A GENERAL PROCEDURE FOR SELECTING AND SCALING GROUND MOTION RECORDS FOR NONLINEAR ANALYSIS OF ASYMMETRIC-PLAN BUILDINGS

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Abstract In performance assessment and design verification of complex structural systems including base-isolated buildings, high-rise structures and structures utilizing advanced lateral force resisting components (e.g., viscous dampers), nonlinear response history analysis (RHA) is now a common engineering tool to estimate seismic demands. Today, majority of ground motion selection and scaling methods are suitable for symmetric plan buildings with first-mode dominant response. There is, therefore, a need for a robust method to select and scale records for nonlinear RHAs of asymmetric-plan buildings with significant torsional response. Presented here is a generalized ground motion selection and scaling procedure called modal pushover-based (MPS) procedure. The proposed procedure explicitly considers structural strength, determined from pushover curves, and determines a scaling factor for each record to match a target value of roof displacement. The accuracy and efficiency of the procedure is evaluated by using computer models of symmetric- and asymmetric-plan buildings subjected to one or two horizontal components of ground motions. Analyses for one component of ground motions were conducted for five existing symmetric-plan buildings of 4, 6, 13, 19 and 52 stories; for two components of ground motion, 48 single-story systems and ten multi-story buildings were analysed. Also examined here is the ASCE/SEI 7 scaling procedure for comparison purposes. This study clearly shows that the MPS procedure provides much superior results in terms of accuracy [true estimates of expected median engineering demand parameters (EDPs)] and efficiency (reduced record-to-record variability of EDPs) than the ASCE/SEI 7 scaling procedure.

1 Introduction

Performance-based procedures for evaluating existing buildings and proposed designs of new buildings in the U.S. require response history analyses (RHAs) for an ensemble of earthquake records to determine EDPs for validation of a targeted performance criterion. Earthquake records selected for RHAs often need to be scaled to a seismic hazard level considered.

Kalkan and Chopra (2009) developed the modal pushover-based scaling (MPS) procedure for selecting and scaling earthquake ground motion records in a form convenient for evaluating existing structures and proposed designs of new structures. This procedure explicitly considers structural strength, obtained from the first-"mode" pushover curve, and determines a scaling factor for each record to match a target value of the deformation of the first-"mode" inelastic SDF system. The MPS procedure has been proven to be accurate and efficient for low-, medium- and high-rise buildings with symmetric plan (Kalkan and Chopra, 2010, 2011 and 2012) subjected to one component of ground motion. Recently, Reyes and Chopra (2011a, 2011b and 2012) extended the MPS procedure for one component (mentioned above) to two horizontal components of ground motion.

Reyes and Quintero (2014) proposed a new version of the MPS procedure for single-story asymmetric-plan buildings. Reyes et al. (2014) extended this procedure to multi-story asymmetric-plan buildings. In this investigation, the developed procedure is compared against the ASCE/SEI 7-10 (ASCE7 henceforth) ground motion scaling procedure for 3D analysis. Based on results from nine multi-story asymmetric-plan buildings with various plan shapes, it is shown that the MPS procedure provides much superior results in terms of accuracy and efficiency than the ASCE/SEI 7-10 ground motion scaling procedure.

2 Modal pushover-based scaling (MPS) procedure

The MPS procedure is implemented here in three phases: (1) computation of target roof displacement and pushover analyses, (2) scaling phase, and (3) selection phase. The step-by-step procedure is presented here in a general form (Reyes et al., 2014).

2.1 Target roof displacement and pushover analyses

(1) For a given site, define the target spectra $\hat{A}_x$ and $\hat{A}_y$, in this study taken as the median of the 5-percent damped pseudo-acceleration response spectra of two components of the ground motions.

(2) Compute the natural frequencies ω_n (periods T_n) and modes ϕ_n of the first few modes of linear-elastic vibration of the building. For each ground motion component direction (x or y), identify the first, second and third modes as the three modes with the largest effective modal mass.

(3) Develop the base shear-roof displacement, $V_{bn} - u_{rn}$, relationship or pushover curve by nonlinear static analysis of the building subjected to the nth-"mode" invariant force distribution:

$$s_n^* = \begin{bmatrix} \mathbf{m}\phi_{xn} \\ \mathbf{m}\phi_{yn} \\ \mathbf{I}_o\phi_{\theta n} \end{bmatrix}$$

where $\mathbf{m}$ is a diagonal matrix of order N with $m_{jj} = m_j$, the mass lumped at the jth floor level; $\mathbf{I}_O$ is a diagonal matrix of order N with $I_{ojj} = I_{oj}$, the moment of inertia of the jth floor diaphragm about a vertical axis through the center of mass (C.M.); and subvectors ϕ_{xn}, ϕ_{yn}, and $\phi_{\theta n}$ of the nth mode ϕ_n represent x, y and θ components of ground motion, respectively. This step should be implemented only for the first three "modes" in the direction under consideration; this step could be omitted for the higher-"modes" if they are treated as linear-elastic (Chopra, 2007).

(4) Idealize the $V_{bn} - u_{rn}$ pushover curve as a bilinear or trilinear curve, as appropriate, and convert it into the force-deformation, $(F_{sn}/L_n) - D_n$, relationship for the nth-"mode" inelastic SDF system using well-known formulations [10]:

$$\frac{F_{sn}}{L_n} = \frac{V_{bn}}{M_n^*} \qquad D_n = \frac{u_{rn}}{\Gamma_n\phi_{rn}}$$

where F_{sn} is a nonlinear hysteretic function of the nth modal coordinate and M_n^* is the effective modal mass for the nth-"mode" (Chopra, 2007).

$$\Gamma = \frac{L_n}{M_n} = \frac{\phi_n^T\mathbf{M}\iota}{\phi_n^T\mathbf{M}\phi_n} \qquad \mathbf{M} = \begin{bmatrix} \mathbf{m} & 0 & 0 \\ 0 & \mathbf{m} & 0 \\ 0 & 0 & \mathbf{I}_o \end{bmatrix} \qquad \iota_x = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \qquad \iota_y = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

$\mathbf{1}$ and $\mathbf{0}$ are vectors of dimension N with all elements equal to one and zero, respectively; and ϕ_{rn} is the value of ϕ_n at the roof.

(5) Establish the target roof displacement $\hat{u}_r$. For a system with known T_n, damping ratio ξ_n, and force-deformation curve (Step 3), determine the peak deformation D_n for the nth-"mode" inelastic SDF system due to each of the unscaled ground motions $\ddot{u}_g(t)$ by solving:

$$\ddot{D}_n(t) + 2\xi_n\omega_n\dot{D}_n(t) + \frac{F_{sn}}{L_n} = -\ddot{u}_g(t) \rightarrow D_n$$

Determine $\widehat{D}_n$ as the median of the D_n values. Calculate roof displacement in the direction under consideration of the nth-"mode" as $\hat{u}_{rn} = \Gamma_n\phi_{rn}\widehat{D}_n$, and compute the roof displacement in the direction under consideration $\hat{u}_r$ from values of $\hat{u}_{rn}$ using a suitable modal combination method (e.g., complete quadratic combination). In practical applications, target deformation $\widehat{D}_n$ can be computed as $\widehat{D}_n = C_{Rn}\widehat{D}_{no}$, where C_{Rn} is the inelastic deformation ratio, estimated from empirical equations (Chopra and Chintanapakdee, 2004), $\widehat{D}_{no} = (T_n/2\pi)^2\hat{A}_n$ and $\hat{A}_n$ is the target pseudo-spectral acceleration at period T_n.

2.2 Scaling phase

(6) Compute the scale factor SF for each record in the direction under consideration by solving the following nonlinear equation: $u_r - \hat{u}_r = 0$, where u_r is the peak roof displacement in the direction under consideration from the scaled records. Because this equation is nonlinear, SF cannot be determined *a priori*, but requires an iterative procedure as shown below:

a) Select an initial value of the scale factor SF, and compute deformation $D_n(t)$ for the nth-"mode" inelastic SDF due to the scaled record by solving: $\ddot{D}_n(t) + 2\xi_n\omega_n\dot{D}_n(t) + F_{sn}/L_n = -SF \times \ddot{u}_g(t) \quad \rightarrow D_n(t)$

b) Compute roof displacement of the nth-"mode" in the direction under consideration: $u_{rn}(t) = \Gamma_n \phi_{rn} D_n(t)$

c) Compute roof displacement in the direction under consideration:
$u_r = max(|\sum_n u_{rn}(t)|)$

d) Estimate error: $\varepsilon = u_r - \hat{u}_r$

e) Adjust the value of the scale factor SF, and repeat steps "a" to "d" until ε is less than a tolerance value.

In this study, step 6 was implemented by a numerical algorithm. By developing steps "a" to "e", separately for the x and y components of the record, scale factors SF_x and SF_y are determined. Note that pushover curves (step 4), and target roof displacement (step 5) will be different for the two horizontal components of the ground motion.

2.3 Selection phase

(7) Select the first k records with the lower values of:
$Error = \sum_{i=4}^{6}(|SF_x A_x(T_i) - \hat{A}_x(T_i)| + |SF_y A_y(T_i) - \hat{A}_y(T_i)|)$
where $\hat{A}_x$ and $\hat{A}_y$ are vectors of spectral values $\hat{A}_i$ at different periods T_i (T_i=T_4,T_5,T_6,); A_x and A_y are vectors of spectral values for the unscaled records over the same periods.

3 Point of comparison (benchmark)

The benchmark or comparison point of an EDP is defined in this study as the median value of EDPs obtained from nonlinear RHAs of the structure subjected to a large set of unscaled records. The accuracy and efficiency of the MPS and ASCE7 procedures are examined by comparing their median EDP estimates from subset of records against the benchmark values, and by comparing record-to-record variability of the EDPs.

4 Study cases for one component RHAs

For a single horizontal component of ground motion, the MPS procedure scales each record by a factor such that the deformation of the first-“mode” inelastic SDF system matches a target value of the inelastic deformation. When steps 1 thru 6 of the procedure shown in section 2 are implemented for one-component of ground motion, the following simplifications may be made: (1) Only the fundamental mode in the direction of analysis is used in steps 3 thru 6; (2) Target deformation $\widehat{D}_1$ may be used instead of a target roof displacement $\widehat{u}_r$; (3) In order to compute the scale factor SF in step 6, the nonlinear equation may be written as $D_1 - \widehat{D}_1 = 0$; (4) The selection phase (step 7) may consider only the unscaled spectral values at the second mode in the direction of analysis instead of the spectral values at T_4, T_5 and T_6. These simplifications may reduce significantly the computational time.

A large group of representative buildings in California were selected to study the one-component MPS and the ASCE7 procedure. This group consists of three existing low- and mid-rise steel special moment resisting frame (SRMF) buildings with 4, 6 and 13 stories, and two existing tall steel SRMF buildings having 19 and 52 stories. A description of these structures and complete details of their analytical models are reported in Kalkan and Chopra (2011 and 2012). For these studies a total of 21 near-fault strong ground motions were selected. These motions were recorded during seismic events with moment magnitude $M_W \geq 6.5$ at fault distances $R_{RUP} \leq 12$ km. Selected records are listed in Table 1 of Kalkan and Chopra (2011 and 2012)

For those five buildings, the median values of EDPs attributable to sets of seven ground motions scaled by the two methods—MPS and ASCE7—were computed by nonlinear RHAs of the buildings and compared against the benchmark EDP values. Representative results for two tall buildings are shown in Figure 1. For the 19-story building, the first three panels of this figure show the benchmark (abraviated as bench) EDPs, and EDPs for the ASCE7 and MPS procedures, respectively. The next three panels display similar results for the 52-story building. The markers and horizontal lines represent the median EDP value ± one standard deviation σ assuming a lognormal distribution. For comparison purposes, the median benchmark values are kept in all sub-plots as a dashed line. The ASCE7 scaling method grossly overestimates the inter-story drift ratios (IDRs) at almost all floors; for example, IDRs are overestimated by as much as 80% for the 19-story building, and almost 170% for the 52-story building. In contrast, IDRs obtained from MPS differ from the benchmark results by less than 10% in most cases. Furthermore, the dispersion in EDPs as a result of the seismic records scaled according to the ASCE7 procedure is much larger than those from the MPS procedure.

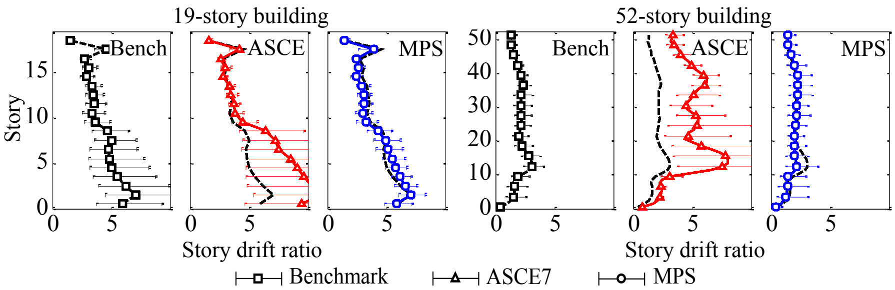

Fig. 1 – Inter-story drift ratios in percentage for the 19- and 52-story buildings. In each case the marker and the horizontal line represent the median value of the EDP ± σ, assuming a log-normal distribution.

Similar results were observed for the other three buildings analysed (low- and mid-rise buildings); these results are not shown due to space limitations. Additional findings can be found in Kalkan and Chopra (2012, 2011 and 2012)

5 Study cases for two components RHAs

The accuracy and efficiency of the MPS procedure for multi-story symmetric-plan buildings subjected to two components of ground motions was examined using a computer model of an existing 9-story steel moment frame building (Reyes and Chopra, 2011b). For asymmetric-plan buildings, two categories of hypothetical buildings were considered: single-story and multi-story buildings. The single-story buildings modelled are 48 structures with fundamental vibration periods T_n equal to 0.2, 0.5, 1 and 2 s, and with yield strength reduction factors R equal to 2, 3, 5, and a value that leads to linear elastic design. Their lateral resisting system consists of buckling restrained braced frames with non-moment-resisting beam–column connections. The structures considered in the multi-story buildings category are nine steel SMRF buildings with 5, 10 and 15 stories. Their plan shapes are shown in Figure 2, where the moment resisting frames are highlighted. The buildings are identified by the letters R, L and T followed by the number of stories: plan R is approximately rectangular, plan T is symmetric about the x axis, and plan L is un-symmetric about both x and y axis. Further details of their structural systems including the fundamental periods, mode shapes, torsional irregularity factors etc. can be found in Reyes and Quintero (2014) and Reyes et al. (2014).

For the single-story buildings, the 30 near-fault records selected were recorded from nine shallow crustal earthquakes with moment magnitude M_W = 6.7 ± 0.2 recorded at distances (R_{RUP}) ranging from 0.1 to 15 km. The seismic scenario for multi-story buildings consists of 30 far-field ground motion records populated from seven shallow crustal earthquakes with moment magnitude $M_W = 6.7 \pm 0.2$ at distances ranging from 20 to 30 km. The selected seismic records are listed in Table 1 in Reyes and Quintero (2014) and Reyes et al. (2014).

The procedure developed in section 2 is compared against the ASCE7 scaling procedure. Representative results from single-story buildings and 15-story building are shown in Figures 3 and 4, respectively. These structures have L-shaped plan with significant plan irregularity. Figure 3 includes three sets of seven records randomly selected (called "MPS-Rand" and "ASCE7-Rand") and one set of seven records selected by implementing an improved selection procedure (called "MPS-Best" and "ASCE7-Best"). Roof displacements (normalized by the corresponding benchmark results) obtained from sets "MPS-Rand" (Fig. 3) are accurate, and show a low "record-to-record" and "set-to-set" variability. Only displacements are unsuccessfully estimated for short-period structures designed for high values of yield strength reduction factors. A considerable improvement in accuracy and "record-to-record" variability is obtained when sets "MPS-Best" (Fig. 3) are used for estimating the roof displacements; in this case, the errors are not greater than 20%. Roof displacements obtained from sets "ASCE7-Rand" (Fig. 3) are in general less accurate and show a large "record-to-record" and "set-to-set" variability; overestimation of roof displacements is as high as 40%.

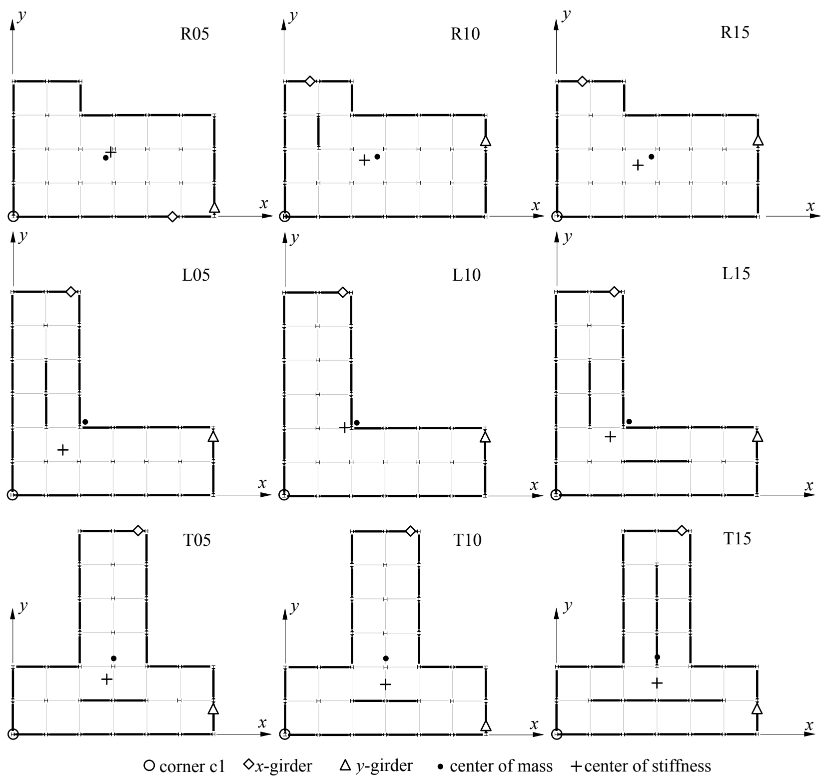

Fig. 2 – Plan views of the nine multi-story asymmetric-plan buildings.

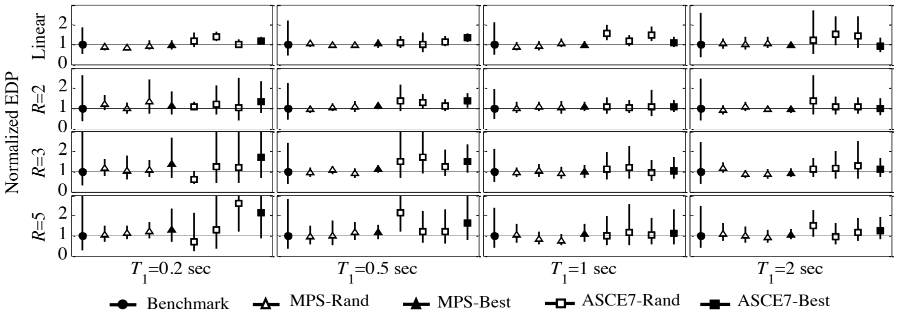

Fig. 3 – Normalized roof displacement (EDP) at point c2 along x-direction of the L-shaped plan single-story buildings (see Fig. 2). For each set the marker and the vertical line represent the median value of the EDP ± one standard deviation, assuming a log-normal distribution.

Figure 4 shows story drifts at a selected corner of the building (c1 in Fig. 2) from records scaled and selected according to MPS and ASCE7 procedures together with benchmark values. This figure confirms that for the multi-story case (L15 building), the records scaled according to the MPS procedure lead to more accurate estimates of median values of EDPs than ASCE7 scaling procedure. The maximum discrepancies encountered by scaling records according to the ASCE7 procedure are reduced when these records are scaled by the MPS procedure; for example, the error in story drifts decreases from 28% to 8%. Due to limited space, we only show here a representative set of results; additional findings can be found in Reyes and Quintero (2014) and Reyes et al. (2014).

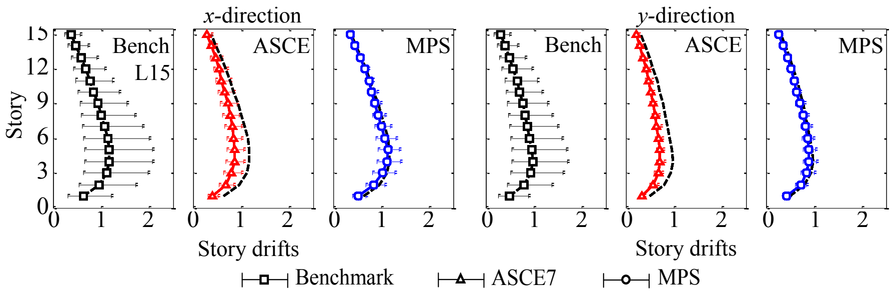

Fig. 4 – Inter-story drift ratios in percentage along x- and y-direction at corner c1 of the L-shaped plan 15-story building (see Fig. 2). In each case the marker and the horizontal line represent the median value of the EDP ± σ, assuming a log-normal distribution.

6 Conclusions

This paper presents summary of a general procedure for selecting and scaling ground motion records for nonlinear response history analyses of asymmetric-plan buildings with significant plan irregularity. Based on results from multiple study cases, it is clearly shown that the modal-pushover-based (MPS) procedure provides much superior computation of EDPs in terms of accuracy and efficiency as compared to the ASCE7 scaling method. This superiority is evident in two respects. First, the ground motions scaled according to the extended MPS procedure provide median values of EDPs that are much closer to the benchmark values than is achieved by the ASCE7. Second, the dispersion (or record to-record variability) in the EDPs due to seven scaled records around the median is much smaller when records are scaled by the MPS procedure compared to the ASCE7 procedure.

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