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Assessment of spectrum matching procedure for nonlinear analysis of symmetric- and asymmetric-plan buildings

Juan C. Reyes [a,*], Andrea C. Riaño [a], Erol Kalkan [b], Oscar A. Quintero [a], Carlos M. Arango [a]

[a] Civil and Environmental Engineering, Universidad de los Andes, Bogotá, Colombia
[b] Earthquake Science Center, United States Geological Survey, Menlo Park, CA, USA

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ABSTRACT

Current performance-based seismic design procedures rely on response history analysis (RHA) for estimating engineering demand parameters (EDPs) of base-isolated structures, high-rise buildings and irregular structural systems. Ground motion records for RHAs should be appositely selected in compliance with site-specific hazard conditions, and properly modified either by amplitude-scaling or spectrum matching (SM) to ensure that the modified records provide accurate and efficient estimates of "expected" median demands. While amplitude-scaling techniques change intensity of the ground motion record, SM methods also alter the record's waveform (in frequency or time domain) to match its response spectrum to a target (or design) spectrum. The research on adequacy of spectrum-matched records for nonlinear RHAs of buildings is not only limited to symmetric-plan buildings subjected to one component of ground motion but also lacks consensus. This study comprehensively examines the accuracy and efficiency of a SM method for nonlinear RHAs under bi-directional earthquake excitations by covering single- and multi-story buildings having symmetric- and asymmetric-plans. For this evaluation, three-dimensional computer models of 48 single-story and nine multi-story buildings were created. Their structural responses were obtained from subsets of seven records modified by SM and separately by amplitude-scaling according to the regulatory ASCE/SEI 7-10 scaling procedure. The accuracy and efficiency of both procedures are examined by comparing their median EDP estimates from subset of records against the median values of EDPs due to a larger set of unscaled records, and by comparing record-to-record variability of the response. It is shown that the time-domain SM procedure provides more accurate median EDP estimates as compared to the ASCE/SEI 7-10 amplitude scaling procedure; however, it critically vanishes the variability of EDPs associated with aleatoric uncertainty in ground motion records. Retaining a certain level of aleatoric variability in EDPs can be an important parameter to be considered for certain projects.

1. Introduction

According to the 2009 International Building Code [1] and 2010 California Building Code [2], earthquake resistant design of special buildings, such as base-isolated structures, high-rise buildings, and irregular structural systems requires the use of nonlinear response history analysis (RHA) according to the ASCE/SEI 7-10 [3] for estimating engineering demand parameters (EDPs: floor displacements, story drifts, internal forces, hinge rotations, etc.) for verification of performance level targeted. Nonlinear RHAs are usually conducted for seven ground motion records, which are selected and modified to obtain results close to the median demands from a large ensemble of ground motions. Selection and modification of ground motions are fraught with several unresolved issues [4].

The main objective of ground motion selection and modification process is to provide few modified records that lead to accurate estimates of median structural responses with reduced record-to-record variability. Most of the proposed procedures for modifying ground motion records fall into one of two categories: amplitude-scaling and spectrum matching (SM). Only the amplitude of the record is modified in the first approach. In contrast, SM methods not only modify the record's amplitude but also alter its frequency content to match its response spectrum to a target spectrum (or design spectrum).

Earlier approaches to generate spectrum-compatible ground motions did not modify an actual record; instead, artificial ground motions were generated from white noise. This approach is generally inaccurate and inefficient for structures responding in nonlinear range because artificially generated accelerograms may

* Corresponding author. Address: Department of Civil and Environmental Engineering, Universidad de los Andes, Cra 1 No. 18A-12, Bogotá, Colombia.
E-mail address: jureyes@uniandes.edu.co (J.C. Reyes).

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have unrealistic phase content, duration and number of cycles [5,6]. Spectrum compatible ground motions generated by modifying an actual ground motion in frequency domain (adjusting the Fourier amplitude spectra) were widely used in design of base-isolated structures [7,8]. Although this method has the advantage of using actual ground motions, it was shown that adjusting motions in frequency domain distorts their velocity and displacement time series, and led to ground motions having unrealistically high energy content [6]. An alternative approach modifies record's time series in time domain by adding wavelets to generate spectrum compatible ground motions; this method introduces less energy into the ground motion than frequency-domain methods, and also preserves the record's original non-stationary characteristics [5].

An early approach for time domain spectral matching was developed by Kaul [9], and it was extended to multiple damping levels by Lilhanand and Tseng [10,11]. Lilhanand and Tseng employed an adjustment wavelet, capable to ensure stability of the method, but their approach did not retain the non-stationary characteristics of the original acceleration time series, and distorted their velocity and displacement waveforms. Based on the work by Lilhanand and Tseng, a computer code "RspMatch" was developed by Abrahamson [12]. The first version of the code used a new adjustment wavelet that preserved the non-stationary characteristic of the original ground motion. Despite this improvement, the wavelet function used results in non-zero termination in the velocity and displacement time series. A modified version of this code "RspMatch2005" offers the following improvements [5]: (1) The wavelet adjustment does not cause drift in velocity or displacement time series; (2) the records may be modified to match relative pseudo-acceleration or absolute acceleration response spectrum at different levels of damping simultaneously. Grant [13] developed another version of RspMatch called RspMatchBi; in his version, two components of ground motion can simultaneously be matched to two different target spectra. A newer version of RspMatch has been recently proposed [14], which does not require baseline correction of the adjusted record after each iteration, and ensures stability and convergence of the solution by the use of an improved tapered cosine wavelet. In this study, RspMatch2005 (a non-commercial computer code), recommended as one of the appropriate spectral matching techniques in ATC-82 report [15], is utilized.

The draft of chapter 16 of the ASCE/SEI 7-16, which will supersede ASCE/SEI 7-10, allows spectrum-matched ground motions to be used in RHAs. According to this draft, each component of the spectrum-matched record is scaled such that the average of their response spectra is not less than the target spectrum over a period range from $0.2T_1$ to $2.0T_1$, where T_1 is the first-"mode" period of the building in the direction considered. This is deliberately a stricter requirement, as compared to the requirement for amplitude scaled ground motions. The use of this procedure is also restricted to far-field ground motions only because of concern that the pulse characteristics of the motions may not be appropriately retained after the spectral matching processes has been completed [Curt Haselton, personal communication, 2013]. Furthermore, the spectrum-matched ground motions are scaled to meet the maximum direction spectral demands individually for both of the horizontal directions. Those criteria are conservative for any particular direction, and are especially conservative when applied to both directions [16]. This requirement imposes another penalty on the use of spectrum-matched ground motions, which is mainly due to lack of consensus in published studies; for example, Carballo [17], Bazzurro and Luco [18], and Huang et al. [19] found that the use of spectrum-matched records could lead to underestimations of nonlinear seismic response, although this conclusion is not supported in Watson-Lamprey and Abrahamson [20], Hancock et al. [21], Grant and Diaferia [22] and Heo et al. [23].

Considering the contradictory conclusions in previous studies, this research examines the SM method proposed by Hancock et al. [5] in order to answer whether this SM technique is accurate (providing unbiased estimates), and to what extend it is efficient (reducing dispersion) for nonlinear RHAs of single- and multi-story buildings having symmetric- and asymmetric-plans subjected to two components of ground motions.

2. Spectrum matching procedure for three-dimensional analysis

The SM procedure developed by Hancock et al. [5] for single component of ground motion is extended here to two horizontal components. The step-by-step procedure applicable to three-dimensional (3D) analysis of buildings is as follows [24–26]:

1. For a given site, select ground motions compatible with site-specific seismic hazard conditions governing the seismic design.
2. Compute the response spectrum $A(T)$ for each ground motion for various damping values (e.g., 2%, 5% and 10%) at evenly spaced periods T_i in a logarithmic scale over the period range from $0.2T_1$ to $1.5T_1$ (in this study, $i = 1, 2, 3, \ldots, 100$).
3. Determine the target pseudo-acceleration response spectrum $\widehat{A}(T)$ as the median spectrum determined in step 2 for various damping ratios. Define $\widehat{A}$ as a vector of spectral ordinates $\widehat{A}_i$ at 5% damping level at the same periods T_i.
4. Estimate the scaling factor SF to minimize the difference between the response spectrum (step 2) and the target spectrum (step 3) for 5% damping by solving the following minimization problem for each ground motion:

$$\min \left\| \ln\left(\widehat{A}\right) - \ln(SF \times A) \right\| \to SF \quad \|.\| = \text{Euclidean norm}$$

   Required for this purpose is a numerical method to minimize scalar functions of one variable. Such methods are available in textbooks on numerical optimization [27]. This minimization ensures that the scaled response spectrum is as close as possible to the target spectrum. At the end of steps 1–4, implemented separately for the two horizontal components of each ground motion record, scaling factors SF_x and SF_y are determined for the x and y components of the ground motion, respectively.
5. Compute the difference between the scaled spectrum $SF \times A(T)$ and the target spectrum for 5% damping (step 2) for each ground motion. Define the error E_{SM}, and rank the scaled records based on their E_{SM} value; the record with the lowest E_{SM} is ranked the highest.

$$E_{SM} = \left\| \ln\left(\widehat{A}_x\right) - \ln\left(SF_x \times A\right) \right\| + \left\| \ln\left(\widehat{A}_y\right) - \ln\left(SF_y \times A\right) \right\|$$

6. From the ranked list, select the first k records with their scale factors determined in step 4. In this study, we used $k = 7$ because previous research shows that minimum of seven records are sufficient for unbiased estimates of EDPs from nonlinear RHAs [28,29].
7. Modify each scaled ground motion, independently, by adding wavelets in time domain to match the target spectrum for various damping values: 2%, 5% and 10%. In the present research, this step is implemented using the non-commercial computer program RspMatch2005. This modified ground motions are used to conduct nonlinear RHA of the structure. Note that this step should be implemented for each horizontal component of ground motion, separately.

The median spectra computed in step 3 for the two horizontal components of records shall be used as target spectra for two orthogonal directions in 3D analyses.

Among three translational components of ground motion, only two horizontal components have commonly been used in the design of new or the assessment of existing structures. This practice is mainly motivated by: (1) the use of far-fault earthquake records where the vertical component of ground motion is weaker than its horizontal counterparts, and (2) the fact that structures have sufficient over-strength against vertical motion since they have already been designed for gravitational acceleration. However, vertical motion can be higher than the horizontal motion, and its peak value may exceed 1 g in the proximity of dip-slip faults [30]. For structures susceptible to large vertical accelerations, the step-by-step procedure above may be extended to vertical motions. Required for this extension is a target spectrum for vertical motion computed at a damping value consistent with the vertical vibration mode of the structure.

3. ASCE/SEI 7-10 ground motion scaling procedure

The ASCE/SEI 7-10 standard (abbreviated henceforth as ASCE7) requires that both components of an earthquake record be scaled by the same scaling factor, determined to ensure that the average of the square root of sum of squares (SRSS) response spectra over all records does not fall below the corresponding ordinate of the target spectrum over the period range $0.2T_1$ to $1.5T_1$. The SRSS spectrum is computed for the 5%-damped response spectra for the two horizontal components of ground motion. The design value of an EDP 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 [31]. To achieve the desirable goal of scaling each record by a factor as close to one as possible, the ASCE7 procedure was implemented using a modified version of the approach described in Appendix A of Reyes and Chopra [32]. The final records selected are those with spectral acceleration values at T_1 close to the target spectrum. This selection procedure was proposed by Reyes and Kalkan [28,29], and is not part of the requirements of the ASCE7. As explained earlier, the target pseudo-acceleration spectrum for the buildings site was taken as the median of the 5% damped pseudo-acceleration response spectra corresponding to the average of the horizontal components of the unscaled records.

4. Ground motions selected

Thirty ground motion records listed in Table 1 were selected from seven shallow crustal earthquakes with moment magnitude 6.7 ± 0.2, at closest fault distances ranging from 20 to 30 km, and with NEHRP site classification C (very dense soil or soft rock) or D (stiff soil). Fig. 1 depicts the 5%-damped median response spectra for x and y components of the ground motions. Because the ground motions selected were not intense enough to drive the multi-story buildings considered far into the inelastic range—an obvious requirement to test any scaling procedure—they were pre-amplified by a factor of 4. These pre-amplified 30 ground motions are treated as "unscaled" records for this investigation. The pre-amplification factor would be much smaller if near-fault records were used; however, far-field records were selected deliberately since it is the requirement of the upcoming ASCE/SEI 7-16 standard.

In Fig. 1, the median spectra are taken as the target spectrum for purposes of evaluating the SM procedure. It should be noted that our objective was to create a sample of records from a representative subset of a population of already recorded and not yet recorded ground motions under similar magnitude, distance and site conditions. The best way to avoid a biased or unrepresentative sample is to select a random sample. Therefore, selection of 30 records from the representative subset of the population was conducted randomly. This process statically allows us to treat the median spectrum of this random sample as the "true" target spectrum. Because all records were up-scaled with the same scaling factor, the assumption of random sampling was not violated [4].

5. Structural systems

For this study, three different types of buildings were utilized; these are identified by letters R, L and T. Plan R stands for quasi-rectangular; plan T is symmetric about y-axis, and plan L is asymmetric about both x and y axes. For multi-story buildings, the letters R, L and T are followed by the number of stories; for example "R05" indicates a five-story rectangular plan building.

5.1. Single-story buildings

The first set of structures considered are 48 single-story buildings (32 of them have an asymmetric plan) with fundamental vibration periods T_1 equal to 0.2, 0.5, 1, and 2 s. 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_y equal to: 2, 3, 5, and a value that leads to linear elastic design; therefore, earthquake design forces F_D were calculated as follows:

$$F_D = F_E/R_y \tag{1}$$

where F_E is the minimum strength required for the structure to remain linearly elastic during the design ground motion. For each horizontal direction, the design spectrum was taken as the median of the 5-percent damped pseudo-acceleration response spectra of the 30 records of Table 1. The lateral resisting system of the buildings consists of buckling-restrained braced frames with non-moment-resisting beam–column connections. Fig. 2 shows the bracing layouts and plan shapes for the buildings with the centers of mass and stiffness highlighted. The group of buildings selected for this investigation includes some short-period structures designed for high response modification factors. Although these structures may be unrealistic, they are included for completeness. Further details of the structural systems including their natural periods, mode shapes, etc., can be found in Refs. [24,33]. Table 2 shows the ratios of the uncoupled torsional to lateral frequencies (ω_θ/ω_x and ω_θ/ω_y) and ratios of eccentricities to radius of gyration (e_x/r and e_y/r) as defined in [34]. Note that structures with plans L and T have high eccentricities, and are torsionally-flexible while structures with plan R have low eccentricities, and are torsionally-stiff. For structures with plans L and T, the ratios of uncoupled torsional to lateral frequencies are close to 1.0 indicating strong coupling between lateral and torsional motions [34]. In Table 2, $\omega_\theta/\omega_x = \omega_\theta/\omega_y$ because the number of moment resistant frames and their properties are the same in x- and y-direction.

To verify that the selected buildings cover a broad range of torsional irregularities, the following irregularity factor was calculated for each building [3]:

$$\beta = \Delta_{\max}/\Delta_{\text{average}} \tag{2}$$

where $\Delta_{\max}$ is the maximum story drift and Δ_{average} is the average story drift at the two ends of the structure. The levels of torsional irregularity according to the ASCE/SEI 7-10 are: (1) No torsional irregularity: $\beta < 1.2$, (2) Torsional irregularity: $1.2 \leqslant \beta \leqslant 1.4$ and

Table 1
List of 30 ground motion records.

Record No.	Earthquake name	Year	Station name	Moment magnitude	Distance (R_{JB}) [km]	NEHRP site class
1	San Fernando	1971	LA – Hollywood Stor FF	6.6	22.8	D
2	San Fernando	1971	Santa Felita Dam (Outlet)	6.6	24.7	C
3	Imperial Valley-06	1979	Calipatria Fire Station	6.5	23.2	D
4	Imperial Valley-06	1979	Delta	6.5	22.0	D
5	Imperial Valley-06	1979	El Centro Array #1	6.5	19.8	D
6	Imperial Valley-06	1979	El Centro Array #13	6.5	22.0	D
7	Imperial Valley-06	1979	Superstition Mtn Camera	6.5	24.6	C
8	Irpinia, Italy-01	1980	Brienza	6.9	22.5	C
9	Superstition Hills-02	1987	Wildlife Liquef. Array	6.5	23.9	D
10	Loma Prieta	1989	Agnews State Hospital	6.9	24.3	D
11	Loma Prieta	1989	Anderson Dam (Downstream)	6.9	19.9	C
12	Loma Prieta	1989	Anderson Dam (L. Abut)	6.9	19.9	C
13	Loma Prieta	1989	Coyote Lake Dam (Downst)	6.9	20.4	D
14	Loma Prieta	1989	Coyote Lake Dam (SW Abut)	6.9	20.0	C
15	Loma Prieta	1989	Gilroy Array #7	6.9	22.4	D
16	Loma Prieta	1989	Hollister – SAGO Vault	6.9	29.5	C
17	Northridge-01	1994	Castaic – Old Ridge Route	6.7	20.1	C
18	Northridge-01	1994	Glendale – Las Palmas	6.7	21.6	C
19	Northridge-01	1994	LA – Baldwin Hills	6.7	23.5	D
20	Northridge-01	1994	LA – Centinela St	6.7	20.4	D
21	Northridge-01	1994	LA – Cypress Ave	6.7	29.0	C
22	Northridge-01	1994	LA – Fletcher Dr	6.7	25.7	C
23	Northridge-01	1994	LA – N Westmoreland	6.7	23.4	D
24	Northridge-01	1994	LA – Pico & Sentous	6.7	27.8	D
25	Kobe, Japan	1995	Abeno	6.9	24.9	D
26	Kobe, Japan	1995	Kakogawa	6.9	22.5	D
27	Kobe, Japan	1995	Morigawachi	6.9	24.8	D
28	Kobe, Japan	1995	OSAJ	6.9	21.4	D
29	Kobe, Japan	1995	Sakai	6.9	28.1	D
30	Kobe, Japan	1995	Yae	6.9	27.8	D

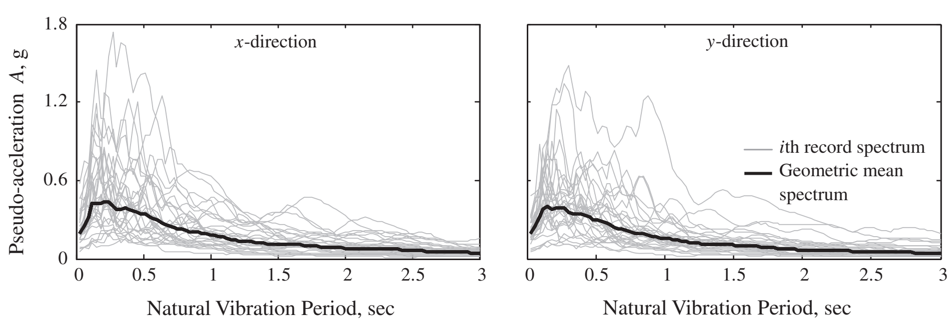

Fig. 1. Geometric-mean pseudo-acceleration response spectra of 30 records for 5% damping; individual response spectra of the records are shown in grey color.

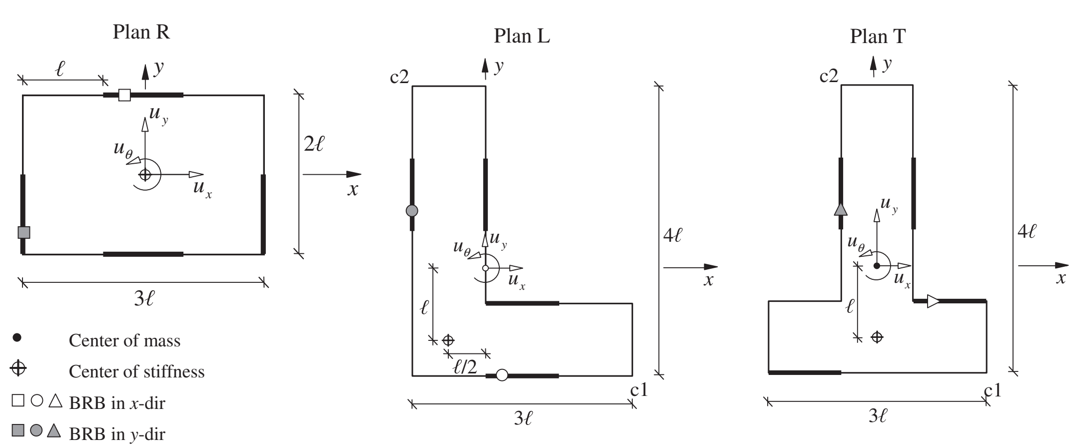

Fig. 2. Schematic isometric and plan views of the selected structural systems with degrees of freedom, centers of mass and centers of stiffness noted; buckling-restrained braced frames are highlighted.

Table 2
Ratio of the uncoupled torsional to lateral frequencies, static eccentricities, and normalized eccentricities.

Plan	$\frac{\omega_\theta}{\omega_x} = \frac{\omega_\theta}{\omega_y}$	$\frac{e_x}{r}$	$\frac{e_y}{r}$	$\frac{e_x}{3\ell^*}$	$\frac{e_y}{4\ell^*}$
R	1.73	0	0	0%	0%
L	0.92	0.42	0.85	16.7%	25%
T	0.94	0	0.77	0%	25%

* ℓ is defined in Fig. 2.

Table 3
Torsional irregularity factors for single-story buildings.

Building	R	L	T
β	1.0	1.6	1.7

(3) Extreme torsional irregularity: $\beta > 1.4$. The values of β are presented in Table 3 for R-, L- and T-plan buildings.

5.2. Multi-story buildings

The structures considered are nine multi-story buildings with 5, 10 and 15 stories. These buildings were designed to be located in Los Angeles, California according to the 2010 California Building Code [2]. The lateral resisting system of the buildings consists of moment resisting frames. Their plan shapes are shown in Fig. 3, where the moment resisting frames are highlighted. The buildings have similar plan areas and floor weights, with a span length of 30 ft (9.14 m) and a story height of 10 ft (3.05 m). The earthquake design forces were determined by bi-directional linear RSA of the building with the design spectrum reduced by a response modification factor $R_y = 8$. However, member sizes were governed by drift limits instead of strength requirements. Further details of the structural systems including their fundamental periods, mode shapes, torsional irregularity factors, etc., can be found in [4,25,26].

The level of torsional irregularity was calculated for the nine buildings using Eq. (2). The buildings selected cover the three levels of torsional irregularity as demonstrated in Table 4. Nonlinear RHA were conducted for these buildings using PERFORM-3D computer program [35] modeled with the following features: (1) girders 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; 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 [36]; (4) columns of moment resisting frames were assumed to be fixed at the base, whereas gravity columns were considered pinned at the base; and (5) effects of nonlinear geometry were approximated by a standard P–Δ formulation (P = axial force; Δ = lateral deformation) for both moment and gravity frames.

6. Assessing spectral matching and ASCE/SEI 7-10 scaling procedures

The structural systems were subjected to sets of seven records modified according to the SM procedure and ASCE7 ground motion-scaling method, and their responses were compared against the benchmark values[1] in order to test the accuracy and efficiency of both procedures. The term "accuracy" means that the modified records should provide median (or mean) responses close to the "exact" responses considering large population of records compatible with the hazard conditions specified. The term "efficiency" means that ground motions after modification with respect to the target spectrum should impose similar seismic demands to the structure. While large record-to-record variability in EDPs leads to uncertainties in design and diminishes the confidence level, small record-to-record variability (dispersion) indicates that modified records represent well the target demand level. Thus, a reliable ground motion modification (either amplitude-scaling or SM) method should not only produce accurate but also efficient estimates of EDPs [4,37].

The benchmark value corresponds to the comparison point calculated as the median values of an EDP obtained from RHAs of the structural systems subjected to the ensemble of recorded ground motions listed in Table 1. We believe that this large randomly populated ground motion set provides unbiased estimates of "true" (that is, expected) median response considering the hazard conditions specified. In this study, it is assumed that EDPs are log-normally distributed, therefore it is appropriate to represent the "mean" response by the geometric mean (or median), instead of the average [38]. For a log-normal distribution of a random variable, the geometric mean ($\hat{\mu}$) and median (x_{50}) are given by the same equation: $x_{50} = \hat{\mu} = e^{\mu}$, where μ is the mean of a log-normal distribution. Therefore, it is not misleading to use median instead of geometric mean. In order to be consistent with comparisons of the SM procedure with the ASCE7, geometric mean was used for the ASCE7 procedure although the ASCE7 requires mean. Use of "mean" instead of "geometric mean" would not affect the conclusions—provided that "mean" is consistently used for both scaling methods. To evaluate the efficiency of the methods, dispersion σ of the results was calculated as $\sigma = \exp\left(\sqrt{\sum((ln(x_i) - \mu)^2)/n}\right)$, where exp() is the exponential function, x_i is each of the EDP values and n is the number of elements of the sample; this expression corresponds to the dispersion of a lognormal distribution.

6.1. Single-story buildings

The accuracy and efficiency of the SM and ASCE7 scaling procedures were examined by comparing the median EDPs due to sets of seven ground motion against the benchmark. These sets are grouped as follows:

- "ASCE7-Rand": These sets comprise EDPs obtained from seven records randomly selected and scaled according to the ASCE7 procedure.
- "SM-Rand": These sets contain EDPs obtained from seven records randomly selected and modified according to the SM procedure. Steps 4 and 5 of the procedure presented in Section 2 are not implemented for these sets.
- "ASCE7-Best": EDPs from these sets are obtained from seven records selected by implementing an improved selection criterium and scaled according to the ASCE7 procedure. Suffix "-Best" means that selection procedure was implemented using a common criterion to obtain a better estimation of EDPs, but the results are not necessarily better than those provided by randomly selected sets. The scaled records in sets "ASCE7-Best" were selected by minimizing the discrepancy between the scaled spectrum of a record and the target spectrum over the period range from $0.2T_1$ to $1.5T_1$, and then identifying the final set of records as those with spectral acceleration values at T_1 close to the target spectrum. This selection procedure was proposed by Reyes and Kalkan [28,29], and is not part of the requirements of the ASCE7.

[1] "Benchmark value" refers to reference median EDP values.

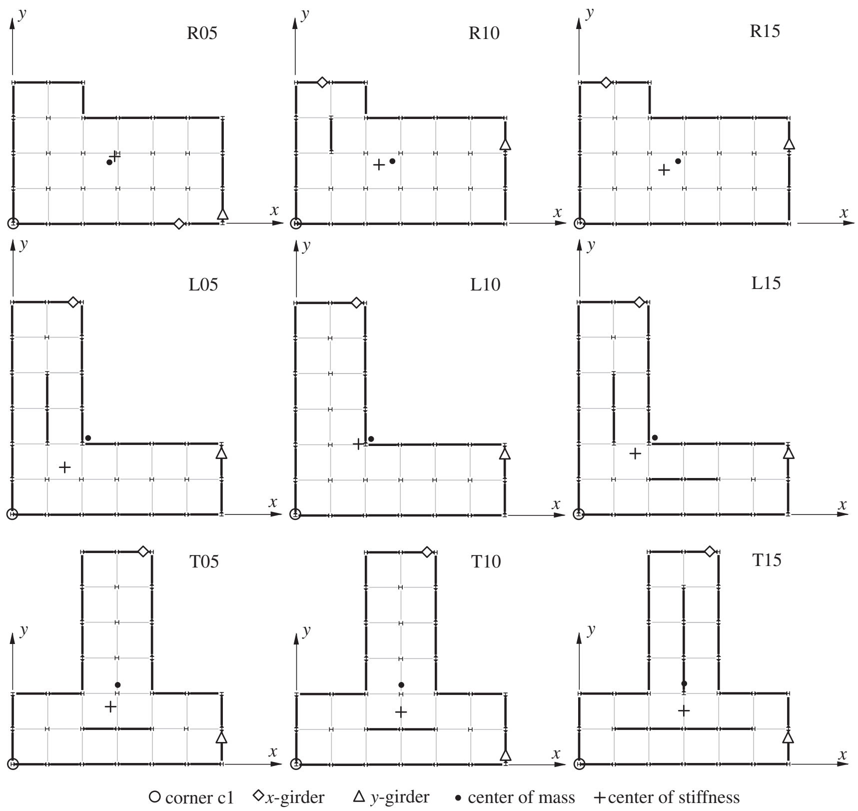

Fig. 3. Plan views of the selected nine multi-story buildings.

Table 4
Torsional irregularity factors for multi-story buildings.

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

- "SM-Best": These sets include EDPs obtained from seven records modified according to the SM procedure. The set "SM-Best" includes ground motions selected in steps 4 and 5 of the procedure presented in Section 2.

To assess the accuracy and efficiency of the spectrum matching procedure for nonlinear analysis, the structures responses were examined considering how far the structures deform beyond the limit of linearly elastic behavior. For this purpose, we calculated the ductility demands (defined as the maximum absolute value of the BRB deformation divided by the yield deformation) for the BRBs highlighted in Fig. 2. For the fundamental periods considered, Fig. 4 shows the relation between R_y and the ductility demand for BRBs in x- and y-direction (see Fig. 2). Results for linear cases are not shown. This figure is a three-by-four array corresponding to twelve combinations of R_y (increasing from top to bottom) and fundamental period of vibration T_1 (increasing from left to right). The vertical axis corresponds to statistics of the BRB's ductility demand values in x- and y-direction, due to the ensemble of 30 ground motions listed in Table 1. The square, circle and triangle markers illustrate the median of 30 ductility demand values for R-, L-, and T-plan buildings, respectively. The black vertical boxes represent the interval of ductility demand values between the first and third quartile of the data. This figure confirms that ductility demand values are approximately equal to R_y for long-period systems and much larger than R_y for short-period systems [39].

EDPs shown in Figs. 5 and 6 are normalized displacements and velocities in x- and y-direction obtained at three locations (Fig. 2): the center of mass (C.M.), corner c1, and corner c2. Note that these EDPs and other EDPs shown later correspond to the maximum absolute values of their time histories. Each part of these figures is a four-by-four array corresponding to sixteen combinations of R_y (increasing from top to bottom) and fundamental period of vibration T_1 (increasing from left to right). The vertical axis of the plots is the displacement or velocity obtained from each set normalized by the corresponding median benchmark value. The solid round marker and vertical line represent the normalized benchmark value ±one standard deviation (σ) based on 30 ground motions assuming a lognormal distribution. A horizontal solid line crosses the round marker to make the comparison between sets and benchmark values easier. Normalized EDPs for each set are indicated with a marker and a vertical line representing the median $\pm\sigma$ based on seven ground motions assuming also a lognormal distribution. The marker assigned to each procedure is indicated in the legend at the bottom of the figures.

Figs. 5 and 6 indicate that displacements and velocities obtained from sets "ASCE7-Rand" are, in general, inaccurate and show a large "record-to-record" (within set or intra-set) and "set-to-set" (between set or inter-set) variability. As demonstrated in Fig. 5c (e.g., R_y = 2 and T_1 = 1 s), the underestimation is as high as 80%. For R- and T-plan structures, the tendency is to overestimate the EDPs. In Fig. 5a (e.g., R_y = 3 and T_1 = 0.2 s) and Fig. 5b (e.g., R_y = 2 and T_1 = 1 s), this overestimation is greater than 50%. The set "ASCE7-Best" (Fig. 5) gives improved results for R- and T-plan structures in terms of accuracy and record-to-record variability. For L-plan structures, there is no considerable improvement in accuracy when sets "ASCE-Best" are used for estimating displacements and floor velocities.

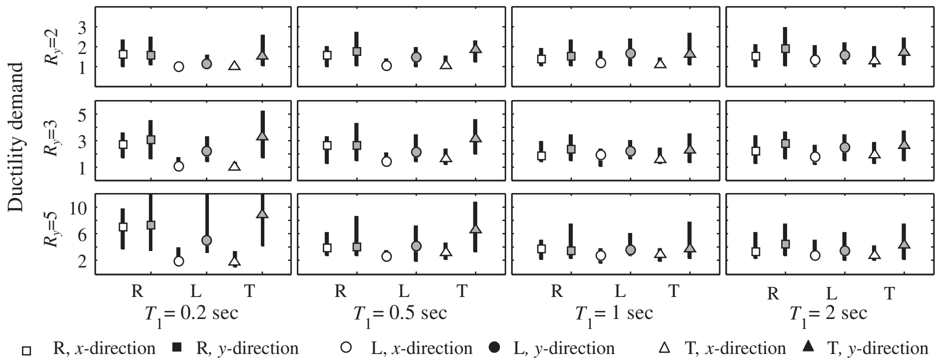

Fig. 4. Ductility demands for selected BRBs in *x*- and *y*-direction (see Fig. 2).

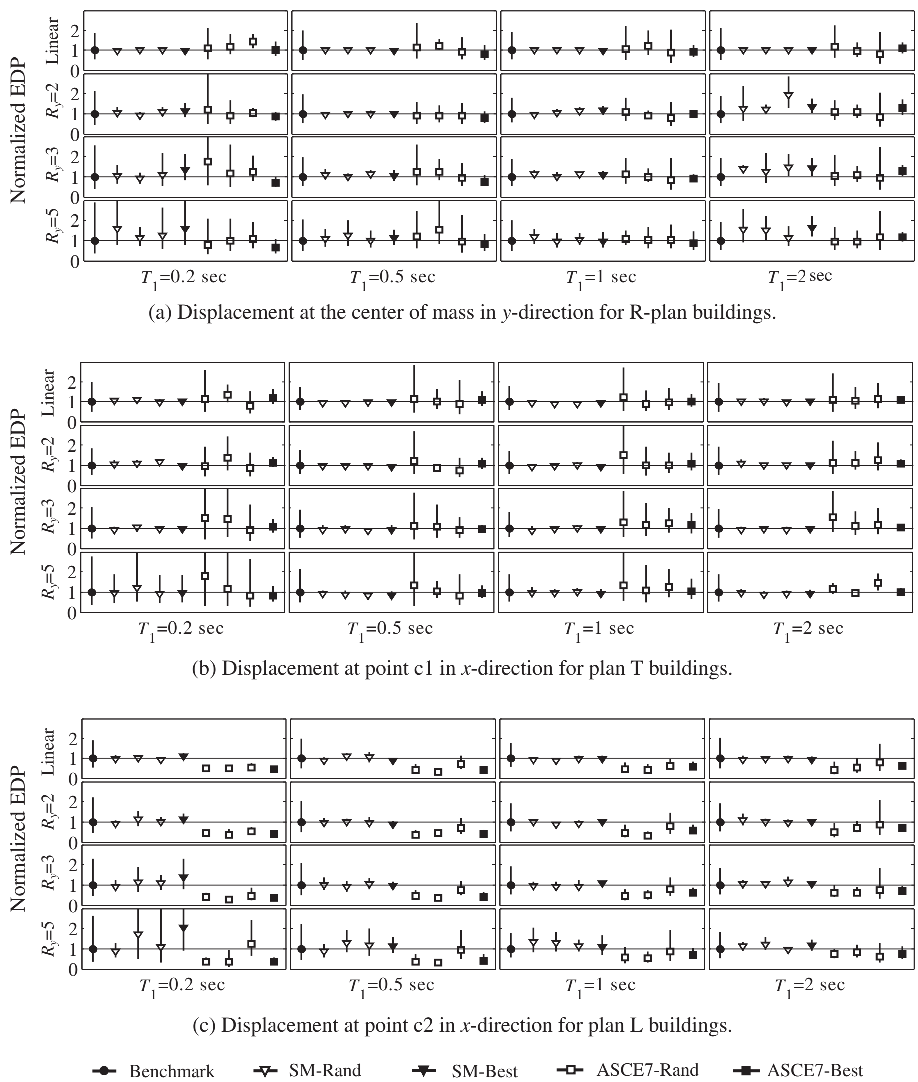

Fig. 5. Normalized results for the displacement (EDP) at the center of mass and points c1 and c2. For each set the marker and the vertical line represent the median value of the EDP ± σ, assuming a log-normal distribution.

A significant improvement of the record-to-record variability is observed with the use of sets "ASCE7-Best". As demonstrated in Fig. 5, if the records are selected randomly, the efficiency of the ASCE7 scaling procedure decreases with increasing R_y value and ductility demand (Fig. 4); efficiency is achieved only if records are selected on the basis of their spectral shape at T_1; this demonstrates that selection based on [28,29] is adequate to improve the efficiency of the ASCE7 scaling procedure. For short periods and large R_y values, the median of randomly selected sets is not similar to the median benchmark values as demonstrated in Figs. 5 and 6. The random selection of records for the ASCE7 may lead to inconsistent results [29].

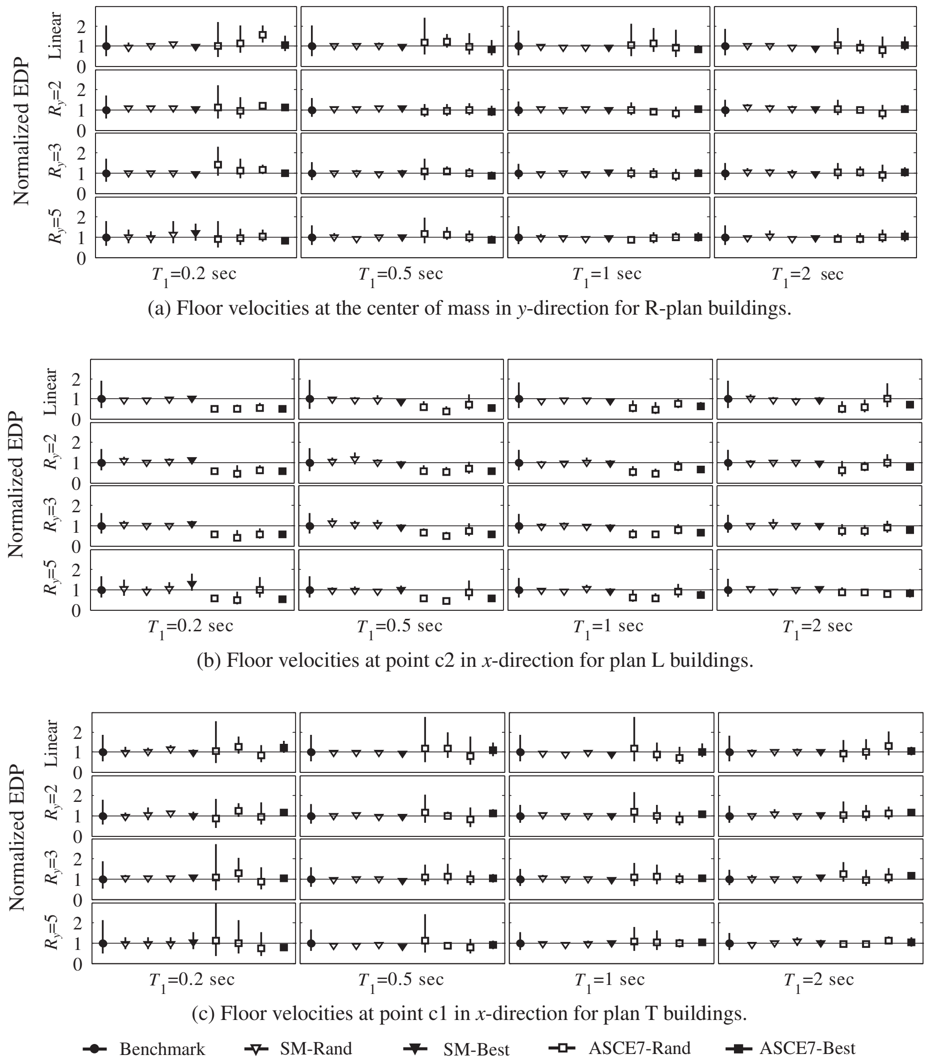

Fig. 6. Normalized results for floor velocities (EDP) at the center of mass and points c1 and c2. For each set the marker and the vertical line represent the median value of the EDP ± σ, assuming a log-normal distribution.

EDPs obtained from sets "SM-Rand" are very 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 R_y confirming that the accuracy of SM procedure is expected to diminish for large ductility demands (Fig. 4). For most cases, displacements and floor velocities obtained from sets "SM-Rand" and "SM-Best" are very accurate for various combinations of structural periods and R_y factors. Results from "SM-Best" sets provide median values of the EDPs that are much closer to the median values than is achieve by the sets "SM-Rand", "ASCE-Best" and "ASCE-Rand". Note that even for torsionally-flexible structures with strong coupling between lateral and torsional motions, bias in estimated EDPs is less than 10%. In general, EDPs obtained from sets "SM-Best" represent a considerable improving in accuracy when compared to EDPs obtained from sets "SM-Rand".

6.2. Multi-story buildings

Figs. 7–10 show story drifts at corner c1 (shown by "o" marker in Fig. 3) for the nine structures considered. First, second and third columns of these figures show EDP values in x-direction for the benchmark, ASCE7 and SM procedures, respectively; the next three columns show similar results in y-direction. The markers and horizontal lines represent the median EDP values $\pm\sigma$ assuming a lognormal distribution. For comparison purposes, the median benchmark values are kept in all sub-plots as a dashed line. Additionally, results for bending moments in girders in 15-story R-, L- and T-plan buildings are shown in Fig. 10; selected girders are highlighted in Fig. 3 by a diamond and a triangle marker. The bending moments are normalized by peak moment values occurred at any floor. Note that sets corresponding to the ASCE7 and SM procedures are one set of seven records selected by implementing an improved selection procedure similar to the ASCE7-Best and SM-Best presented earlier for the SDF systems.

The records scaled according to the SM procedure provide median EDPs that are much closer to the benchmark values than is achieved by the ASCE7 scaling procedure and at the same time the record-to-record variability in EDPs is reduced when the SM procedure is implemented. As demonstrated in Fig. 7, for the R-plan buildings, the 30% maximum discrepancy in story drifts encountered by scaling records according to the ASCE7 procedure is reduced to 10% when these records are modified by the SM procedure. Note that the errors obtained with the ASCE7 procedure correspond to underestimations of the median EDPs, while those encountered with SM are mostly overestimations, lower than 12%.

The record-to-record variability is lesser in EDPs due to a set of records modified according to the SM procedure (columns 3 and 6

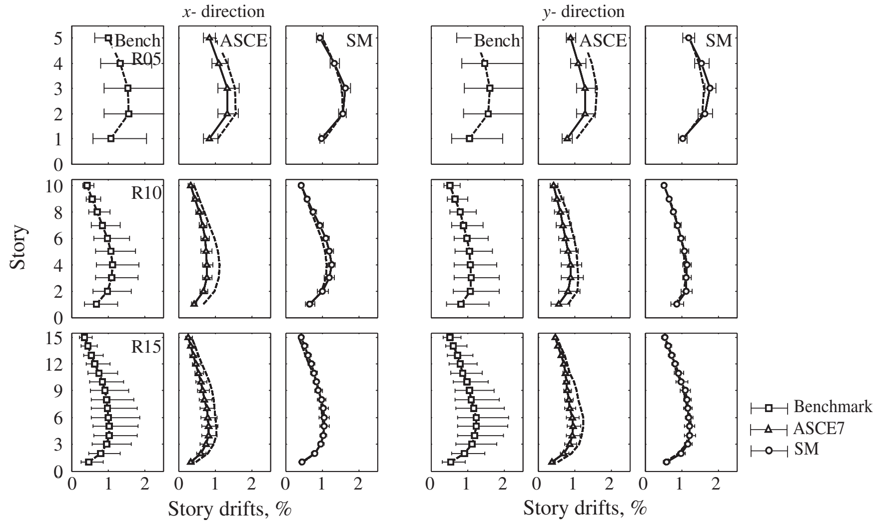

Fig. 7. Story drifts (EDP) in *x*- and *y*-direction in corner c1 for 5, 10- and 15-story R-plan buildings. In each case the marker and the horizontal line represent the median value of the EDP ± σ, assuming a log-normal distribution.

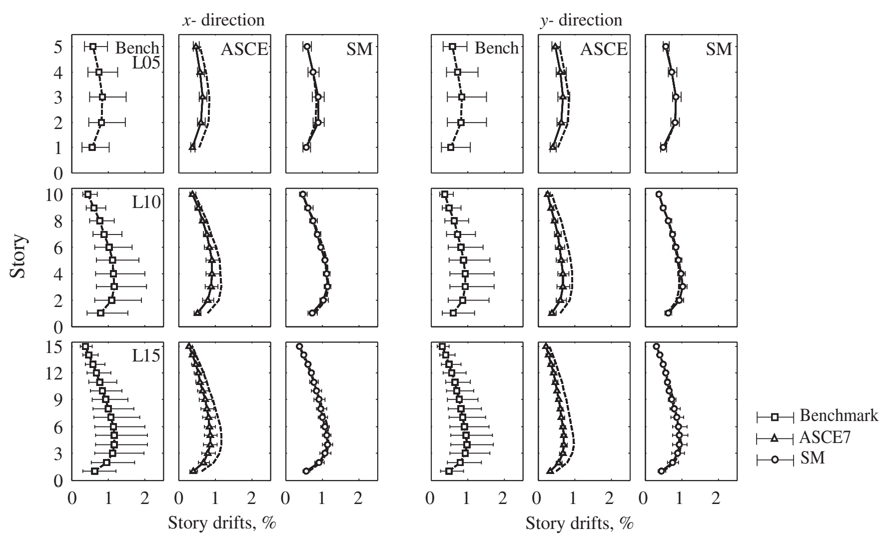

Fig. 8. Story drifts (EDP) in *x*- and *y*-direction in corner c1 for 5, 10- and 15-story L-Plan buildings. In each case the marker and the horizontal line represent the median value of the EDP ± σ, assuming a log-normal distribution.

of Fig. 7) compared to the records scaled by the ASCE7 procedure (columns 2 and 5 of Fig. 7). For L-Plan structures ($1.2 \leqslant \beta \leqslant 1.4$), the records modified according to the SM procedure lead to more accurate estimates of median EDPs than those achieved by the ASCE7 procedure. This improvement in accuracy is demonstrated in Fig. 8, where story drifts are shown at corner c1 (Fig. 3). Story drift due to a set of records scaled by the ASCE7 procedure presented errors over 20% in all cases. The maximum error in story drifts encountered with the ASCE7 procedure is reduced from 28% to 8% by implementing the SM procedure. Likewise, the error in bending moments (Fig. 10) is reduced from 20% to 4%. Similar to the results for R- and L-plan structures, EDPs obtained from sets ASCE7 are less accurate than those obtained from SM for T-plan structures; for example, compare columns 5 and 6 of Fig. 9. Even for T-plan structures with extreme torsional irregularities ($\beta > 1.4$), the SM procedure is highly efficient. For example, compare columns 5 and 6 of Fig. 9 for building T10; the maximum discrepancy of 37% in story drifts encountered by scaling records according to the ASCE7 procedure is reduced to about 2% when these records are scaled by the SM procedure.

For the ASCE7 procedure, the error in internal moments (see Fig. 10) is generally smaller than the error in story drifts because internal moments vary slowly with hinge rotation for members that deform beyond the elastic limit at both ends [40]. As a result, even a large error in story drifts lead to only a small error in the internal moments. The greatest error associated with the ASCE7 procedure is approximately 20%; this error corresponds to an underestimation of the EDP value. The errors obtained with the SM procedure are overestimations on average lesser than 10%. Evidently, the EDPs obtained with the SM procedure provided improved results in comparison with those obtained with the ASCE7 scaling procedure. Due to limited space, we only show here representative set of results; additional findings can be found in [4,25,26].

7. Conclusions and recommendations

Spectrum matching is a technique in which an actual ground motion is modified in time or frequency domain for purpose of

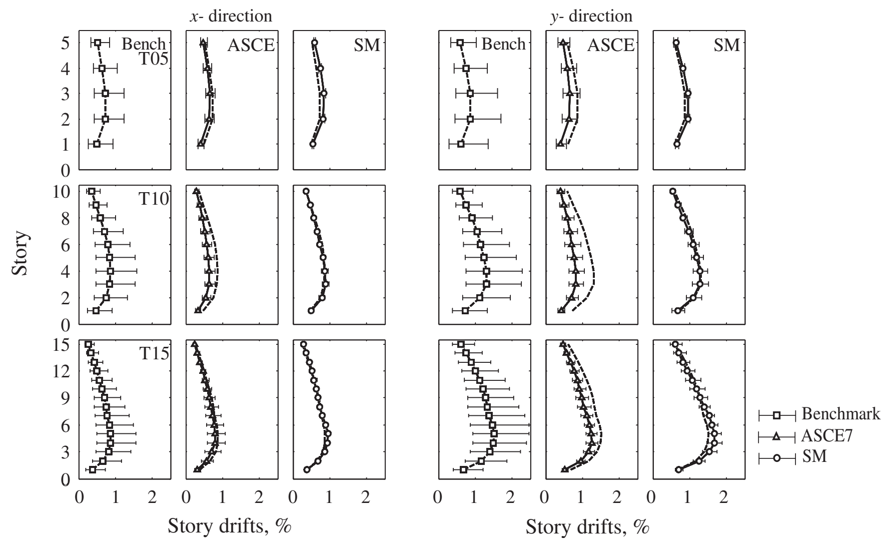

Fig. 9. Story drifts (EDP) in x- and y-direction in corner c1 for 5, 10- and 15-story T-Plan buildings. In each case the marker and the horizontal line represent the median value of the EDP ± σ, assuming a log-normal distribution.

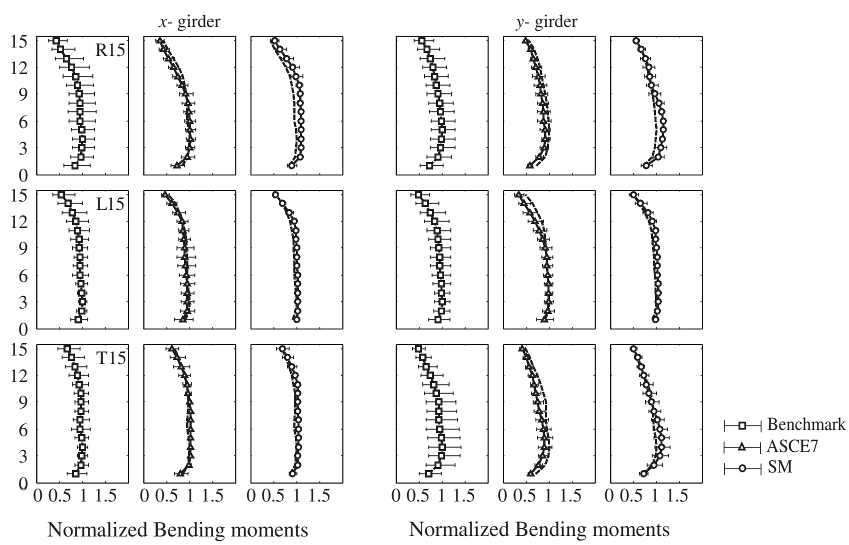

Fig. 10. Normalized bending moments (EDP) in selected girders for 15-story R-, L- and T-plan buildings. For each set the marker and the horizontal line represent the median EDP values ± σ, assuming a log-normal distribution.

matching its elastic response spectrum to a target spectrum across a range of periods and conceivably multiple damping values. This study investigates whether spectrum-matched records provide accurate (unbiased) estimates of median EDPs and to what extend the variability in EDPs is reduced. The accuracy of the SM procedure was evaluated by comparing the median values of the engineering demand parameters (EDPs) due to sets of seven records modified according to the SM procedure against the benchmark values, defined as the median values of the EDPs due to 30 unscaled records. The efficiency of the SM 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. For this evaluation, 3D computer models of 48 single-story and nine multi-story symmetric and asymmetric-plan buildings were utilized. Their structural responses were obtained from subsets of seven records modified by SM and separately by amplitude-scaling according to the ASCE/SEI 7-10 scaling procedure for comparison. The key conclusions of this study are:

1. Definition of target spectrum should be consistent when spectrum matching is conducted for two-component ground motions independently, that is, one component matched to a x-spectrum and the other to y-spectrum.
2. For both symmetric- and asymmetric plan buildings, use of spectrum-matched ground motions for nonlinear response-history analysis under bi-directional excitations provides accurate (no or low bias) estimates of median EDP values when compared with a rigorous benchmark.
3. Spectrum-matched ground motions remove the variability in the ground motion spectra as a result the record-to-record variability of the input is significantly reduced. Although this leads to stable estimates of the median response using fewer structural analyses, the variability in response associated with inherent aleatoric uncertainty in earthquake recordings is artificially reduced. Therefore, spectrum-matched records should not be used to estimate percentile values of response other than the median because it cannot provide the distribution of response.

4. Due to significantly reduced variability in response, no less than seven records used for nonlinear response-history analysis should be used if the motions are spectrum-matched.
5. As compared to the ASCE7 ground motion scaling procedure, spectrum-matching procedure provide median values of EDPs that are much closer to the benchmark values than is achieved by the ASCE7 procedure. The dispersion in the EDPs due to seven scaled records around the median is much smaller when records are modified with the SM procedure compared to the ASCE7. Thus, the SM method is found to be more accurate and efficient than the ASCE 7 scaling procedure.
6. It can also be argued that the spectral accelerations of ground motions at elastic modal periods of the system are not necessarily reliable ground-motion intensity measures; thus for higher inelastic response, the accuracy of spectrum-matched records is expected to diminish. For such cases, scaling methods that are based on the inelastic deformation spectrum or that consider the response of the first-"mode" inelastic SDF system are more appropriate.

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