EVALUATION OF THE MPA PROCEDURE FOR ESTIMATING SEISMIC DEMANDS: RC-SMRF BUILDINGS

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ABSTRACT:

The median seismic demands for 4-, 8-, 12-, and 20-story reinforced concrete special moment resisting frame (RC-SMRF) buildings—designed to comply with current codes—due to an ensemble of 78 ground motions scaled to four intensity levels were computed by MPA and nonlinear RHA, and compared. It is demonstrated that, even for the most intense ground motions that deform the buildings far into the inelastic range, the MPA procedure demonstrates an adequate degree of accuracy that should make it useful for practical application in estimating seismic demands for RC-SMRF buildings. In contrast the FEMA-356 force distributions are inadequate in estimating seismic demands for the 8-, 12-, and 20-story buildings at all excitation intensities, from the weakest that causes response essentially within the linearly elastic range to the strongest that drives the buildings far into the inelastic range.

KEYWORDS: MPA procedure, buildings, pushover, reinforced concrete, seismic demands

1. INTRODUCTION

According to the nonlinear static procedure (NSP), also known as pushover analysis, described in FEMA-356 and ATC-40 (FEMA, 2000; ATC, 1996) guidelines for seismic evaluation of existing buildings, seismic demands may be computed by nonlinear static analysis of the structure subjected to monotonically increasing lateral forces with a specified, usually invariant, height-wise distribution until a pre-determined target displacement is reached. Developing improved NSPs has also been the subject of much research by many researchers. One such procedure is the modal pushover analysis (MPA) (Chopra and Goel, 2002). Based on structural dynamics theory, MPA has been shown to achieve superior estimates of seismic demands for buildings while retaining the conceptual simplicity and computational attractiveness of standard NSPs. Analyses of several steel moment resisting frame buildings covering a range of heights and a range of ground-motion intensities have demonstrated that the MPA procedure estimates the seismic demands for such buildings responding into the inelastic range to a degree of accuracy that is comparable—only slightly worse—to that of the standard response spectrum analysis (RSA) procedure for linearly elastic systems (Chopra, 2007, Section 19.8.3).

This paper evaluates the accuracy of the MPA procedure for a different class of buildings: reinforced concrete special moment resisting frame (RC-SMRF) buildings, characterized by deterioration of strength and stiffness under cyclic deformations, and evaluates the accuracy of MPA and the FEMA-356 NSP in estimating seismic demands for RC-SMRF buildings. This paper summarizes the results of a comprehensive investigation reported in Bobadilla and Chopra (2007).

2. STRUCTURAL SYSTEMS, MODELING ASSUMPTIONS, AND GROUND MOTIONS

The structural systems considered in this study are 4-, 8-, 12-, and 20-story RC-SMRF buildings (Haselton and Deierlein, 2007). They were designed for a site in a highly seismic region in the Los Angeles metropolitan area, according to the IBC-2003, ASCE 7-2002, and the ACI 318-2002 codes. Modeled using the OpenSees computer program, their fundamental vibration periods were 1.09, 1.67, 1.96, and 2.56 sec for the 4-, 8-, 12-, and 20-story buildings, respectively. Inelastic behavior of beams and columns occurs at plastic-hinge zones located at the end of each element. The peak-oriented model developed by Ibarra and Krawinkler (2005) was selected to represent the hysteretic behavior of the plastic hinge. The parameters of the peak-oriented model were calibrated against experimental data for ductile RC elements (Bobadilla and Chopra, 2007).

3. GROUND MOTIONS

A total of 39 ground acceleration records from 14 different earthquakes with magnitudes ranging from 6.5 to 7.6 were selected according to the following criteria (Haselton and Deierlein, 2007; Bobadilla and Chopra (2007). Each of the 39 records includes two orthogonal components of horizontal ground motion, leading to a total of 78 ground motions.

All the 39 records were scaled to represent the same seismic hazard defined by $A(T_1)$, the pseudo-acceleration at the fundamental vibration period T_1 of the structure. Both components of a record were scaled by the same factor selected to match their *geometric mean*, defined as $A(T_1)_{gm} = \sqrt{A(T_1)_{comp1} \times A(T_1)_{comp2}}$, where $A(T_1)_{comp1}$ and $A(T_1)_{comp2}$ are the $A(T_1)$ values for the two horizontal components of the record, to the selected seismic hazard. Table 1 lists the values of $A(T_1)$ selected to define ground motion ensembles for four different intensities; the highest intensity chosen is $A(T_1)_{2\%/50}$, corresponding to the seismic hazard spectrum.

4. MODAL PUSHOVER ANALYSIS FUNDAMENTALS

The equilibrium equations governing the lateral displacements $\mathbf{u}$ of the N floors of a symmetric-plan building due to horizontal ground acceleration $\ddot{u}_g(t)$ along one axis of symmetry are

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{f}_S(\mathbf{u}, \dot{\mathbf{u}}) = -\mathbf{m}\boldsymbol{\iota}\ddot{u}_g(t) \tag{4.1}$$

where $\mathbf{m}$ and $\mathbf{c}$ are the mass and damping matrices, $\boldsymbol{\iota}$ is the influence vector, and $\mathbf{f}_S(\mathbf{u}, \dot{\mathbf{u}})$ describes the inelastic lateral force-deformation relation including P-Δ effects. Although modal analysis theory is strictly not valid for inelastic systems, Bobadilla and Chopra (2007) have demonstrated that elastic modes are coupled only weakly in the response of inelastic RC-SMRF systems, thus validating the assumption underlying the MPA procedure.

In this procedure, the effective earthquake forces given by,

$$\mathbf{p}_{eff}(t) = -\mathbf{m}\boldsymbol{\iota}\ddot{u}_g(t) \tag{4.2}$$

are expanded into their modal components. The spatial distribution of these forces, defined by the vector $\mathbf{s} = \mathbf{m}\boldsymbol{\iota}$, can be expanded as a summation of modal inertia force distributions (Chopra, 2007),

Table 1 Selected values of $A(T_1)$ corresponding to four ground-motion intensities.

Building	Intensity 1 (g)	Intensity 2 (g)	Intensity 3 (g)	Intensity 4 (g)
4-story	0.05	0.25	0.45	0.765
8-story	0.05	0.25	0.40	0.565
12-story	0.05	0.15	0.30	0.465
20-story	0.05	0.15	0.25	0.355

Note: Intensity 4 corresponds to the seismic hazard spectrum for 2% probability of exceedance in 50 years.

$$\mathbf{s} = \sum_{n=1}^{N} \mathbf{s}_n \qquad \mathbf{s}_n = \Gamma_n \mathbf{m} \phi_n \tag{4.3}$$

where $\boldsymbol{\phi}_n$ is the nth natural vibration "mode" of the system vibrating in its linear range and $\Gamma_n = \phi_n^T \mathbf{m}\iota / \phi_n^T \mathbf{m} \phi_n$. Thus,

$$\mathbf{p}_{eff,n}(t) = -\mathbf{s}_n \ddot{u}_g(t) \tag{4.4}$$

is the nth-mode component of effective earthquake forces.

In the MPA procedure, the peak response of the building to $\mathbf{p}_{eff,n}(t)$—or the peak "modal" demand r_n—is determined by a nonlinear static or pushover analysis using the modal force distribution $\mathbf{s}_n^* = \mathbf{m}\phi_n$ [based on Eqn. (4.3b)] at the peak roof displacement u_{rn} associated with the nth-"mode" inelastic SDF system. The peak modal demands r_n are then combined by an appropriate modal combination rule to estimate total demand.

The hysteretic model for the nth-"mode" inelastic SDF system is chosen to represent the global behavior of RC-SMRF buildings. Figure 1 shows the monotonic and cyclic force-deformation relations for the first-"mode" SDF system, determined from the corresponding modal pushover curves using equations in Section 19.7.2 of Chopra (2007). This global behavior is idealized by the peak-oriented model (Ibarra and Krawinkler, 2005; Ibarra et al., 2005), with the monotonic curve idealized as trilinear (Figure 1a), with its parameter values and cyclic deterioration parameters are available in Bobadilla and Chopra (2007).

5. ACCURACY OF MODAL PUSHOVER ANALYSIS

The structural dynamics theory underlying the MPA procedure for inelastic systems is based on two principal approximations: (1) neglecting the weak coupling of "modes" in computing the peak "modal" response r_n to $\mathbf{p}_{eff,n}(t)$; and (2) combining the r_n by modal combination rules, known to be approximate, to compute the peak value of the total response. Because the latter is the only source of approximation in the RSA procedure, now standard for analysis of linearly elastic systems, the resulting error in the response of these systems serves as a baseline for evaluating the additional approximations in MPA for inelastic systems.

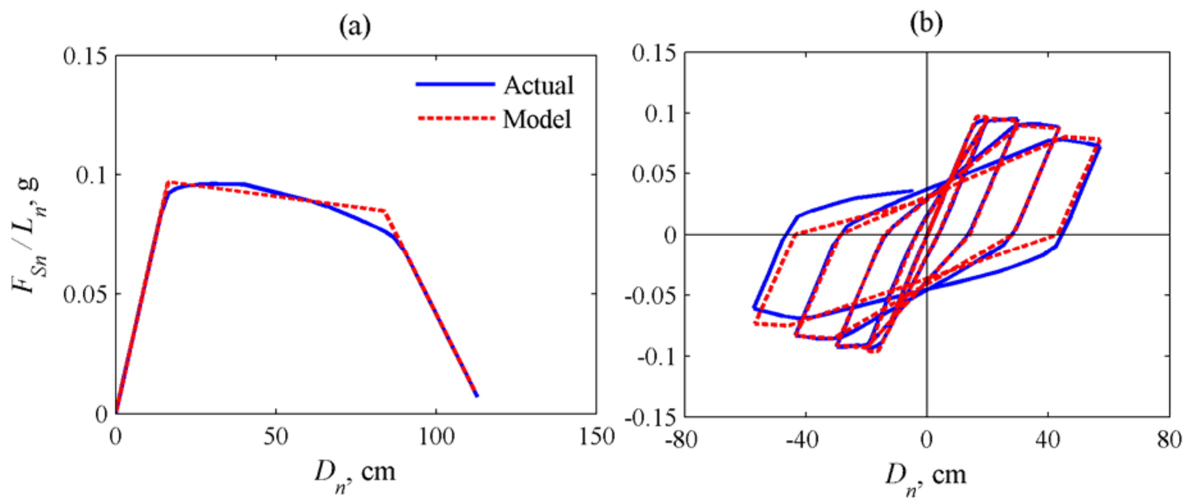

Figure 1 First-"mode" force-deformation relation for the 20-story building: (a) pushover curve (solid line) and its trilinear model (dashed line); and (b) cyclic pushover curve (solid line) and its hysteretic model (dashed line).

Figure 2 compares the accuracy of MPA in estimating the response of inelastic systems with that of RSA in estimating the response of elastic systems. These results were obtained by including 2, 3, 3, and 5 modes in the analyses of 4-, 8-, 12-, and 20-story buildings, respectively. For each of the four buildings, the results are organized in two parts: (a) story drift demands for these buildings treated as elastic systems determined by RSA and RHA procedures; and (b) demands for inelastic systems determined by MPA and nonlinear RHA. These results are for the most intense ground motions considered (with 2% probability of exceedance in 50 years) that deform the buildings far into the inelastic range. Therefore, the results of Figure 2 provide an extreme test of the accuracy of MPA.

Observe that the RSA procedure underestimates the median response for all four buildings (except in the lower stories of the 8-story building). This underestimation tends to increase from the bottom to top of buildings, consistent with the height-wise variation of contribution of higher modes to response (Chopra, 2007, Chapter 18). The height-wise average underestimation is 5%, 6%, 5%, and 11%, and the height-wise largest underestimation is 15%, 19%, 23%, and 29% for the 4-, 8-, 12-, and 20-story buildings, respectively. The discrepancy in the RSA procedure tends to increase for taller (or longer-period) buildings because higher-mode contributions are known to be more significant for such buildings (Chopra, 2007, Chapter 18). By pervasive use of commercial software based on modal combination approximation, the profession tacitly accepts this approximation. However, it appears that the research community has not recognized fully that RSA may lead to such significant underestimation of response, especially for taller buildings, or effectively communicated this discrepancy to the profession.

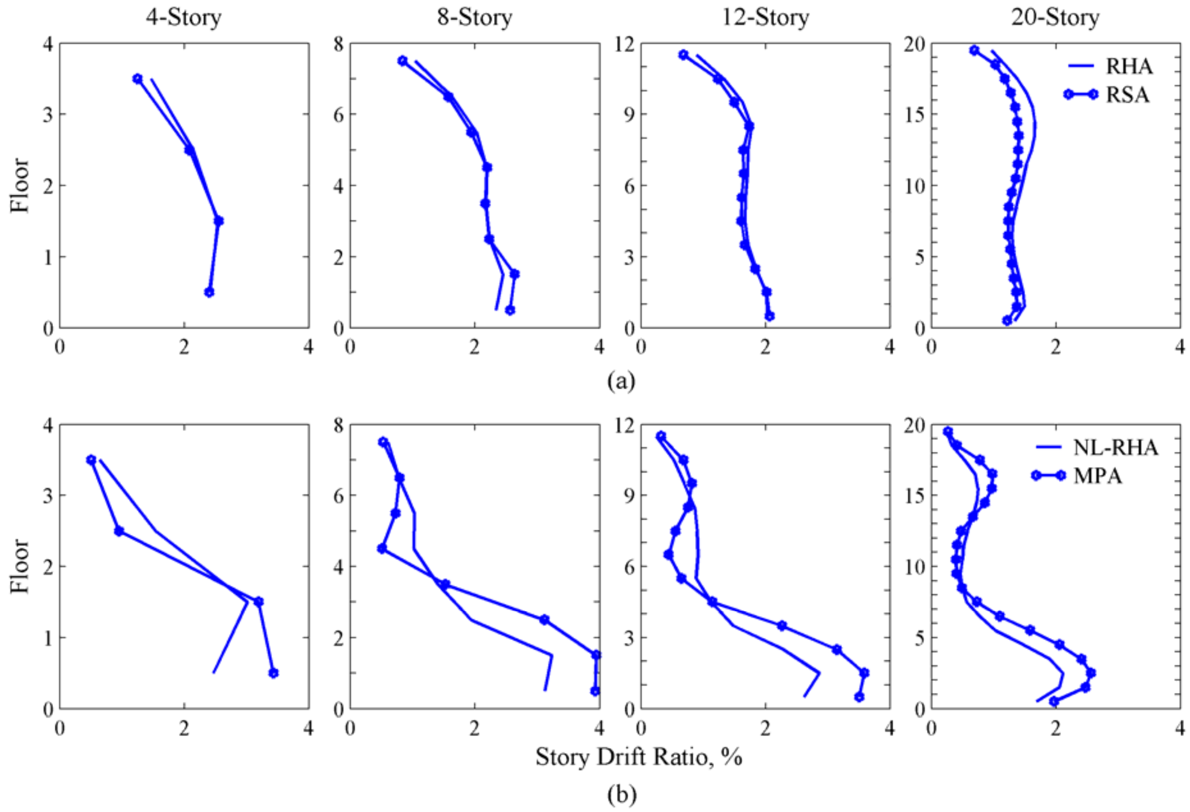

Figure 2 Median story drifts due to ground motions scaled to $A(T_1)_{2\%/50}$ for: (a) linearly elastic systems determined by RSA and RHA procedures, and (b) inelastic systems determined by MPA and nonlinear RHA procedures. Results are for 4-, 8-, 12-, and 20-story buildings.

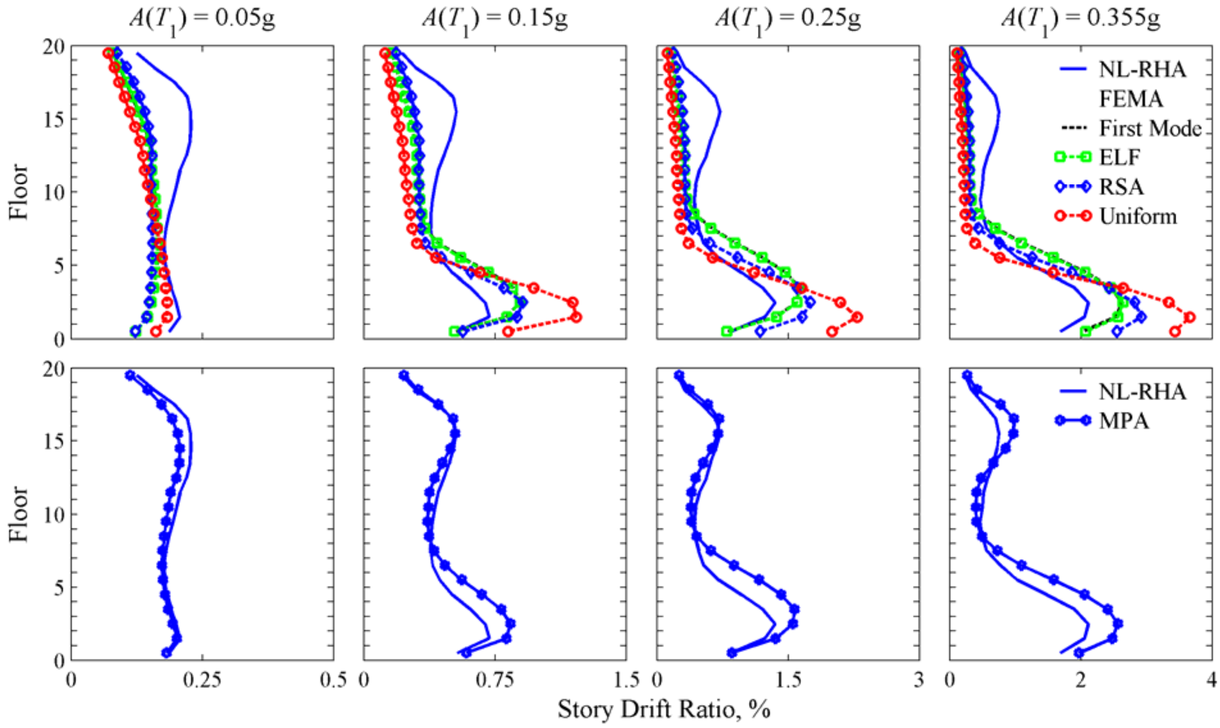

Figure 3 Median story drifts for 20-story building determined by three procedures: (1) nonlinear RHA, (2) four FEMA-356 force distributions (upper boxes), and (3) MPA (lower boxes). Results are presented for ground-motion ensembles scaled to four different values of $A(T_1)$.

The additional errors introduced by neglecting modal coupling in the MPA procedure, which are apparent by comparing parts (a) and (b) of Figure 1, are significant. Having said that, even for the most intense ground motions that deform the buildings far into the inelastic range, the MPA procedure offers an adequate degree of accuracy that should make it useful for practical application in estimating seismic demands for buildings. The accuracy tends to improve as the intensity of the ground motion decreases (Figure 3b).

6. COMPARATIVE EVALUATION OF FEMA-356 AND MPA PROCEDURES

Commonly used for seismic assessment of existing buildings, the NSP in FEMA-356 (FEMA, 2000) requires development of a pushover curve by nonlinear static analysis of the structure, subjected first to gravity loads, followed by monotonically increasing lateral forces with a specified, invariant height-wise distribution. At least two force distributions must be considered. The first is selected from among the following: first-“mode” distribution, equivalent lateral force (ELF) distribution, and RSA distribution; the second distribution is either the “uniform” distribution or an adaptive distribution; several options are allowed for the latter, which varies with change of deflected shape of the structure. This study evaluates the first four lateral force distributions, which are described in Section 22.4 of Chopra (2007).

Figure 3 shows the median story drift demands for the 20-story building due to ground-motion ensembles scaled to the four intensity levels mentioned earlier; similar results for other buildings are available in Bobadilla and Chopra (2007). The target displacement for FEMA analysis was not determined by the empirical equations in FEMA-356, but was taken equal to the MPA value to ensure a meaningful comparison of the two sets of results. In the upper part of the figure, the FEMA-356 estimate of story drifts are compared with the “exact” value determined by nonlinear RHA. In the lower part, the MPA estimate (including all significant modes) of seismic demands is compared with the “exact” value. It is obvious by comparing the two parts of this figure and of other figures in Bobadilla and Chopra (2007) that MPA provides much superior results for the 8-, 12-, and 20-story buildings for the entire range of excitation intensities. For the 4-story building, MPA results are similar to the FEMA estimates.

FEMA force distributions underestimate the story drifts, especially in the upper stories, due to low-intensity ground motions—$A(T_1) = 0.05\text{g}$—that produce response within the elastic range. Although the ELF and RSA distributions are intended to account for higher-“mode” responses, they do not provide satisfactory estimates of seismic response even for buildings responding within their elastic range. The MPA procedure estimates seismic demands much better than do FEMA force distributions.

For higher ground-motion intensities, FEMA force distributions generally underestimate story drifts in upper stories and overestimate them in lower stories, especially the “uniform” distribution. The other force distributions provide story drifts similar to those due to the first-“mode” force distribution, although the ELF and RSA force distributions are intended to account for higher-“mode” response. In contrast, for all excitation intensities, the MPA procedure provides a much better estimate of story drift demands in the upper stories of the 8-, 12-, and 20-story buildings, because it includes higher-“mode” contributions to the response; these higher-“mode” contributions are especially noticeable for the 20-story building. In the lower stories, the MPA estimate is slightly better than the FEMA-356 estimates. Because the response of the 4-story building is dominated by the first-“mode,” the FEMA-356 force distributions are adequate and MPA does not offer improvement in the demand estimate.

In summary, even for the most intense excitations, the MPA procedure estimates seismic demands to a degree of accuracy useful for practical application in seismic evaluation of buildings (see Figure 4). In contrast, the FEMA-356 force distributions are inadequate in estimating seismic demands for the 8-, 12-, and 20-story buildings at all excitation intensities, from the weakest to the strongest.

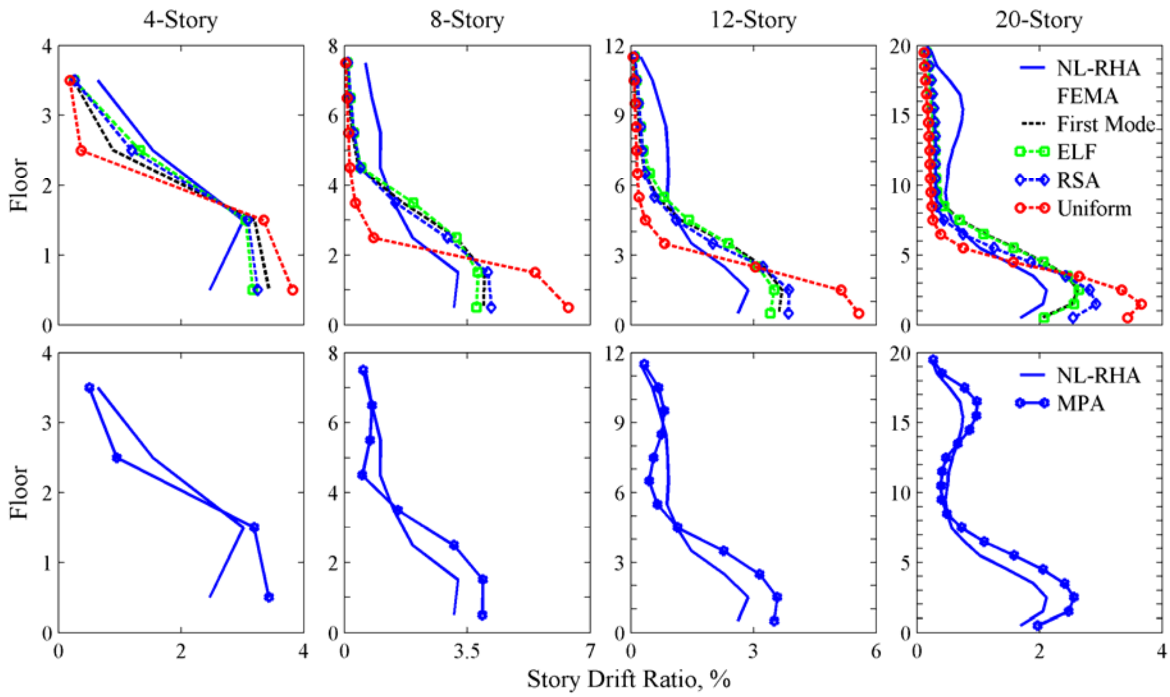

Figure 4 Median story drifts for 4-, 8-, 12-, and 20-story buildings due to ground motions scaled to $A(T_1)_{2\%/50}$ determined by three procedures: (1) nonlinear RHA, (2) four FEMA-356 force distributions (upper boxes), and (3) MPA (lower boxes).

7. CONCLUSIONS

The median seismic demands for 4-, 8-, 12-, and 20-story RC-SMRF buildings—designed according to current building codes—due to an ensemble of 78 ground motions were computed by MPA and nonlinear RHA procedures and compared. These ground motions were scaled to four different intensity levels to evaluate the accuracy of the MPA procedure over a wide range of building responses from essentially within the linearly elastic range to far into the inelastic range. The presented results have led to the following conclusions:

1. The modal combination approximation used in the RSA procedure for linearly elastic systems, a standard tool in structural engineering practice, may lead to significant (15% to 29% for the four buildings) underestimation of story drift demands in the upper stories.

2. Although neglecting modal coupling in MPA introduces additional errors, even for the most intense ground motions that deform the buildings far into the inelastic range, the MPA procedure demonstrates an adequate degree of accuracy that should make it useful for practical application in estimating seismic demands for RC-SMRF buildings.

A comparison of the seismic demands computed by MPA, FEMA-356 NSP, and nonlinear RHA procedures has determined that even for the most intense excitations, which represent a very severe test, the MPA procedure estimates seismic demands for RC-SMRF buildings to a useful degree of accuracy. In contrast, the FEMA-356 force distributions are inadequate in estimating seismic demands for 8-, 12-, and 20-story buildings at all excitation intensities, from the weakest that causes response essentially within the linearly elastic range, to the strongest that drives the buildings far into the inelastic range.

ACKNOWLEDGMENTS

We are most grateful to Professor Greg G. Deierlein from Stanford University and Professor Curt Haselton from California State University at Chico for providing the structural models and ground motion data that served as the basis for this study.

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