RESPONSE TO:

B. Maison's Discussion of "Evaluation of Modal and FEMA Pushover Analyses: SAC Buildings"

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The authors agree with the discusser that even improved pushover analysis procedures can be inaccurate for buildings deforming far into the inelastic range—in the region of negative post-yield stiffness with significant degradation of lateral capacity. However, estimates of seismic demands obtained by MPA were much better than from FEMA force distribution over a wide range of responses—from essentially elastic response of Boston buildings to strongly inelastic response of Los Angeles buildings. For a wide range of buildings and ground motions, MPA estimates of seismic demands were accurate enough relative to the results of nonlinear RHA to be useful in the seismic evaluation of buildings. The potential and limitations of every approximate analysis procedure, including the NSP used in current practice and MPA, should be documented so that the procedure is not used outside its range of applicability. This was one of the objectives of our paper.

Because MPA is based on structural dynamics theory, it offers three theoretical advantages. First, when applied to elastic systems it is equivalent to standard response spectrum analysis (RSA) (Chopra and Goel 2002, 2004) available in commercial software used by the profession. Second, although modal pushover analysis theory is strictly not valid for inelastic systems, the fact that elastic modes are coupled only weakly in the response of inelastic systems to modal inertia forces (Chopra and Goel 2002, 2004) permitted development of MPA, an approximate procedure. Third, the theory and concepts underlying MPA are extendable to unsymmetric-plan buildings (Chopra and Goel 2004).

Contrary to the discusser's interpretation of MPA as "an intricate ten-step procedure," MPA retains the conceptual simplicity of current NSP with invariant force distribution, now common in structural engineering practice. Because higher-mode pushover analyses are similar to the first-mode analysis, MPA is conceptually no more difficult than procedures now standard in structural engineering practice. Because pushover analyses for the first two or three modal force distributions are typically sufficient in MPA, it requires computational effort that is comparable to the *FEMA-356* procedure,

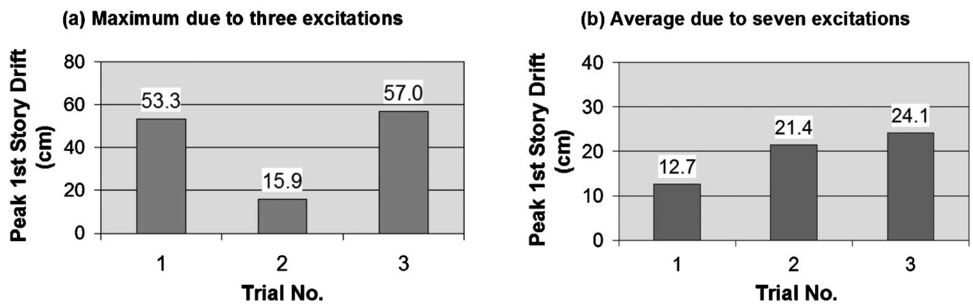

Figure 1. First-story drift: (a) maximum of demands due to 3 excitations, and (b) average of demands due to seven excitations. The excitations were selected randomly three times from an ensemble of 17 excitations.

which requires pushover analysis for at least two force distributions. Without additional conceptual complexity or computational effort, MPA estimates seismic demands much more accurately than *FEMA-356* procedures.

In principle, the authors agree with the discusser that nonlinear RHA should be the preferred method to estimate seismic demands, with the important proviso that such analyses are implemented prudently, a requirement that may not always be satisfied in current practice. For example, the *FEMA-356* specifications for nonlinear dynamic procedure (NDP) state that the seismic demand may be estimated as (1) the maximum of demands due to three ground motions, or (2) the mean value of demands due to seven ground motions. These estimates can vary widely, as demonstrated next for the SAC–Los Angeles nine-story building subjected to an ensemble of 20 SAC ground motions; nonlinear RHA predicted collapse of the building during three of these excitations. The nonlinear RHA results for the first-story drift led to a mean value of 20.4 cm over 17 excitations (excluding three that caused collapse of the building).[1] The results, shown in Figure 1, demonstrate large variation in the drift estimated by three implementations of both versions of the *FEMA-356* criteria. Such wide variability obviously implies that different engineers following the same criteria could arrive at contradictory conclusions about seismic safety and rehabilitation requirements for an existing building.

The discusser's claim that "there is not much difference in the level of effort to create a building model and perform either static or dynamic analysis" should be judged in light of the observations described below.

Nonlinear RHA is an onerous task for several reasons. First, an ensemble of site-specific ground motions compatible with the seismic hazard spectrum for the site must be simulated. Second, in spite of increasing computing power, nonlinear RHA remains computationally demanding, especially for unsymmetric-plan buildings—which require three-dimensional analysis to account for coupling between lateral and torsional

[1] Ignoring the three collapses in computing the mean is strictly incorrect. Working with the median value would be better, but the mean of the data for 17 excitations was used to remain consistent with *FEMA-356* guidelines.

motions—subjected to two horizontal components of motion. Third, such analyses must be repeated for many excitations because of the wide variability in the demand due to plausible ground motions, and the statistics of response must be considered. Fourth, commercial software is so far not robust, reliable, or convenient enough for structural modeling and interpretation of response results, especially for unsymmetric-plan buildings. Fifth, an independent peer review of nonlinear-RHA results is required by *FEMA-356*, adding to the project duration and cost.

In contrast, MPA and the current NSP has the advantage that seismic demands can be computed directly from the prescribed seismic hazard spectrum for the site, thus avoiding dynamic analyses for many ground motions and statistical analysis of the response results. Furthermore, the progression of yielding gleaned from various stages of pushover analysis provides an understanding of the building behavior, an advantage that is widely recognized. Less known, perhaps, is the additional understanding of building behavior gleaned from higher-mode pushover analyses (Sasaki et al. 1998).

Opinions within both the research and professional communities differ on whether nonlinear RHA and the implementing software are ready for practical application. The authors believe that even if nonlinear RHA is ripe for application, it is unreasonable to require nonlinear RHA for every building—no matter how simple—and of every structural engineering office—no matter how small. Therefore, simplified methods are expected to continue to play an important role in structural engineering practice. To be reliable, simplified methods must be rooted in structural dynamics theory, and their underlying assumptions and range of applicability identified. Nonlinear RHA can be employed for final evaluation of those combinations of buildings and ground motions where a simplified procedure begins to lose its accuracy.

REFERENCES

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