Modal Pushover-Based Scaling of Two Components of Ground Motion Records for Nonlinear RHA of Buildings

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Abstract

The accuracy and efficiency of the modal-pushover-based-scaling (MPS) procedure is evaluated here by applying it to an existing 9-story building, symmetric in plan. The computer model developed for the building is validated against motions of the building recorded during the 2008 Chino-Hills earthquake. It is demonstrated that nonlinear response history analysis (RHA) of the building for a small set of records scaled by the MPS procedure provided a highly accurate estimate of the engineering demand parameters, accompanied by significantly reduced record-to-record variability of the responses. Furthermore, the MPS procedure is shown to be much superior to the procedure specified in the ASCE/SEI 7-05 standard for scaling two components of ground motion records.

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 the subject of much research in recent years.

The objective of amplitude scaling procedures is to determine scale 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. Development of such procedures has come a long way from scaling records to match target peak ground acceleration, target elastic response spectrum at the fundamental vibration period T_1 of the structure, some combination of the spectral ordinates at the first two vibration periods, or the inelastic response spectrum at T_1. A convenient summary of amplitude scaling methods was compiled in PEER (2009); individual references are too numerous to list here.

Recently, developed is a 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 (Kalkan and Chopra, 2010). 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 proven to be accurate and efficient for low-, medium-, and high-rise buildings with symmetric plan subjected to one component of ground motion (Kalkan and Chopra, 2010). The MPS procedure has been extended to scale two horizontal components of ground motion for use in three-dimensional analysis of structural systems (Reyes, 2009).

This paper investigates the accuracy and efficiency of the MPS procedure for a 9-story symmetric-plan building and compares it against the scaling procedure recommended in the ASCE/SEI 7-05 standard (ASCE, 2006).

GROUND MOTION RECORDS

The twenty-eight records selected for this investigation [listed in Reyes (2009)] were recorded from earthquakes with moment magnitude, $M_w \geq 6.5$ at distances ranging from 7 to 28 km. Because the twenty-eight ground motions selected were not intense enough to drive the building considered far into the inelastic range—an obvious requirement to test any scaling procedure—they were amplified by a factor of 3.0; the resulting 28 ground motions are treated as "unscaled" records for this investigation. Shown in Figure 1 are the 5%-damped median response spectra for x and y components of the “unscaled” ground motions. The median spectrum is taken as the design spectrum for purposes of evaluating the MPS and other scaling procedures.

Common practice determines the design value of an EDP as its median value over a set of seven ground motions. Thus, to evaluate the MPS scaling procedure, two sets of seven ground motions were selected. To facilitate this selection, the peak deformation of the first-“mode” inelastic SDF system due to the twenty-eight “unscaled” ground motions were determined, and sorted in ascending order. The seven ground motions that led to the smallest deformations in y direction were grouped as set 1, whereas the seven ground motions that drove the SDF system to its largest deformations in y direction were defined as set 2; obviously, the choice of these sets depends on the building and represents a very severe test of the scaling procedure.

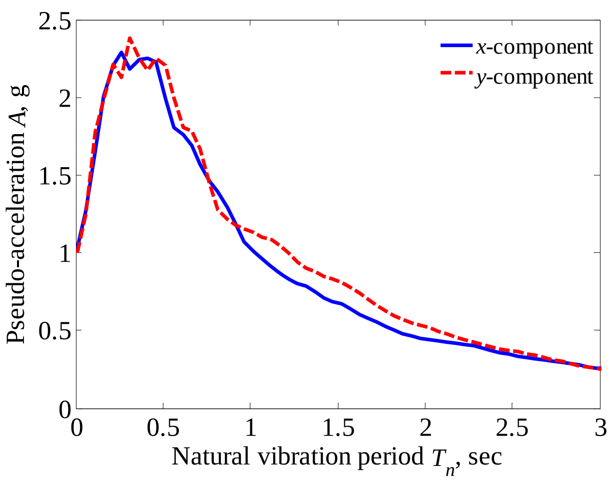

Figure 1. Median response spectra of 28 ground motions in the *x* and *y* directions; damping ratio 5%. Recorded ground motions were amplified by a factor of 3.0.

BUILDING SELECTED AND COMPUTER MODEL

The structure considered is an existing 9-story steel building, symmetric in plan, located in Aliso Viejo, CA (Figure 2); its west elevation and the plan of floors 3 to 8 are shown in Figure 3. The lateral load resisting system consists of two ductile steel moment frames in the longitudinal and transverse directions (Figure 3b) with SSDA beam slot connections; all structural members are standard I-sections and the typical floors are made-up of 3 in. metal deck with 3¼ in.-thick light weight concrete fill. The building façade consists of concrete panels and glass (Figure 2), and there is a heliport on the roof (Figure 3a). Designed as an office building according to 2001 California Building Code for seismic zone 4 and soil profile S_d, the earthquake forces were determined by linear response spectrum analysis (RSA) for the code design spectrum reduced by a response modification factor of 8.5.

Analyzed by the PERFORM-3D computer program (CSI 2006), the building was 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 beam stiffness was modified to include the effect of the slab, and the axial load-moment interaction for the columns was based on plasticity theory; (2) The braces below the heliport were modeled using fiber sections to model buckling behavior; (3) 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; (4) The tab connections were modeled using rigid-perfectly-plastic hinges that can include in-cycle and cyclic degradation; (5) The contribution of non-structural elements was modeled by adding four shear columns located close to the perimeter of the building, with their properties obtained from simplified models of the façade and partitions; nonlinear behavior of these elements was represented using rigid-plastic shear hinges; (6) Ductility capacities of girders, columns, and panel zones were specified according to the ASCE/SEI 41-06 standard; (7) Columns of moment resisting frames and the gravity columns were assumed to be clamped at the base; and (8) Effects of nonlinear geometry were approximated by a standard P-Δ formulation.

The computer model was calibrated against motions of the building recorded during the 2008 magnitude 5.4 Chino Hills earthquake (Reyes, 2009).

Figure 2. Nine-story symmetric-plan building in Aliso Viejo, California.

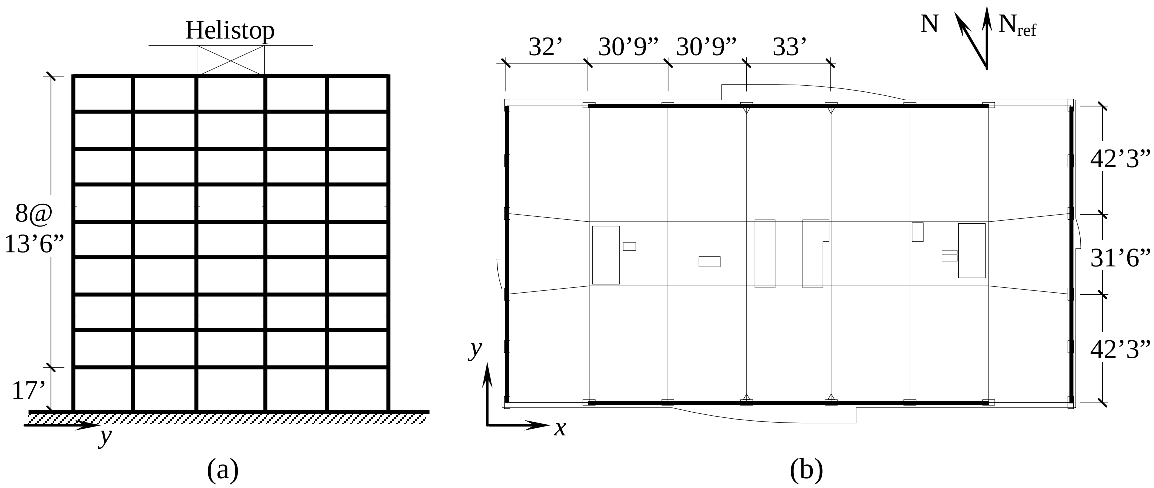

Figure 3. (a) West elevation; (b) typical floor plan of the selected 9-story symmetric-plan building.

EVALUATING MPS PROCEDURE

The accuracy of the MPS procedure was evaluated by comparing the median (defined as the geometric mean) 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 the twenty-eight unscaled ground motions. A scaling procedure is considered to be efficient if the dispersion of an EDP due to the set of seven scaled ground motions is small.

Benchmark Responses

Figure 4 shows the benchmark values of the EDPs: floor displacements (normalized by building height), story drift ratios (story drift÷story height). Also included are the responses to individual records to demonstrate their large dispersion. Most of these ground motions drive the building far into the inelastic range, as demonstrated in Figure 5 where the deformation values due to twenty-eight ground motions are identified on the first-mode pushover curve. The median deformation exceeds the yield deformation by factors of 3.5 and 3.1 in the x and y directions, respectively. Recall that the two values of median deformation shown in Figure 4 are the target values $\hat{D}_1$ that are to be matched by the scaling procedure.

One-Mode MPS Procedure

The MPS scaling procedure allowing for different scaling factors for the two components of a record is promising because the peak deformation of the first-“mode” inelastic SDF system due to each scaled component is identical to the corresponding target deformation, as shown in Figure 6. As a result, the MPS procedure provides an accurate estimate of the median EDPs and reduces the record-to-record variability of the responses. This is demonstrated in Figure 7 where the median values of EDPs due to the seven scaled records of sets 1 and 2 are shown together with the benchmark EDPs; also included are the EDPs due to each of the seven scaled records to show their dispersion. The height-wise average discrepancy in floor displacements is 11% and 5% for record sets 1 and 2, respectively; in story drifts this discrepancy is 12% and 10% for record sets 1 and 2, respectively. As will be seen later, this discrepancy will be greatly reduced when the response in the second “mode” of vibration is considered in ranking and selecting ground motions. The MPS procedure is efficient in the sense that the dispersion (record-to-record variability) of the EDPs due to scaled records (Figure 7) is much smaller than the dispersion of the responses to unscaled records (Figure 4); numerical values of the dispersion are available in (Reyes 2009).

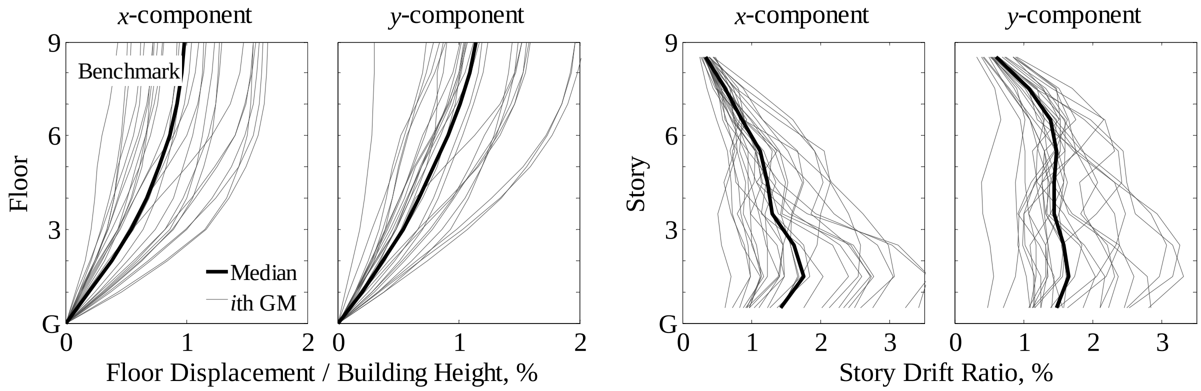

Figure 4. Median values of EDPs determined by nonlinear RHA of the building subjected to two components, simultaneously, of 28 unscaled records; individual results for the 28 excitations are included.

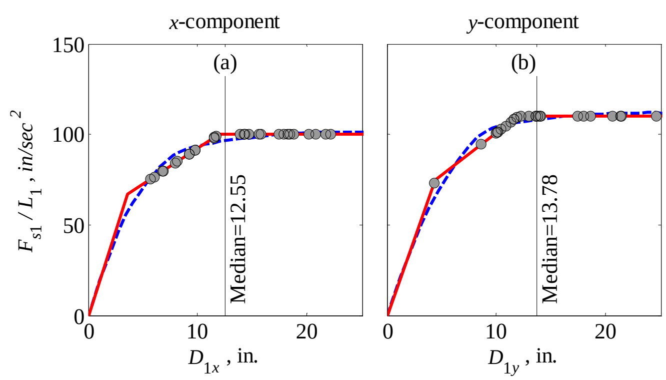

Figure 5. Force-deformation curves for the first "modes" of lateral vibration of the building in *x* and *y* directions and their tri-linear idealization. Peak deformations due to 28 unscaled records are identified.

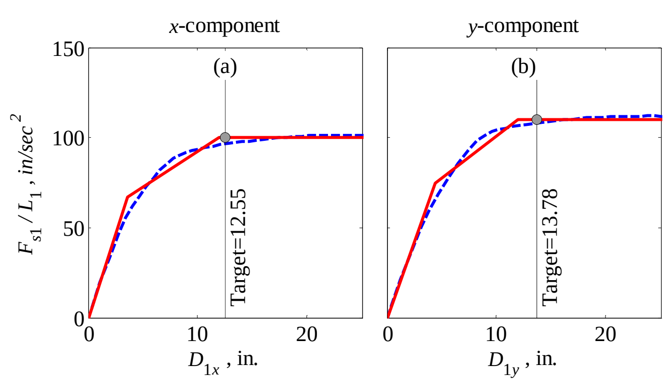

Figure 6. Force-deformation curves for the first "modes" of lateral vibration of the building in *x* and *y* directions and their tri-linear idealization. Peak deformations due to 28 records scaled by the one-mode MPS procedure are identified.

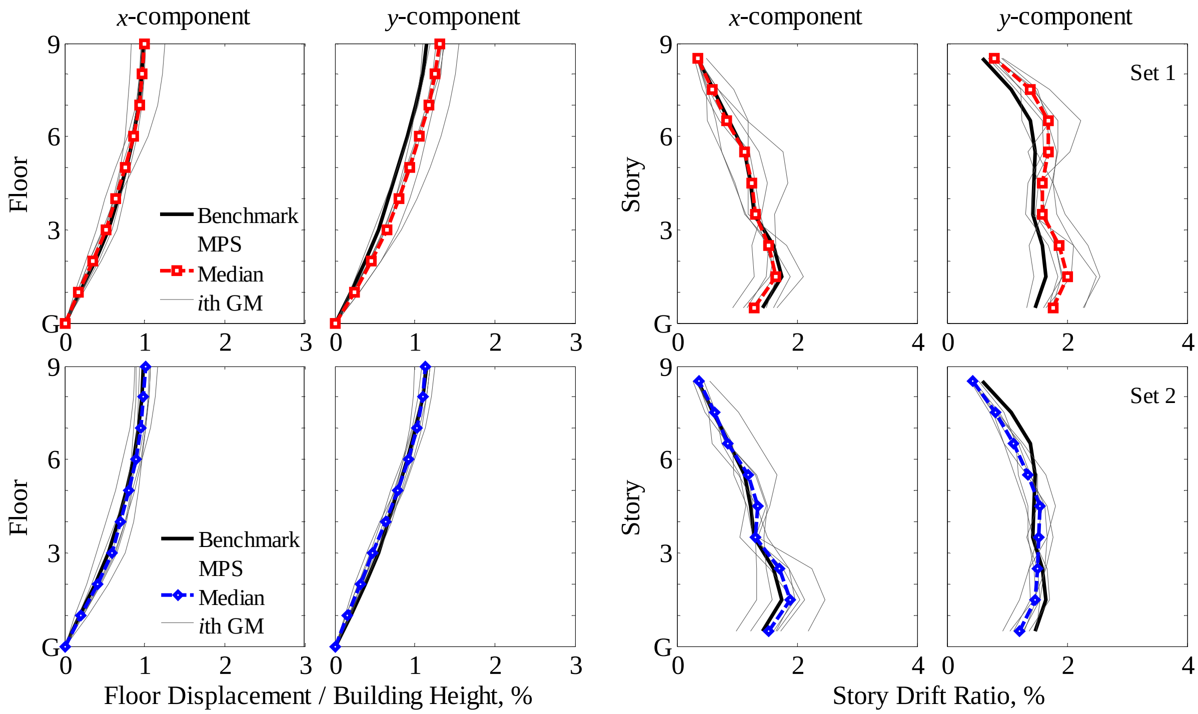

Figure 7. Comparison of EDPs due to record sets 1 and 2 scaled according to the one-mode MPS procedure and the benchmark EDPs; individual results for seven scaled records are included.

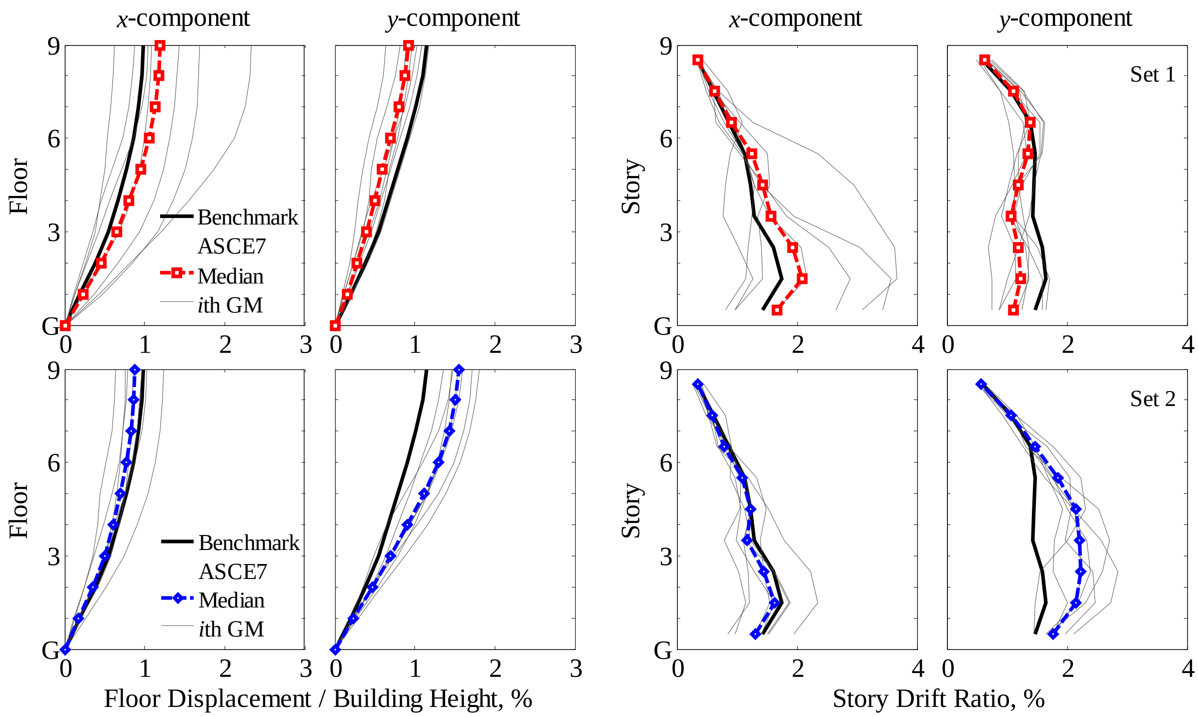

Figure 8. Comparison of EDPs due to record sets 1 and 2 scaled by the ASCE7 procedure against benchmark values; individual results for seven scaled records are included.

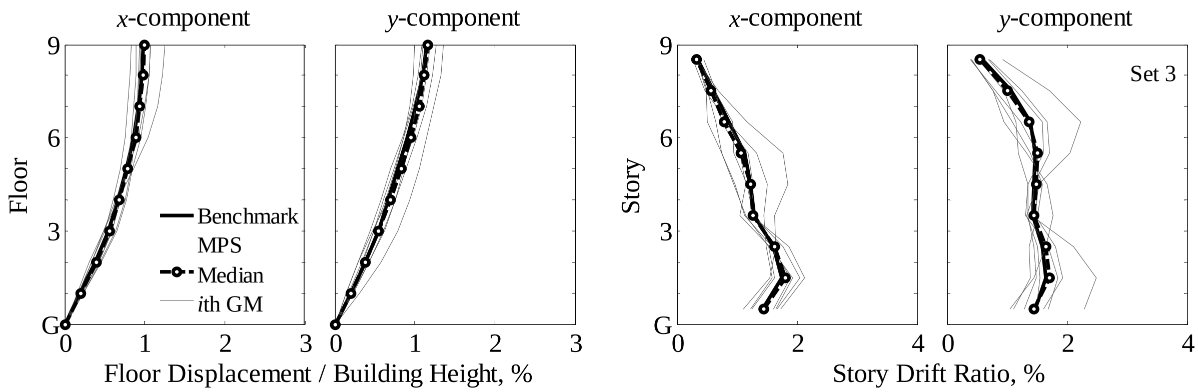

Figure 9. Comparison of median EDPs for record set 3 scaled by the MPS procedure (considering higher modes) with benchmark EDPs; individual results for the seven scaled records are included.

Comparative Evaluation of One-Mode MPS and ASCE7 Scaling procedures

The one-mode MPS procedure for scaling ground motions leads to much more accurate estimates of seismic demands compared to the ASCE7 scaling procedure. Figure 8 presents the median values of EDPs due to the seven records of sets 1 and 2, scaled by the ASCE7 procedure together with the benchmark EDPs; also included are the EDPs due to each of the seven scaled records to show their dispersion. For each record set, 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 ASCE7 scaling procedure; compare Figures 7 and 8. The height-wise average discrepancy of 22% in floor displacements encountered by scaling set 2 records according to the ASCE7 procedure is reduced to 5% when these records are scaled by the MPS procedure; likewise, the height-wise average error in story drift ratios is reduced from 16% to less than 10%. The record-to-record variability is much less in EDPs due to a set of records scaled by the one-mode MPS procedure (Figure 7) compared to the records scaled by the ASCE7 procedure (Figure 8); numerical values for the dispersion are available in (Reyes 2009).

MPS with Higher Mode Considerations

The fourteen records of sets 1 and 2, scaled by the one-mode MPS procedure, were ranked by considering their accuracy in estimating the response of the second mode SDF system and the seven records with the highest rank were defined as record set 3.

Considering the second "mode" in ranking and selecting the ground motions in the MPS procedure provides accurate estimates of the median EDPs and reduces slightly the record-to-record variability, compare Figures 7 and 9; numerical values for dispersion are available elsewhere (Reyes 2009). This improvement in accuracy is demonstrated in Figure 9 where the median values of floor displacements and story drifts due to record set 3 are shown together with the benchmark values. It is evident by comparing Figures 7 and 9 that this new set leads to much more accurate estimates of median demands compared to sets 1 and 2; the height-wise average discrepancy in floor displacements is reduced from 11% (set 1) to 2% (set 3); in story drift ratios, this discrepancy is reduced from 12% (set 1) to 4% (set 3). Thus, the MPS method considering higher mode contributions to response selects a set of scaled records for nonlinear RHA of the building that provides highly accurate estimates of EDPs, which are even more superior to the ASCE7 procedure than was possible with ground motion sets 1 and 2 where higher modes were not considered; this is evident by comparing Figures 7, 8, and 9.

CONCLUSIONS

Based on analysis of an actual 9-story symmetric-plan building with its computer model calibrated against its motions recorded during an earthquake, this evaluation of the MPS procedure has led to the following conclusions:

1. The MPS procedure allowing for different scaling factors for the *x* and *y* components of a record provided a highly accurate estimate of the median EDPs and reduced the record-to-record variability of the responses; in particular, the height-wise average discrepancy in story drift ratios was less than 4% relative to the benchmark values.

2. The 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. The height-wise average discrepancy of 15% in

story drift ratios (relative to the benchmark values) determined by scaling records according to the ASCE7 procedure is reduced to 4% when records are scaled by the MPS 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.

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