsystems. However, damage to other nonstructural components (e.g., mechanical equipment)

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and building contents is often sensitive to floor acceleration and velocity. Thus, these quantities are also relevant EDPs for performance assessment.

If the issue is global collapse (a major [but not the only] source of loss of lives), then the maximum story drift over the height of the structure is an appropriate EDP. However, global system collapse does not occur when the maximum story drift attains a certain value, and it rarely occurs when a single component attains a limiting force or deformation. It mostly occurs when the structural system is incapable of resisting gravity loading and fails in a P-delta mode (dynamic instability). Moreover, this limit state is only approached after individual components have severely deteriorated in strength and stiffness. Global collapse can be predicted with sufficient confidence only if this deterioration is incorporated in the analytical model. An example of an incremental dynamic analysis of a 9-story frame with either ductile or deteriorating component properties is illustrated in Figure 1. The figure shows the maximum story ductility over the height, plotted against ground motion intensity represented by $[S_a(T_1)/g]$□ The curves illustrate the increase in maximum story ductility as the intensity of the ground motion [represented by $S_a(T_1)$] is increased, or the strength of the structure [represented by □$= V_y/W$] is decreased. The curves for the non-deteriorating and deteriorating systems start to deviate once deterioration sets in, and the deteriorating system becomes dynamically unstable at $[S_a(T_1)/g]/$□ approximately equal to 3.4 (the story drift increases at a very high rate for a minute increase in the ground motion intensity). This figure serves to demonstrate that realistic collapse evaluation necessitates the incorporation of deterioration.

The dependence of EDPs on the intensity and frequency content of the ground motions is of primary concern in seismic demand evaluation. By now it is widely acknowledged that for many sites the long return period hazard (e.g., 2/50 hazard) is controlled by near-fault ground motions with forward directivity. These ground motions are characterized by a strong pulse of period T_p that occurs early in the time history and sets the frequency content of such ground motions apart from that of "ordinary" ground motions. In turn, the response of structures will depend strongly on the ratio T_1/T_p, as is shown in the elastic story drift response profiles presented in Figure 2. For such ground motions the widely used intensity measure $S_a(T_1)$ is believed to be inadequate, which has initiated important PEER research on the search for improved intensity measures that cover the full range of ground motions, including near-fault records. The results presented on the following two pages are based on ordinary ground motions without near-fault effects, and assuming that $S_a(T_1)$ is an "efficient" and "sufficient" intensity measure IM.

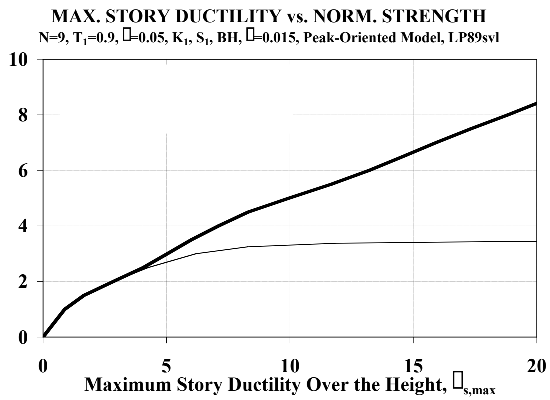

Figure 1. Incremental dynamic analysis of a 9-story frame without and with deterioration

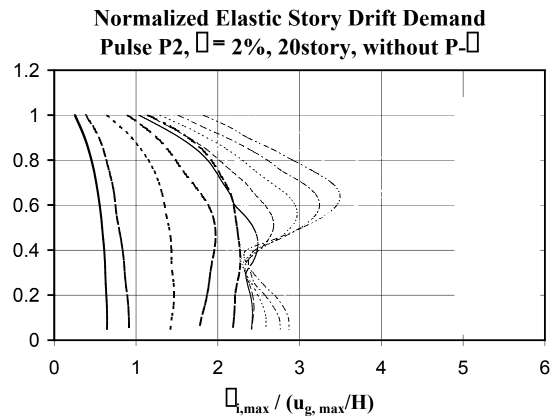

Figure 2. Elastic story drift demands for MDOF systems, various ratios of T/Tp, pulse input motion

Probabilistic Seismic Demand Analysis

In the context of the PEER PBEE framework equation, a convenient form of expressing, for a given structure, the relationship between an EDP and an appropriate IM is through a mean annual frequency of exceedance, i.e.,

$$\lambda_{EDP}(y) = \int P\left[EDP \geq y \mid IM = x\right] \left| d\lambda_{IM}(x) \right| \tag{1}$$

P[EDP ≥ y_IM = x can be obtained from incremental dynamic analyses (IDAs) for a series of "representative" ground motions. An example of IDAs, together with median and 84th percentile curves, is shown in Figure 3, using $S_a(T_1)$ as an IM. Equation (1) can be evaluated for any given IM hazard curve through numerical integration. To provide a closed form solution, the following procedure (Cornell) may be implemented to develop EDP hazard curves.

Hazard analysis on the intensity measure usually results in a hazard curve of the type

$$\lambda_{IM}(x) = P\left[IM \geq x\right] = k_o x^{-k} \tag{2}$$

The procedure requires local (around the return period of primary interest) fitting of a median relationship to the EDP - IM data. The convenient form of this relationship is

$$\hat{EDP} = a\left(IM\right)^b \tag{3}$$

If the conditional distribution of the EDP for a given IM can be assumed as log-normal, i.e.,

$$P\left[EDP \geq y \mid IM = x\right] = 1 - \Phi\left(\ln[y/ax^b]/\beta_{\ln EDP|IM}\right) \tag{4}$$

(Φ is the "standardized" Gaussian distribution function), then under certain simplifying assumptions (Cornell) the mean annual frequency of exceeding any specified EDP value of y can be calculated in closed analytical form as

$$\lambda_{EDP}(y) = P\left[EDP \geq y\right] = k_o\left[(y/a)^{1/b}\right]^{-k} \exp\left[\frac{1}{2}\frac{k^2}{b^2}\beta^2_{\ln EDP|IM}\right] \quad (5)$$

Representative results of drift hazard curves, obtained from numerical integration and from eq. (5), are shown in Figure 4.

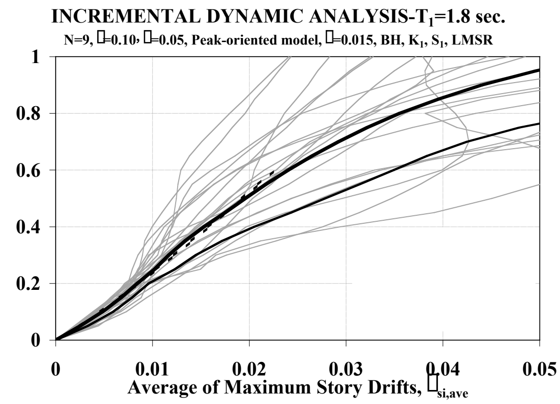

Figure 3. IDAs for 9-story frame, T_1 = 1.8 sec., $\gamma = V_y/W = 0.1$; EDP = av. of max. story drifts

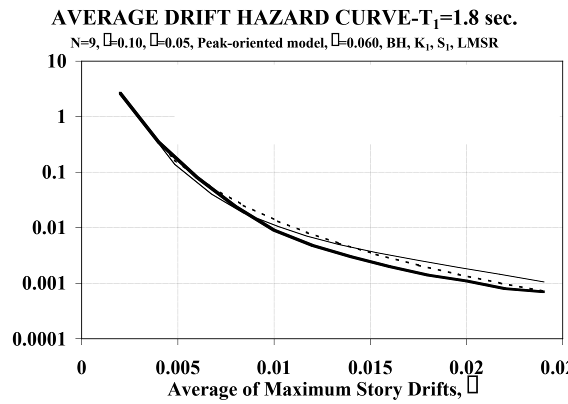

Figure 4. Drift hazard curves for 9-story frame, T_1 = 1.8 sec., $\gamma = V_y/W = 0.1$

Collapse Assessment of Deteriorating Systems

As illustrated in Figure 1, global collapse, which is synonymous with the inability of a structure to sustain gravity loads, usually occurs after significant deterioration of component hysteretic properties has occurred. Models have been developed that permit description of important modes of strength deterioration and stiffness degradation (e.g., Ibarra et al.), which for MDOF structures may be applied to each individual component (as is done in the response illustrated in Fig. 1), or for SDOF systems may be applied to the global system, see Figure 5. Work is in progress to evaluate the effects of different deterioration modes on SDOF and MDOF system responses, with an emphasis on collapse assessment.

As seen from Figure 1, for each system and ground motion the IM associated with collapse (the last stable IM value of the IDA curve) can be found. If IDAs are performed for a set of ground motions, a CDF of these IM values can be obtained, which can be interpreted as a collapse fragility curve (defining the probability of collapse, given the value of IM). Figure 6 illustrates such fragility curves for SDOF systems with T = 0.5 sec. The “intensity measure” represented on the horizontal axis is $(S_a/g)/\eta$, where $\eta = F_y/W$. Since this representation is for SDOF systems, this measure is equal to the conventional R-factor. The figure shows the large sensitivity of the probability of collapse to the hysteretic properties, defined by a deterioration parameter γ, the ratio δ_c/δ_y (see Figure 5), and the post cap “softening” stiffness $\alpha_c K_e$.

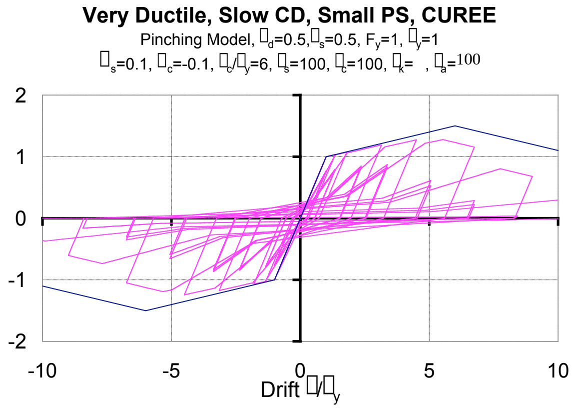

Figure 5. Example of degrading hysteresis model, subjected to CUREE wood loading protocol

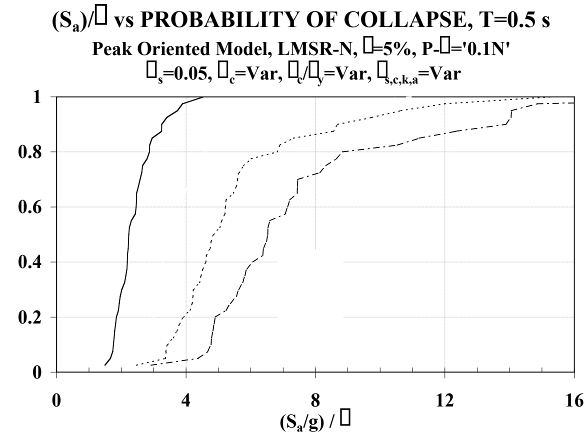

Figure 6. SDOF collapse fragility curves for various hysteretic systems, T = 0.5 sec.

References

Cornell, C. A. (1996). “Calculating building seismic performance reliability; a basis for multi-level design norms,” *Proc. Eleventh World Conference on Earthquake Engineering*, Acapulco, Mexico.

Ibarra, L., Medina, R., and Krawinkler, H. (2002). “Collapse assessment of deteriorating SDOF systems,” *Proc. Twelfth European Conference on Earthquake Engineering*, Paper Ref. 665, Elsevier Science Ltd.

Keywords

Seismic demands, hazard curves, engineering demand parameters, performance assessment, probability of collapse