Modal pushover-based scaling of records for nonlinear RHA of one-story unsymmetric-plan buildings

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SUMMARY:
The modal-pushover-based-scaling (MPS) procedure, currently restricted to symmetric-plan buildings, is extended herein to unsymmetric-plan buildings. The accuracy of the extended MPS procedure was evaluated for a large set of three-degree-of-freedom unsymmetric-plan structures with variable stiffness and strength. The structures were subjected to nonlinear response history analysis considering sets of seven records scaled according to the MPS procedure. Structural responses were compared against the benchmark values, defined as the median values of the engineering demand parameters (EDPs) due to 30 unscaled records. This evaluation of the MPS procedure has led to the following conclusions: (1) The MPS procedure provided a highly accurate estimate of the median EDPs and reduced the record-to-record variability of the responses. (2) The MPS procedure is found to be much superior compared to the ASCE/SEI 7-05 scaling procedure for three-dimensional analysis.

Keywords: ground motion record, pushover, nonlinear RHA, amplitude scaling, unsymmetric-plan building.

1. INTRODUCTION

The earthquake engineering profession has been moving away from traditional code procedures to performance-based procedures for evaluating existing buildings and proposed designs of new buildings. Although nonlinear static (or pushover) analysis continues to be used for estimating seismic demands, nonlinear response history analysis (RHA) is now being increasingly employed. In the latter approach, engineering demand parameters (EDPs)—floor displacements, story drifts, member forces, member deformations, etc.—are determined by nonlinear RHA of a computer model of the building for an ensemble of multi-component ground motions. Fraught with several challenging issues, selection and scaling of ground motions necessary for nonlinear RHA remains a subject of much research in recent years. Most of the procedures proposed to modify ground motion records fall into one of two categories: spectrum matching (Lilhanand & Tseng, 1988) and amplitude scaling.

The objective of amplitude scaling procedures is to determine scaling factors for a small number of records such that the scaled records provide an accurate estimate of median structural responses, and, at the same time, are efficient, i.e. reduce the record-to-record variability of response. Most existing scaling procedures may not be appropriate for near-fault sites where the inelastic deformation can be significantly larger than the deformation of the corresponding linear system, or for tall buildings where the higher mode responses are significant, or for unsymmetric-plan buildings where two coupled lateral torsional vibration modes may provide comparable contributions to response.

The modal-pushover-based-scaling (MPS) procedure, developed by Kalkan and Chopra (2010a), explicitly considers structural strength and determines a scaling factor for each record to match a target value and selects a small set of scaled records that lead to accurate and efficient estimates of EDPs. This paper extends the MPS procedure, currently restricted for symmetric-plan buildings, to unsymmetric-plan buildings, and investigates the accuracy and efficiency of the developed MPS procedure for nonlinear RHA of one-story three-degree-of-freedom structural systems. In addition, the developed procedure is compared against the ASCE/SEI 7-05 (ASCE, 2005) scaling procedure for three-dimensional analysis. Based on the results for 32 one-story unsymmetric-plan buildings, it is shown that the MPS procedure provides much superior results than the ASCE/SEI 7-05 scaling procedure.

2. MPS PROCEDURE

The existing MPS procedure scales independently each component of the record by a factor such that deformation of the first-“mode” inelastic single-degree-of-freedom (SDF) system—established from the first-“mode” pushover curve for the building—due to the scaled record matches a target deformation value (Kalkan & Chopra, 2010a; Reyes & Chopra, 2012). The target deformation is estimated by performing nonlinear RHA of the first-“mode” inelastic SDF system, and then computing the median of the resulting deformation values. The final set of records are selected by ranking the scaled ground motions based on the difference between the peak deformation of the second-“mode” SDF system—treated as elastic—and the target deformation for that mode; the record with the smallest difference is ranked the highest. Higher mode effects in response due to both components of ground motion are considered in ranking ground motions. Nonlinear RHA of the structure is conducted for a small number of the top-ranked scaled records. This scaling procedure has been demonstrated to be accurate and efficient (Kalkan & Chopra, 2010a; Reyes & Chopra, 2012).

The existing MPS procedure is extended herein to unsymmetric-plan buildings by introducing one substantial change: scale factors are estimated using roof displacements instead of deformation of the first-“mode” inelastic SDF system. Scaling factors *SF* for each ground motion are obtained independently for each horizontal direction by solving the nonlinear equation:

$$u_r - \hat{u}_r = 0 \qquad (2.1)$$

where u_r is the peak roof displacement calculated by implementing the uncoupled modal response history analysis (UMRHA; Chopra A. K., 2007) and $\hat{u}_r$ is the target roof displacement. In practical implementation, the target roof displacement may be estimated from the response spectrum by combining inelastic “modal” displacements, just as for linear systems. This application of modal combination rules to nonlinear systems obviously lacks a rigorous theoretical basis, but seems reasonable if the modes are only weakly coupled. The deformation D_n of the nth-mode inelastic SDF system that is needed to estimate the “modal” displacement u_{rn} can be calculated by multiplying the spectral displacement of nth mode by an empirical inelastic deformation ratio C_{Rn} (Chopra & Chinatanapakdee, 2004). However, in this study, the deformation D_n was computed as the median value of the peak deformations of the first-“mode” inelastic SDF system due to an ensemble of unscaled records. A full version of the procedure is available in Quintero (2012).

The accuracy of the extended MPS procedure was evaluated for a large set of three-degree-of-freedom unsymmetric-plan structures with variable stiffness and strength. The structures were subjected to sets of seven records scaled according to the MPS procedure and their responses were compared against the benchmark values, defined as the median values of the EDPs due to 30 unscaled records.

3. ASCE/SEI 7-05 PROCEDURE

The ASCE/SEI 7-05 standard (abbreviated to ASCE7) requires that both components of an earthquake record be scaled by the same factor, determined to ensure that the average of the SRSS response spectra over all records does not fall below 1.3 times the target spectrum by more than 10% over the period range $0.2T_1$ to $1.5T_1$. The SRSS spectrum is defined as the square-root-of-sum-of-squares (SRSS) of the 5%-damped response spectra for the two horizontal components of ground motion. The design value of an EDP—member forces, member deformations, story drifts, etc.—is taken as the average value of the EDP if at least seven scaled records are used in the analyses, or the maximum value of the EDP otherwise. Various combinations of scaling factors for individual records can satisfy the preceding requirement for the average SRSS response spectrum.

To achieve the desirable goal of scaling each record by the smallest possible factor, the ASCE7 procedure was implemented as described in Appendix A of Reyes & Chopra (2012). The target pseudo-acceleration spectra $\hat{\mathbf{A}}_x$ and $\hat{\mathbf{A}}_y$ for the *x* and *y* components of ground motion for the building site, were taken as the geometric-mean of the 5-percent damped pseudo-acceleration response spectra of the fault parallel and fault normal components of unscaled records, respectively.

Despite a new version of the ASCE/SEI 7 standard has been released, the 2005 version was used in this study because it is part of the current building code provisions in the state of California.

4. SELECTED NEAR-FAULT GROUND-MOTIONS

The thirty near-fault records selected for this investigation were recorded from nine shallow crustal earthquakes compatible with the following scenario:

- Moment magnitude: M_w=6.7±0.2
- Closest distance: $R_{closest}$<15 km
- Record lowest usable frequency: ≤ 1/6 Hz.

Figure 4.1 shows their magnitude-closest distance distribution. These ground motions were rotated to the fault-normal (FN) and fault-parallel (FP) orientations using the following equations:

$$\ddot{u}_{\mathrm{FP}} = \ddot{u}_1 \cos(\beta_1) + \ddot{u}_2 \cos(\beta_2) \tag{4.1}$$

$$\ddot{u}_{\mathrm{FN}} = \ddot{u}_1 \sin(\beta_1) + \ddot{u}_2 \sin(\beta_2) \tag{4.2}$$

where $\beta_1 = \alpha_{strike} - \alpha_1$, $\beta_2 = \alpha_{strike} - \alpha_2$, α_{strike} is the strike of the fault, α_1 and α_2 are the azimuths of the instrument axes as shown in Figure 4.2a. Buildings are orientated in a way that their *x* and *y* axis are aligned with azimuths of FP and FN components of the records. Shown in Figure 4.3 are the 5-percent-damped geometric-mean response spectra for the as-recorded and the FN-FP components of the unscaled ground motions.

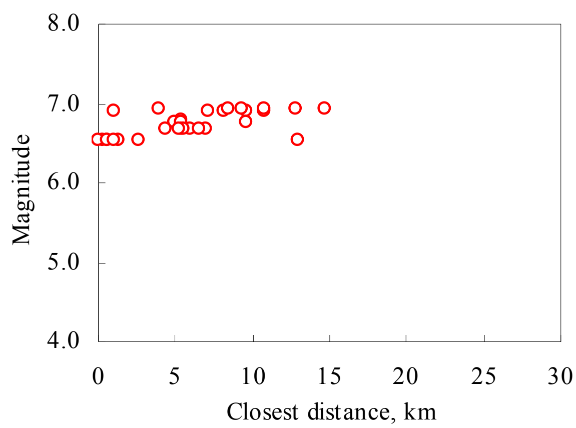


Figure 4.1. Distribution of magnitude and closest distance for the thirty selected ground motions.

5. STRUCTURAL SYSTEMS SELECTED

The structures considered are single-story buildings having un-symmetric plans. The single-story structures with three-degrees of freedom are 32 buildings with fundamental vibration periods T_n equal to 0.2, 0.5, 1, and 2 sec., and yield strength reduction factors R equal to 2, 3, 5, and a value that leads to linear elastic design. The lateral resisting system of the buildings consists of buckling-restrained braced frames with non-moment-resisting beam-column connections. The plan shapes and bracing layouts are shown in Figure 5.1. Buildings are identified by the letters A and B depending on the plan shape; plan A is symmetric about y axis and unsymmetric about x axis while plan B is unsymmetric about both x and y axes. The group of buildings selected for this investigation includes some short-period structures designed for high yield strength reduction factors. Although these structures may be unrealistic, they are included for the sake of completeness.

Design spectrum was taken as the geometric-mean of the 5-percent damped pseudo-acceleration response spectra of the FN-components of the records. The earthquake design forces were determined by bi-directional linear response spectrum analysis (RSA) of the building with the spectrum reduced by a response modification factor R. The constitutive model used for the buckling restrained braces (BRBs) is the trilinear model shown in Figure 5.2. This model was obtained based on experimental results (Merrit et al; 2003a and 2003b). Values of k and q_y are equal for all BRBs of a building.

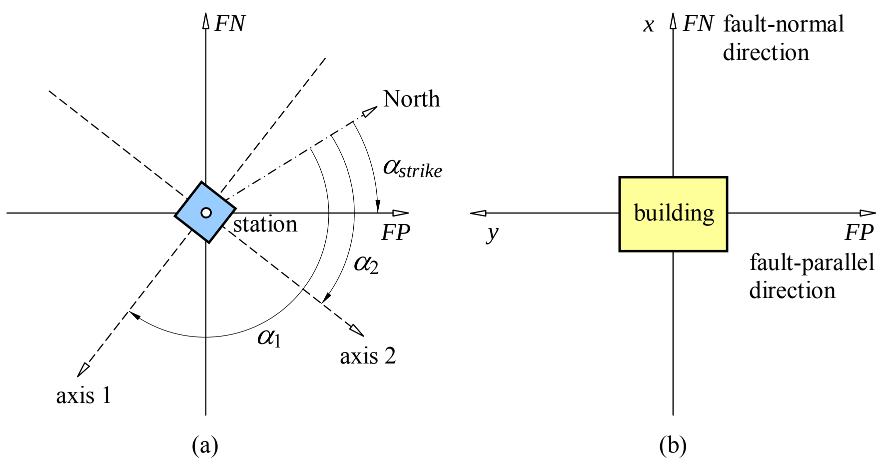


Figure 4.2. (a) Reference axes for the fault and the instrument with relevant angles noted. (b) Reference axis for the building.

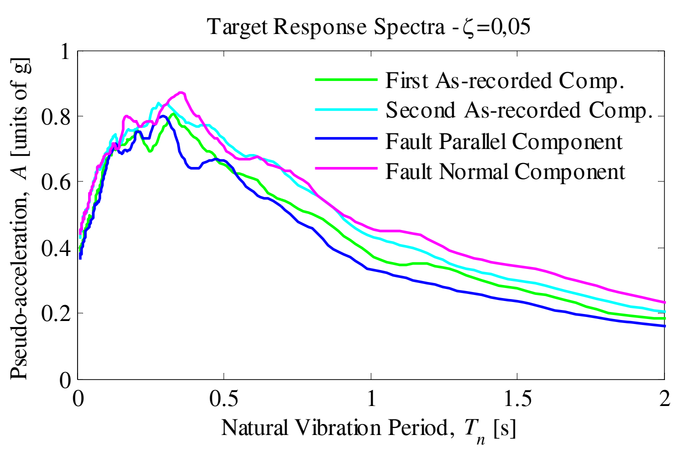


Figure 4.3. Geometric-mean pseudo-acceleration response spectra of 30 unscaled records.

Natural periods T_n, modes ϕ_n, and effective modal masses M_n^* of the buildings presented in Quintero (2012) permit the following observations. (1) Coupled lateral-torsional motions occur in the first and third modes of both plans whereas lateral displacements dominate motion in the second mode. According to the ASCE/SEI 7-05, both plans present an extreme torsional irregularity. (2) Higher-mode contributions to forces are expected to be significant for both types of buildings because the effective mass of the first lateral modes is less than 50% of the total mass.

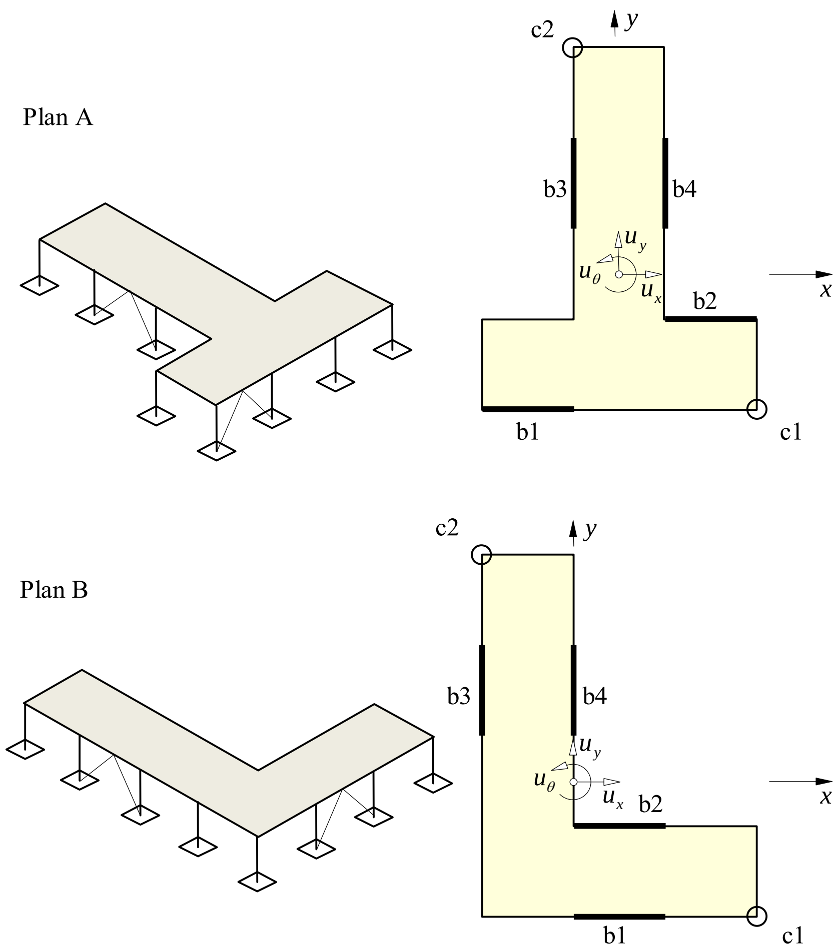


Figure 5.1. Schematic isometric and plan views of the selected structural systems with degrees of freedom noted; buckling-restrained braced frames are highlighted.

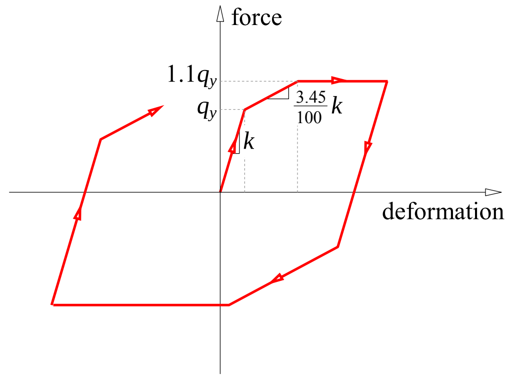


Figure 5.2. Constitutive model used for the buckling-restrained braces (BRBs).

6. EVALUATING MPS PROCEDURE

The "true" or expected value of an EDP (benchmark) is defined in this study as the geometric mean of EDPs obtained from nonlinear RHA of the structure subjected to 30 unscaled records. The MPS and ASCE7 procedures were implemented to select and scale sets of seven records. Figures 6.1 and 6.2 show displacements obtained at three locations: the center of mass, point c1, and point c2 (Fig. 5.1). Each part of these figures is a 4x4 array corresponding to 16 combinations of yield strength reduction factor *R* (increasing from top to bottom) and fundamental periods of vibration (increasing from left to right). The vertical axis of the plots is the displacement obtained from each set normalized by the corresponding benchmark value. The blue round marker and vertical line represent the normalized benchmark value ± one standard deviation, assuming a log-normal distribution with unit median. A horizontal thin black line crosses the blue round marker to make the comparison between sets and benchmark values easier. Parallel to the thin black line, two dashed lines are plotted, indicating the normalized benchmark value ± 20%. Normalized EDPs for each set are indicated with a marker and a vertical line representing the geometric mean ± one standard deviation, assuming a log-normal distribution. The color assigned to each procedure is indicated in the legend at the bottom of figures.

As explained earlier, the MPS and ASCE7 procedures are composed of two phases: a scaling phase (in which scale factors are found) and a selection phase (in which a small set of records is chosen). For each procedure, Figures 6.1 and 6.2 include 5 sets of seven records randomly selected (called "*MPSRand*" and "*ASCERand*") in order to evaluate the robustness of the selection phase and one set of seven records selected by implementing an improved selection procedure (called "*MPSBest*" and "*ASCEBest*"). Suffix "*-Best*" means that a selection procedure has been implemented trying to obtain a better estimation of EDPs, but the results are not necessary better than those provided by randomly selected sets.

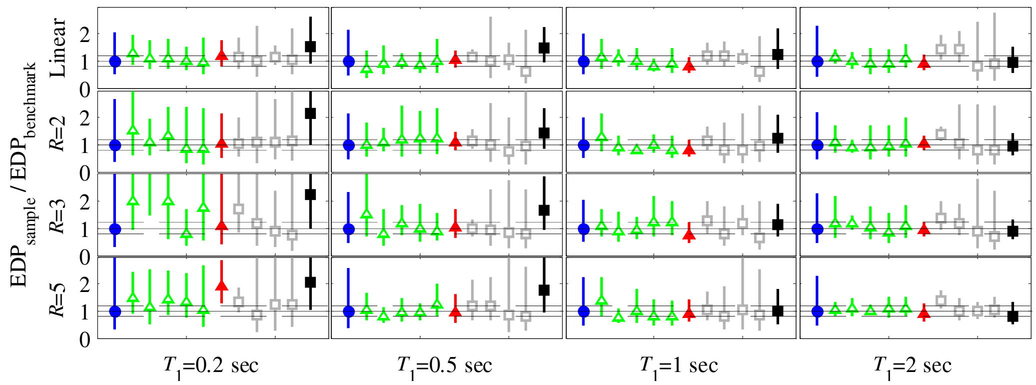
Displacements obtained from sets "*MPSRand*" (green lines, triangular markers, in Figure 6.1 and 6.2) give accurate estimations and reduced "record-to-record" and "set-to-set" variability of displacements, except for the case of short-period structures designed for high values of yield strength reduction factors; as mentioned before, this case may be unrealistic. For most cases, displacements obtained from sets "*MPSBest*" (red lines, triangular markers, in Figure 6.1 and 6.2) represent a considerable improving in accuracy and "record-to-record" variability when compared to displacements obtained from sets "*MPSRand*".

Displacements obtained from sets "*ASCE7Rand*" (gray lines, square markers, in Figure 6.1 and 6.2) are in general inaccurate and show a large "record-to-record" and "set-to-set" variability; overestimation of displacements is as high as 100%. In general, the "record-to-record" variability decreases with increasing fundamental periods. Similar to the MPS procedure, the ASCE7 procedure leads to inaccurate estimates of median displacements accompanied by large “record-to-record” variability of the responses for short-period structures designed for large values of yield strength reduction factors. The set “*ASCE7Best*” (black lines, square markers, in Figure 6.1 and 6.2) gives improved results for structures with long fundamental periods. This may be due to the similitude between elastic and inelastic spectra for systems in the velocity and displacement sensitive region.

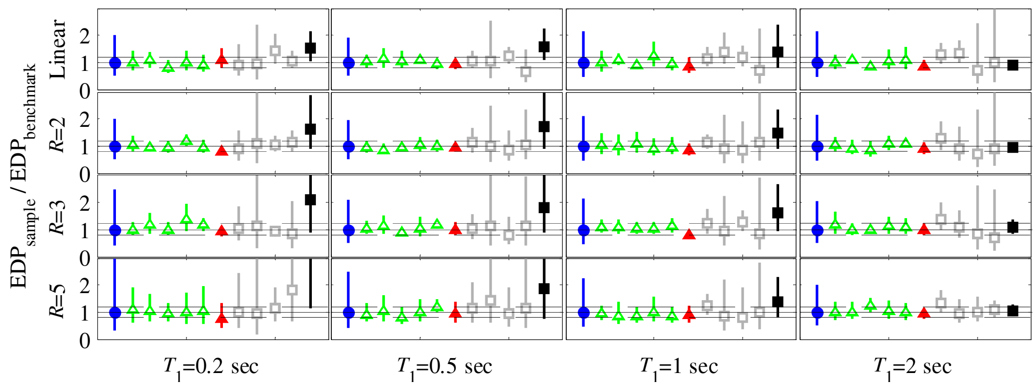
7. CONCLUSIONS

With the goal of developing effective procedures for selection and scaling of multi-component ground motion records to be used in nonlinear RHA of structures, a modal-pushover-based-scaling (MPS) procedure was developed. The objective of this amplitude scaling procedure was to determine scale factors for a small number of records such that the scaled records provide an accurate estimate of median structural responses, and are also efficient, i.e., reduce the record-to-record variability of response. The accuracy of the extended MPS procedure was evaluated by comparing the median values of the engineering demand parameters (EDPs) due to a set of seven records scaled according to the MPS procedure against the benchmark values, defined as the median values of the EDPs due to 30 unscaled records. The efficiency of the MPS and ASCE7 scaling procedures was evaluated by computing the dispersion of the responses due to the seven scaled ground motions; small dispersion indicates that the scaling procedure is efficient. A large set of one-story unsymmetric-plan buildings was selected to test the procedure. This evaluation of the MPS procedure has led to the following conclusions:

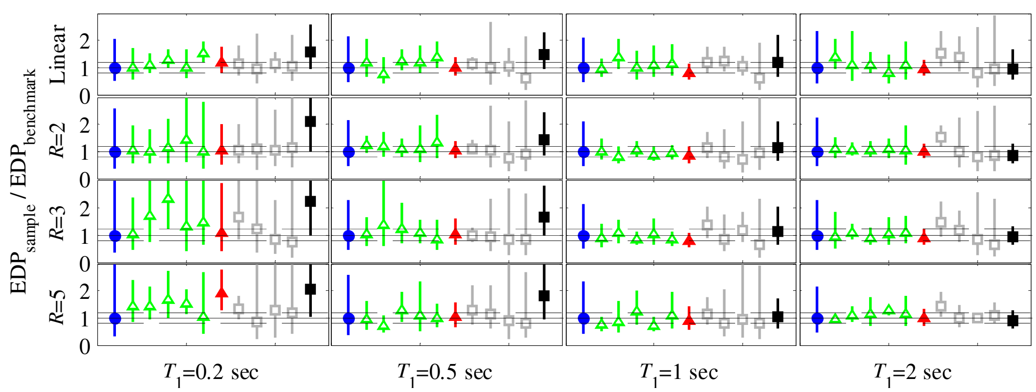
1. The extended MPS procedure leads to a highly accurate estimate of the median EDPs and reduced the record-to-record variability of the responses compared to the benchmark responses.
2. The extended MPS procedure is much superior compared to the ASCE7 procedure for scaling two components of ground motion records. This superiority is evident in two respects. First, the ground motions scaled according to the MPS procedure provide median values of EDPs that are much closer to the benchmark values than is achieved by the ASCE7 procedure. 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 scaling procedure.
3. Neither the extended MPS procedure nor the ASCE7 procedure are recommended for short-period structures designed for large values of yield strength reduction factors.



(a) Plan A - EDP: Displacement. - Direction: *x* – Point: Center of mass.

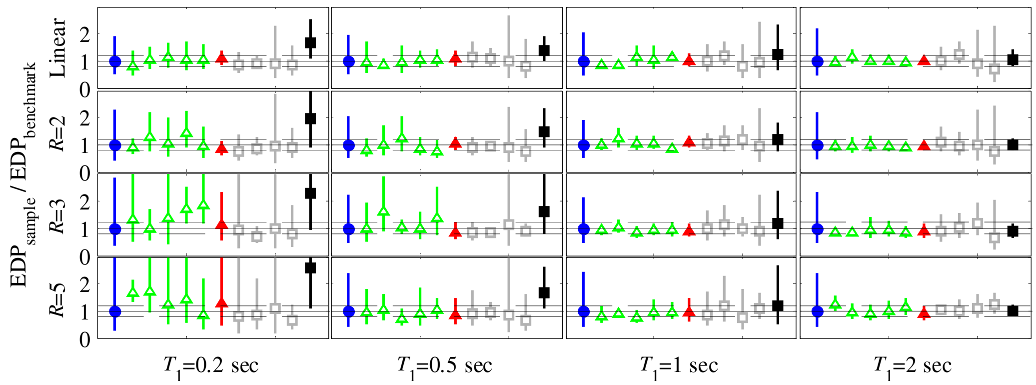


(b) Plan A - EDP: Displacement. - Direction: *x* – Point: c1.

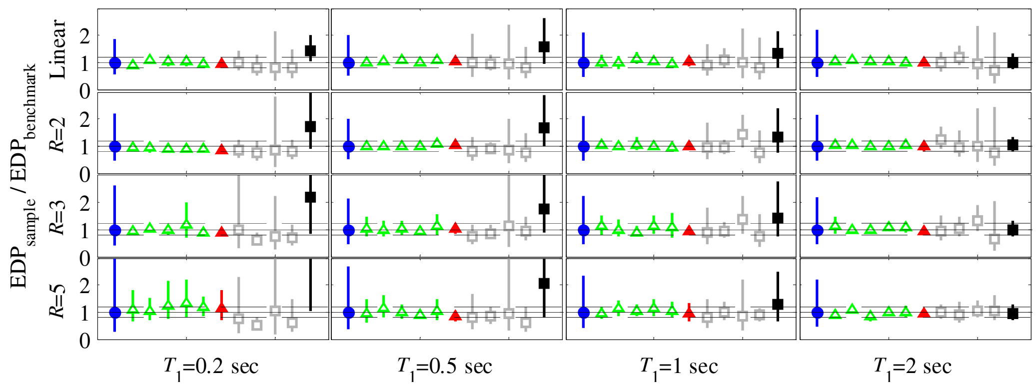


(c) Plan A - EDP: Displacement. - Direction: *x* – Point: c2.

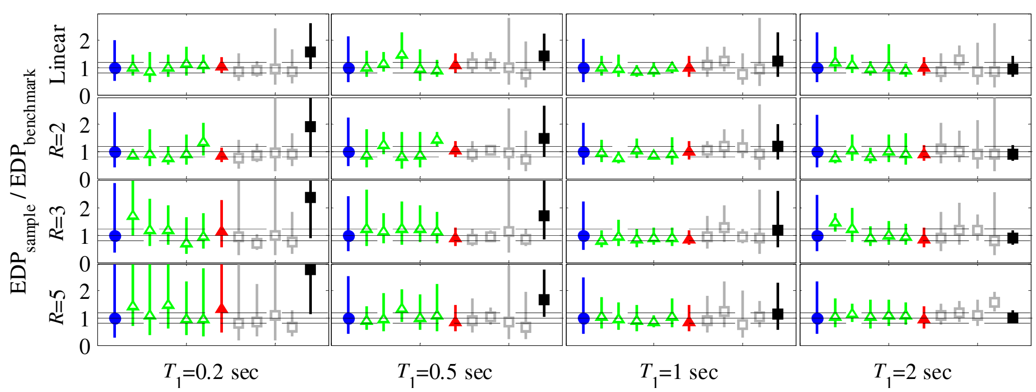
Figure 6.1. Normalized results for the displacement (EDP) at different points in direction *x* for plan A: (a) Center of mass. (b) Point c1. (c) Point c2. For each set the marker and the vertical line represent the median value of the EDP ± one standard deviation, assuming a log-normal distribution.



(a) Plan B - EDP: Displacement. - Direction: *x* – Point: Center of mass.



(b) Plan B - EDP: Displacement. - Direction: *x* – Point: c1.



(c) Plan B - EDP: Displacement. - Direction: *x* – Point: c2.

Benchmark --- + ó - 20% *MPSRand* *MPSBest* *ASCERand* *ASCEBest*

Figure 6.2. Normalized results for the displacement (EDP) at different points in direction *x* for plan B: (a) Center of mass. (b) Point c1. (c) Point c2. For each set the marker and the vertical line represent the median value of the EDP ± one standard deviation, assuming a log-normal distribution.

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