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EXTENDING MODAL PUSHOVER-BASED GROUND MOTION SCALING PROCEDURE TO UNSYMMETRIC-PLAN MULTI-STORY BUILDINGS

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ABSTRACT

The modal pushover-based scaling (MPS) procedure explicitly considers structural strength, and determines a scaling factor for each record to match an inelastic target deformation value, and then selects a small set of scaled records that lead to accurate and efficient estimates of engineering demand parameters (EDPs). This paper extends the MPS procedure, currently restricted for symmetric-plan buildings, to multistory unsymmetric-plan buildings, and investigates the accuracy and efficiency of the developed MPS procedure for nonlinear RHA of three-dimensional (3D) structural systems. In addition, the developed procedure is compared against the ASCE/SEI 7-10 scaling procedure for 3D analysis. The accuracy of the extended MPS procedure was evaluated for nine unsymmetric-plan structures with 5, 10 and 15 stories. These buildings cover two levels of horizontal irregularity defined in ASCE/SEI 7-10. This evaluation of the MPS procedure has led to the following conclusions: (1) The MPS procedure provided accurate estimates of median values of EDPs, and reduced record-to-record variability of the responses; (2) The MPS procedure is much superior compared to the ASCE/SEI 7-10 procedure.

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ABSTRACT

This investigation extends the Modal Pushover-based Scaling (MPS) procedure for selecting and scaling earthquake ground motion records, currently restricted for symmetric-plan buildings, to multistory unsymmetric-plan buildings, and investigates the accuracy and efficiency of the developed MPS procedure for nonlinear response-history analyses of three-dimensional (3D) structural systems. In addition, the developed procedure is compared against the ASCE/SEI 7-10 scaling procedure for 3D analysis. The accuracy of the extended MPS procedure was evaluated for nine unsymmetric-plan structures with 5, 10 and 15 stories. These buildings cover two levels of horizontal irregularity defined in ASCE/SEI 7-10. This evaluation of the MPS procedure has led to the following conclusions: (1) The MPS procedure provided accurate estimates of median values of engineering demand parameters, and reduced record-to-record variability of the responses; (2) The MPS procedure is much superior compared to the ASCE/SEI 7-10 procedure in terms of accuracy and efficiency.

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 engineering demand parameters (EDPs) for validation of a targetted performance criteria. Earthquake records selected for RHAs often need to be scaled to a seismic hazard level considered.

Among many procedures proposed to modify ground motion records, the most widely used approaches are amplitude scaling and spectrum matching [1]. 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 structural responses given the considered hazard level, and at the same time are efficient, i.e. reduce the record-to-record variability (dispersion) of the responses.

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Kalkan and Chopra [2] 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, determined 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 [2, 3, 4] and ordinary standard bridges [5, 6] subjected to one component of ground motion. Recently, Reyes and Chopra [7] extended the MPS procedure for one component of ground motion (mentioned above) to two horizontal components.

Reyes and Quintero [8] proposed a new version of the MPS procedure for single-story unsymmetric-plan buildings. This investigation [9] extends this procedure to multi-story unsymmetric-plan buildings. In addition, the developed procedure is compared against the ASCE/SEI 7-10 ground motion scaling procedure for 3D analysis. Based on results from nine multi-story unsymmetric-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.

Ground Motions Selected

The 30 records selected for this investigation listed in references [10, 11, 12] were recorded from seven shallow crustal earthquakes with moment magnitude $M_W = 6.7 \pm 0.2$, at distances ranging from 20 to 30 km, and with NEHRP site classification C or D (very dense soil and soft rock or stiff soil sites). Shown in Figure 1 are the 5%-damped median response spectra for x and y components of the ground motions.

Because the 30 ground motions selected were not intense enough to drive the buildings considered far into the inelastic range—an obvious requirement to test any scaling procedure—they were pre-amplified by a factor of 4.0. These pre-amplified ground motions are treated as "unscaled" records for this investigation. 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 the 30 "unscaled" records that naturally produce the target inelastic deformation value [3, 7, 8, 11, 12, 13].

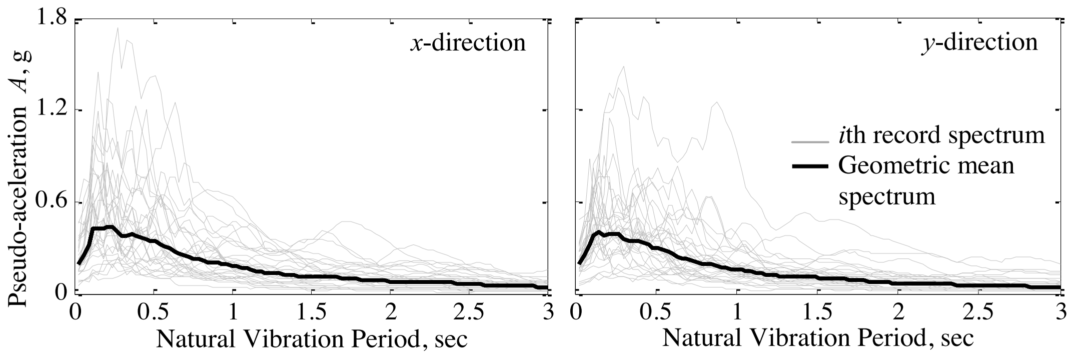

Figure 1. Geometric-mean pseudo-acceleration response spectra of 30 records for 5% damping; individual response spectra of the records are also shown.

Structural Systems

The structures considered are nine unsymmetric plan hypothetical buildings with 5, 10 and 15 stories. These buildings were designed according to the 2009 International Building Code [14] to be located in Los Angeles, California, covering the levels of horizontal irregularity defined in the ASCE/SEI 7-10 standard [15]—torsional irregularity and extreme torsional irregularity. In addition, three buildings were designed with a regular plan configuration for comparison purposes. The lateral resisting system of the buildings consists of moment resisting frames. 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 follow by the number of stories: Plan R is rectangular with two axes of symmetry, plan T is symmetric about the y axis, and plan L is unsymmetric about both x and y. The buildings have similar plan areas and floor weights, with a span length of 30 ft and a story height of 10 ft. The earthquake design forces were determined by bi-directional linear response spectrum analysis of the building with the design spectrum reduced by a response modification factor R=8. However, member sizes were governed by drift limits instead of strength requirements.

Analyzed by the PERFORM-3D computer program [16], the buildings were modeled as follows: (1) Beams and columns were modeled by a linear element with tri-linear plastic hinges at the ends of the elements that can include in-cycle strength deterioration, but not cyclic stiffness degradation; the axial load-moment interaction for the columns was based on plasticity theory; (2) Panel zones were modeled as four rigid links hinged at the corners with a rotational spring that represents the strength and stiffness of the connection; (3) Ductility capacities of girders, columns, and panel zones were specified according to the ASCE/SEI 41-06 standard [17]; (4) Columns of moment resisting frames and the gravity columns were assumed to be clamped at the base; and (5) Effects of nonlinear geometry were approximated by a standard P-Δ formulation to account for secondary effects.

To verify that the selected buildings cover a broad range of torsional irregularities, the following factor was calculated for each building [15]:

$$\beta = {}^{\Delta_{max}}\!\big/_{\Delta_{average}} \tag{1}$$

where Δ_{max} is the maximum story drift and $\Delta_{average}$ is the average story drift at the two ends of the structure. The level of torsional irregularity was qualified as stated in the ASCE/SEI 7-10 standard [15]: no torsional irregularity: $\beta < 1.2$, torsional irregularity: $1.2 \leq \beta \leq 1.4$ and extreme torsional irregularity: $\beta > 1.4$. The buildings selected cover these three levels of torsional irregularity as demonstrated in Table 1, where the values of β are shown in ascending order. The irregular factor was called β in here for convenience.

Table 1. Torsional irregularity factors.

Building	R05	R15	R10	L10	L15	T15	L05	T10	T05
β	1.00	1.10	1.13	1.20	1.26	1.30	1.35	1.41	1.43

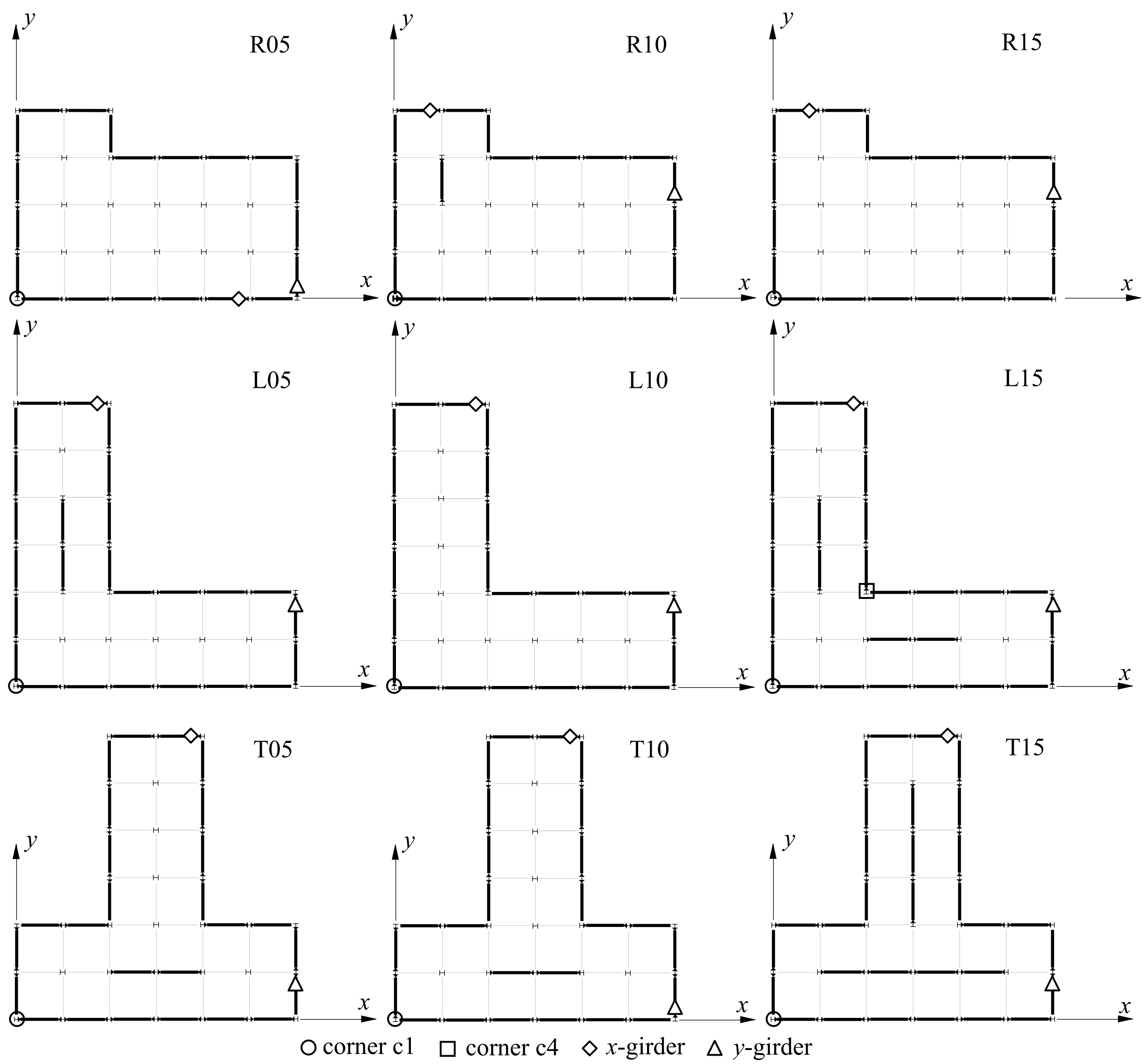

Figure 2. Plan views of the selected nine unsymmetric plan buildings.

Figure 3 shows the buildings' effective modal masses normalized by the total masses. This figure permits the following observations: (1) Lateral displacements dominate motion of the R-plan and L10 buildings in modes 1 and 2, whereas torsion dominates motion in the third mode, indicating weak coupling between lateral and torsional components of motion. Additionally, the period of the dominantly-torsional mode is much shorter than the periods of the dominantly-lateral modes. (2) Coupled lateral-torsional motions occur in the first and third mode of the L05, T05 and T10 buildings whereas lateral displacements dominate motion in the second mode. (3) Lateral displacement dominates motion in the first mode whereas coupled lateral-torsional motions occur in the second and third mode of the T15 plan. It is evident that the contribution of higher modes will be important in the selection and modification of seismic records, especially in structures where the effective mass of the fundamental mode is low. Further details of the structural systems including their fundamental periods, mode shapes, etc. can be found in references [11, 12].

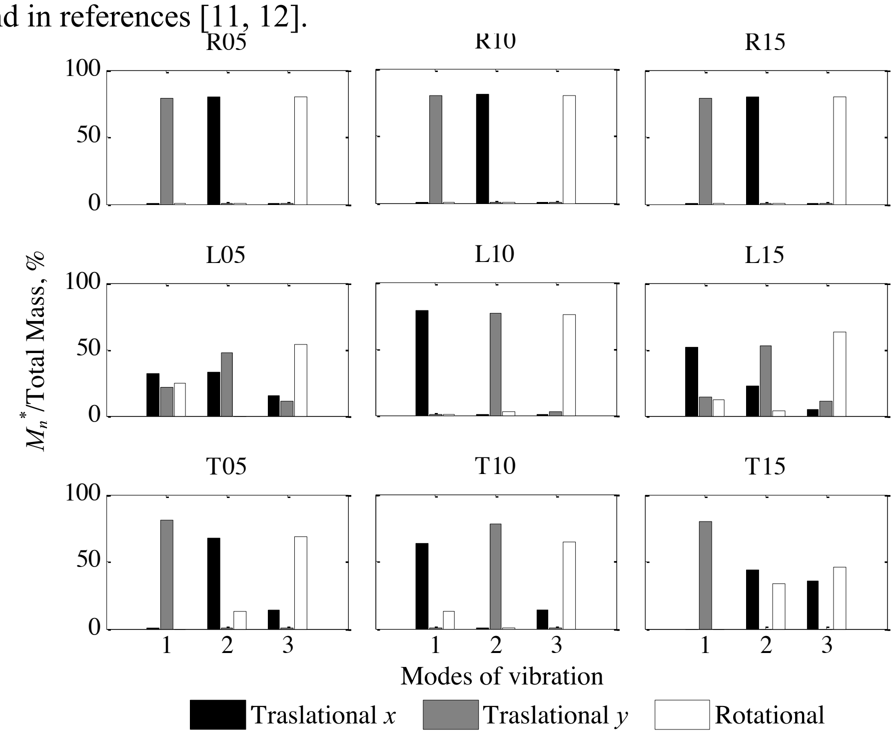

Figure 3. Normalized effective modal masses M_n* of the buildings selected.

MPS Procedure

The accuracy and efficiency of the MPS procedure was evaluated by comparing the median value of an EDP due to a set of seven scaled ground motions against the benchmark value, defined as the median value of the EDP due to 30 "unscaled" ground motions. The term "accuracy" means that the scaled records should provide median responses close to the "exact" responses considering a large population of records compatible with the hazard conditions specified. The term "efficiency" means that ground motions after scaling to the design (target) spectrum should impose similar seismic demands to the structure. The MPS procedure was implemented here in three phases: (1) Target roof displacement and pushover analyses, (2) scaling phase, and (3) selection phase. Phases (1) and (2) of this procedure are included in Reyes and Quintero [8]; a step-by-step procedure including phases (1), (2) and (3) for 3D analysis of multistory buildings is presented in references [9, 11, 12].

Comparative Evaluation of MPS and ASCE/SEI 7-10 Scaling Procedures

Figures 4-6 show story drifts at corner c1 (shown by the "o" marker in Fig. 2) for the nine structures considered. The first, second and third columns of these figures show EDP values in the *x*-direction for the benchmark, ASCE/SEI 7-10 and MPS procedures, respectively; the next three columns show similar results in the *y*-direction. 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. In order to be consistent in comparisons of the MPS procedure with the ASCE/SEI 7-10 procedure, geometric mean was used for the latter even though the ASCE procedure requires mean. The use of "mean" instead of "geometric mean" would not affect the conclusions—provided that "mean" is consistently used for both scaling methods. Additionally, results for bending moments in girders in the 15-story buildings are shown in Figure 7; selected girders are highlighted in Figure 2 by a diamond and triangle marker. The bending moments are normalized by peak values occurring at any floor.

As demonstrated in Figures 4-7, the records scaled according to the MPS procedure provide median values of EDPs that are much closer to the benchmark values than is achieved by the ASCE/SEI 7-10 scaling procedure; for example, compare columns 5 and 6 of Figure 4. The maximum discrepancy of 30% in story drifts encountered by scaling records according to the ASCE procedure is reduced to a maximum of 10% when these records are scaled by the MPS procedure. The record-to-record variability is much less in EDPs due to a set of records scaled by the MPS procedure (columns 3 and 6 of Figs. 4-7) compared to the records scaled by the ASCE/SEI 7-10 procedure (columns 2 and 5 of Figs. 4-7). Small "record-to-record" variability increases the confidence level by indicating that records scaled appropriately with the target spectrum thus impose similar seismic demands. These results show that EDPs obtained from MPS represent a considerable improvement in accuracy and efficiency as compared to EDPs obtained from ASCE/SEI 7-10. Note that even for R-plan structures (buildings without torsional irregularities $\beta < 1.2$), the ASCE/SEI 7-10 procedure leads to large underestimations especially for story drifts as shown in Figure 4. For the ASCE/SEI 7-10 procedure, the error in internal forces (see Fig. 7) is generally smaller than the error in story drifts because internal forces vary slowly with hinge rotation for members that deform beyond the elastic limit at both ends [18]. As a result, even a large error in story drifts leads to only small error in the internal forces.

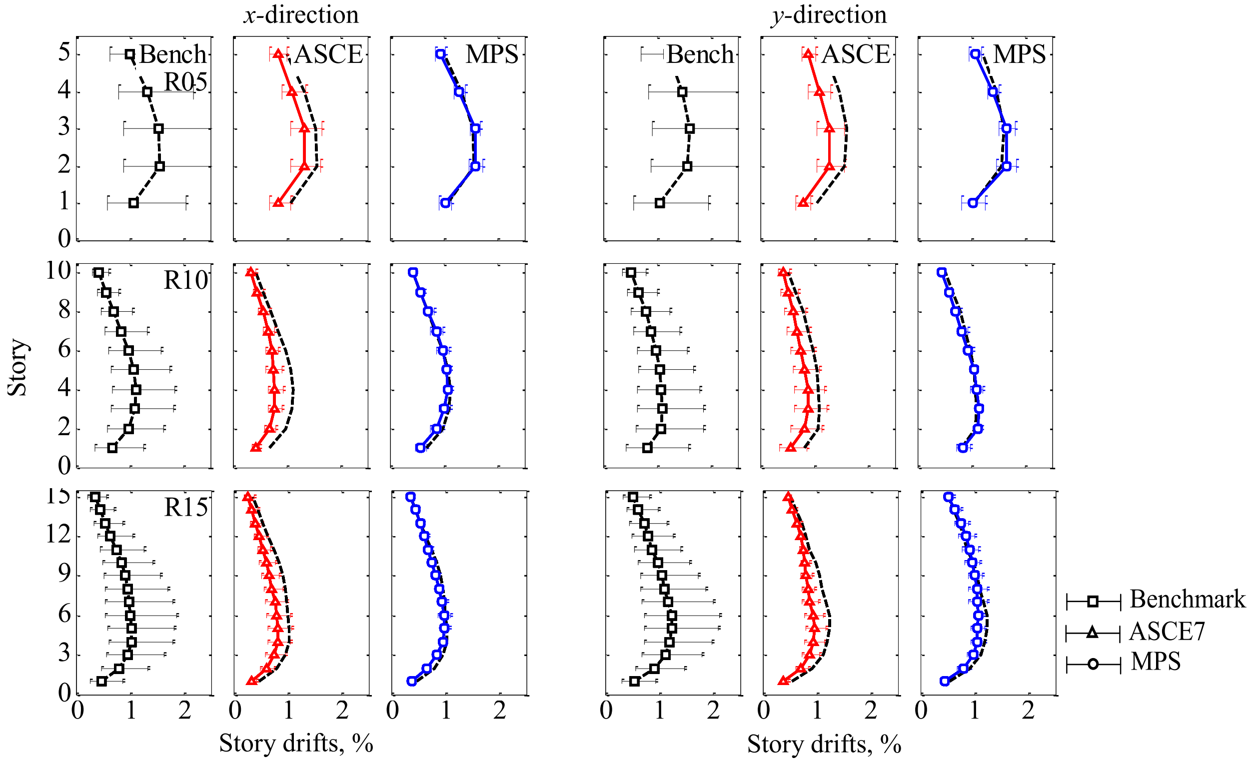

Figure 4. Story drifts in percent in *x*- and *y*-direction in corner c1 for R-plan structures.

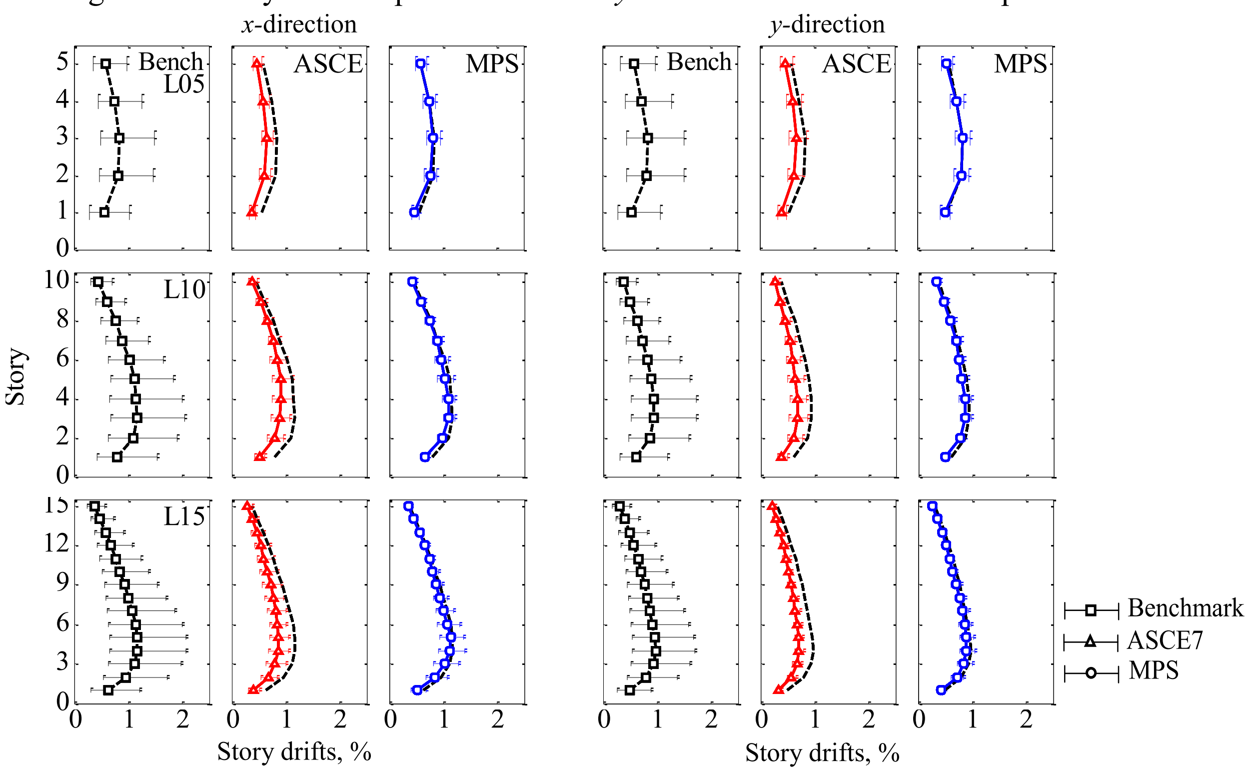

Figure 5. Story drifts in percent in *x*- and *y*-direction at corner c1 for L-plan structures.

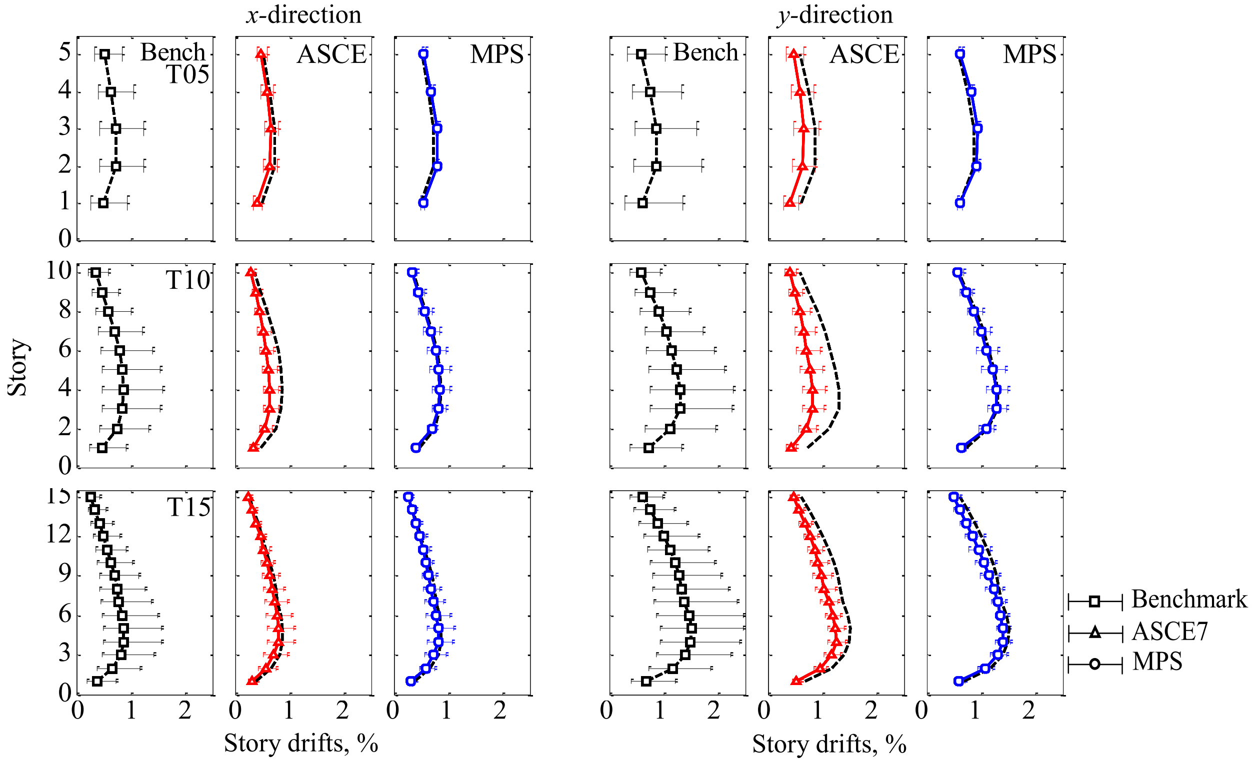

Figure 6. Story drifts in percent in *x*- and *y*-direction at corner c1 for T-plan structures.

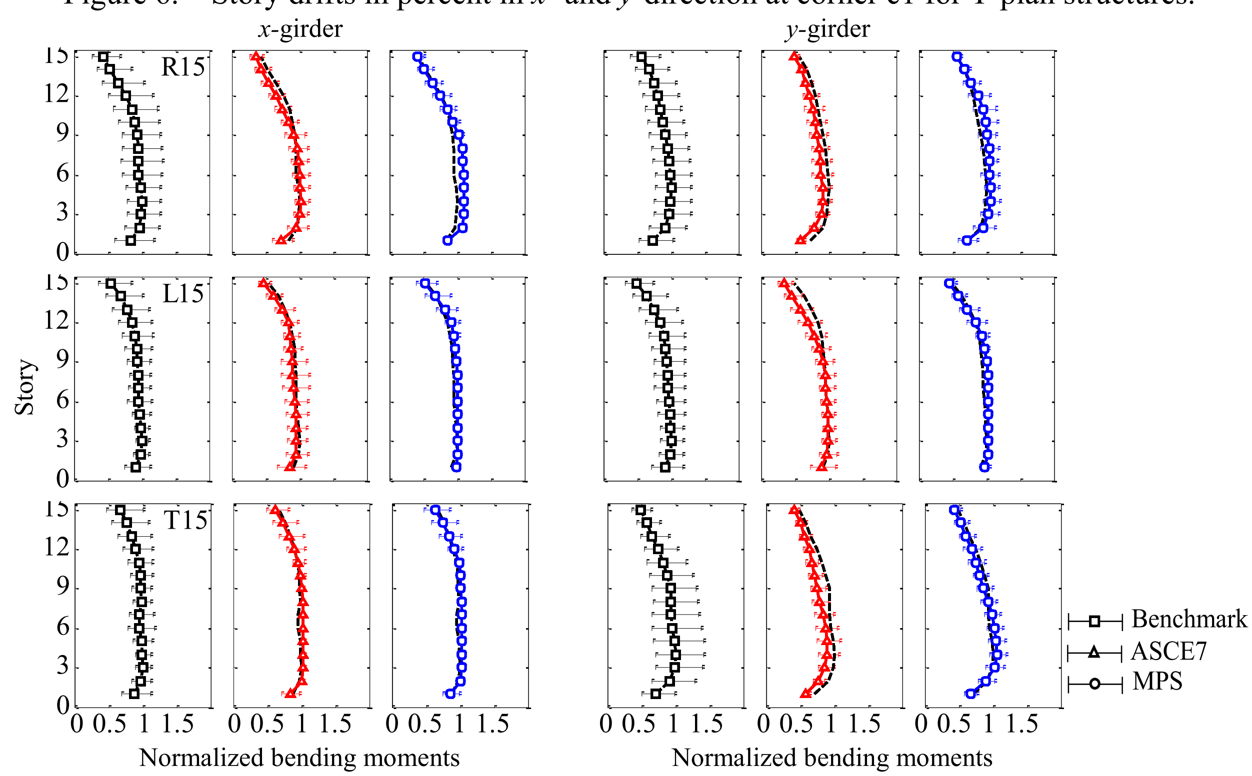

Figure 7. Normalized bending moments in girders (Fig. 2) for 15-story buildings.

For L-Plan structures ($1.2 \leq \beta \leq 1.4$), the records scaled according to the MPS procedure lead to more accurate estimates of median values of EDPs than the ASCE/SEI 7-10 scaling procedure. This improvement in accuracy is demonstrated in Figure 5 where story drifts are shown at corner c1 (Fig. 2). Estimated story drifts due to a set of records scaled by the ASCE/SEI 7-10 procedure present errors over 20% in all cases. For the ASCE/SEI 7-10 scaling procedure, the smallest error occurs when $\beta = 1.2$ (L10 building). The maximum discrepancies encountered by scaling records according to the ASCE/SEI 7-10 procedure are reduced when these records are scaled by the MPS procedure; for example, the maximum error in story drifts encountered with ASCE/SEI 7-10 procedure is reduced from 28% to 8% by implementing the MPS procedure. Likewise, the error in bending moments is reduced from 16% to 10%. These results clearly indicate that the MPS procedure is more appropriate than the ASCE/SEI 7-10 procedure for multi-story buildings with plan irregularities.

Similar to the results for R- and L-plan structures, EDPs obtained from ASCE/SEI 7-10 are less accurate than those obtained from MPS for T-plan structures. The ASCE/SEI 7-10 procedure generally underestimates story drifts in lower stories. In contrast, the MPS procedure provides a more accurate estimate of story drift demands in all stories of these buildings because it considers structural strength and higher-"mode" contributions to the response; for example, compare columns 5 and 6 of Figure 6. Even for T-plan structures with extreme torsional irregularities ($\beta > 1.4$), the MPS procedure is highly accurate and efficient. For example, compare columns 5 and 6 of Figure 6 for building T10; for this building, the maximum discrepancy of 37% in story drifts encountered by scaling records according to the ASCE/SEI 7-10 procedure is reduced to around 1% when these records are scaled by the MPS procedure. Due to space limitation, we only show here representative results; additional results are available in references [9, 11, 12].

Conclusions

In this study, the MPS procedure has been extended to multi-story unsymmetric-plan buildings in order to appositely select and scale ground motion records to be used in nonlinear RHA. The accuracy of the extended MPS procedure was evaluated against the ASCE/SEI 7-10 scaling procedure by comparing the median values of engineering demands parameters (EDPs) due to a set of seven records scaled according to both procedures against the benchmark values. The efficiency of the scaling procedures was evaluated by computing the dispersions of the responses due to scaled ground motions; small dispersion indicates that the scaling procedure is efficient. A set of nine multi-story unsymmetric-plan buildings was selected for testing. This evaluation of the MPS procedure has led to the following conclusions:

1. The extended MPS procedure is much superior compared to the ASCE/SEI 7-10 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 ASCE/SEI 7-10 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 ASCE/SEI 7-10 scaling

procedure. Small dispersion increases confidence in EDPs obtained from nonlinear RHAs by indicating that records are selected and scaled appositely so that they impose similar seismic demands as deemed.

2. In all cases, ASCE/SEI 7-10 leads to underestimation of story drifts. Even for structures that respond dominantly in the first-"mode", the ASCE/SEI 7-10 scaling procedure does not offer improvement in the demand estimate.
3. The ASCE/SEI 7-10 procedure uses the same scaling factor for both components of ground motion; the use of the same scale factors for each component provides inaccurate estimates of the median EDPs in one or both horizontal directions. In contrast, the MPS procedure allowing for different scaling factors for *x* and *y* components, provides an accurate estimate of the median EDPs and reduces the record-to-record variability of the responses. The reasons for using different scale factors for two horizontal components of a ground motion record are explained in Reyes and Chopra [7].
4. The extended MPS procedure offers a sufficient degree of accuracy that should make it useful for practical application in estimating seismic demands—floor displacements, velocities, accelerations, story drifts, internal forces—for multi-story unsymmetric-plan buildings due to two horizontal components of ground motion applied simultaneously. By including structural strength and contributions of all significant modes of vibration, MPS is able to adequately capture important variation of EDPs.

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