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RESEARCH ARTICLE

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Interstory drift based scaling of earthquake ground motions

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Abstract

A novel amplitude scaling procedure is proposed in this study where the ground motion scaling factors are defined as the ratio of interstory drift distributions under target spectrum versus under the associated ground motion spectrum. The advantage of employing interstory drift ratio in ground motion scaling, compared to employing spectral intensity directly, is that it provides a strong theoretical link between the target spectrum intensity and the fundamental dynamic characteristics of the structure. Hence, scaling is conditioned on structural response, which is in turn a function of seismic intensity. The interstory drift-based scaling procedure (IDS) is presented herein for planar frames for brevity. Accuracy and efficiency of the IDS procedure is assessed under a set of near fault strong motions from large magnitude events. The results revealed that the proposed procedure is accurate since the resulting bias in estimating linear elastic interstory drifts is negligibly small. Further, it is noticeably more effective as compared to the conventional procedures suggested in recent seismic codes, yet it is simpler.

KEYWORDS

accuracy, bias, dispersion, drift based scaling, efficiency, ground motion selection, higher modes, nonlinear response

1 | INTRODUCTION

Earthquake ground motions in engineering design practice are represented by linear elastic design spectra, which express the mean intensity of ground motions expected at a given site. They are traditionally obtained by conducting probabilistic seismic hazard analysis (PSHA), where the probability of exceeding a spectral intensity is uniform over the considered period range. Modal response spectrum analysis (RSA) of linear elastic systems is well established and documented in modern seismic codes.[1–3] When it is required to determine the seismic performance of a newly designed or an existing structure however, it is necessary to evaluate the nonlinear response of the system by conducting either incremental nonlinear static analysis (single or preferably multi-mode pushover) or nonlinear response history analysis (NRHA). This necessity is becoming quite common with the increasing popularity of performance-based earthquake engineering, especially for critical as well as non-standard structures such as tall buildings and buildings equipped with seismic isolation or damping devices. Recent advances in computational power and structural analysis software development render NRHA and accordingly seismic performance assessment possible even for standard structures. Then, the remaining question is, under which ground motions?

Ground motions can be selected from the large databases of recorded ground motions, for example,[4–6] and modified in order to satisfy an earthquake hazard scenario that is usually defined by a response spectrum, such as the design spectrum prescribed by a given seismic code or a site-specific spectrum obtained from PSHA carried out for a project site. This spectrum is called the "target spectrum" within the context of ground motion selection and modification. A natural requisite of selecting the unmodified ground motions is that the source and site characteristics of ground motions should represent the seismicity of the site (magnitude, distance from causative faults, soil type, etc.) as much as possible. If the target spectrum is a uniform hazard spectrum obtained by PSHA, then this requirement is inevitably not easy to fulfil. Nevertheless, the selected unmodified ground motions are then modified such that the mean spectrum of the scaled records match the target spectrum along the period range encompassing the vibration modes of structures as close as possible for achieving a desired accuracy.[7,8]

One critical parameter in record selection and modification, particularly scaling is the intensity measure (IM) of ground motions. The basic criteria for selection and modification are *accuracy, efficiency*, and *sufficiency* of the intensity measure.[9] An intensity measure is accurate, or unbiased if the mean value of responses calculated under a set of ground motions having the same intensity are equal to the response calculated under target spectrum. An intensity measure on the other hand is efficient if the variability of the responses calculated under a set of ground motions having the same intensity are small. It is also sufficient if the responses calculated for the same set are independent of magnitude and source-to-site distance of the ground motions in the set. The first criterion facilitates accuracy of calculated responses, while the second criterion reduces the required number of ground motions. Possible candidates that are easily available or *computable* are PGA and spectral acceleration at the fundamental period. Shome et al.[10] showed earlier that PGA correlates poorly with the inelastic response of structures, however scaling with respect to spectral acceleration at the fundamental period $S_a(T_1)$ is efficient. As an additional advantage, this choice reduces also the importance of magnitude-distance combination in selection. S_a (T_1) has been employed by several researchers in order to obtain the amplitude scaling factors of ground motions that lead to least scatter in the inelastic structural response parameters.[11–14] These studies showed that response variability increases with increasing ductility demand,[13] and scaling according to S_a (T_1) introduces significant bias in the median nonlinear structural response.[14]

Although S_a (T_1) is a superior IM compared to PGA, it has several shortcomings: T_1 is not stable during inelastic response, and first mode spectral acceleration is not a sufficient predictor of inelastic structural response. Vector valued spectral intensity measures have been proposed for improving the spectral acceleration-based predictions of structural response, which further facilitate seismic risk assessment.[15–17] These IM's consider spectral accelerations at more than one modal period as well as their functional combinations. Another group of studies accounts for the variability in target intensity levels for realizing the full probability distribution of spectral intensity rather than their mean value only in order to obtain more realistic estimates of structural response parameters.[18–21] Improved selection algorithms that account for the variability of critical response parameters have also been proposed, leading to more reliable response estimates.[22]

All IM's utilized in the previous studies briefly summarized above, link hazard (i.e., response spectrum) to structural response through modal periods. Clearly, representation of structural response merely with modal period information is far from being sufficient. A noteworthy improvement to spectrum-based IM's is achieved with structure-specific IM's, which was first introduced by Luco and Cornell in their seminal work.[9] These IM's "approximately" account for the relation between spectrum-based modal intensities S_{an} (T_n) and a computable structural response parameter, that is, story displacements or interstory drift, by weighting modal intensities with modal participation factors.[9,23–25] A further improvement is proposed by using the first mode spectral displacement directly as an IM, which is in turn a function of spectral displacement through basic principles of structural dynamics.[26,27] First mode spectral displacement is converted into inelastic modal displacement in these studies through empirical relations.

Seismic design/assessment codes, on the other hand, prescribe scaling procedures of ground motions using more general terms and conditions, thus providing engineers with some freedom on how to go about their selection and scaling of ground motions.[1,3] The respective text of ASCE 7–16[1] for amplitude scaling is quoted here: "The average of the maximum direction spectra from all the ground motions shall not fall below 90% of the target response spectrum for any period within the considered period range." Eurocode 8–1[2] states a simpler definition: "The mean of the zero period spectral response acceleration values from individual time histories should not be smaller than a_g.S (i.e., PGA) of the site." Eurocode 8-1 procedure is quite similar to PGA scaling discussed above. The narrowest period range is practically from $0.2T_1$ to $2T_1$ in both codes, which intends to cover all significant modal periods as well as the lengthening of T_1 due to inelastic response.

A new amplitude scaling procedure is proposed in this study where the ground motion scaling factors are defined as the ratio of interstory drift distributions under target spectrum versus under the associated ground motion spectrum. Interstory drift ratio is the structural response parameter conditioned on modal spectral intensities. It provides a strong theoretical link between the target spectrum intensity and the fundamental dynamic characteristics of the structure, namely modal periods, mode shapes, and modal mass participations. The interstory drift-based scaling procedure (IDS) is presented for planar frames herein for brevity. Its extension to unsymmetrical-plan frames is theoretically straightforward, and is currently under development. The accuracy and efficiency of the IDS procedure is assessed in comparison to both the ASCE 7–16 and Eurocode 8-1 scaling procedures.

2 | IDS METHODOLOGY

Maximum interstory drift at the *j*'th story of a linear elastic structure can be determined by RSA through the SRSS combination of modal drifts $\Delta_{j,n}$.

$$\Delta_{j,max} = \sqrt{\sum_{n} [\Delta_{j,n}]^2} \tag{1}$$

where

$$\Delta_{j,n} = \Gamma_n \, D_n \left(\phi_{n,j} - \phi_{n,j-1}\right) \tag{2}$$

In Equation (2), $\Gamma_n = L_n / M_n$; L_n is the modal excitation factor; M_n is the modal mass, D_n is the spectral displacement of the *n*'th mode and $\phi_{n,j}$ is the *j*'th element of the *n*'th mode eigenvector ϕ_n.

When $\Delta_{j,max}$ in Equation (1) is calculated under the target response spectrum for amplitude scaling, it is called the target interstory drift $\Delta_{j,target}$ in our methodology. Hence, $\Delta_{j,target} = \Delta_{j,max}$. Similarly, $\Delta_{j,i}$ is the *j*'th story maximum drift calculated from Equation (1) under the response spectrum of *i*'th ground motion. Then the amplitude scale factor SF_i for the *i*'th ground motion is calculated from,

$$SF_i = \frac{\sum_j \Delta_{j,target}}{\sum_j \Delta_{j,i}} \tag{3}$$

The summation over all maximum interstory drifts Δ_j in Equation (3), both at the numerator and the denominator, is an averaging operation for maximum interstory drifts in order to account for the entire interstory drift distribution along the building height. This choice proves to be more effective and stable for ground motion scaling, compared to employing the "maximum of maximum interstory drifts" obtained at a particular story.

D_n in Equation (2) can be replaced by its inelastic counterpart through modification with an empirical inelastic displacement ratio. It may be expected that such modification increases the accuracy and efficiency of amplitude scaling. However, inelastic-to-elastic displacement ratios are usually derived statistically where their values have significant variance. Moreover, such conversion applies equally to the ground motions representing target spectra and the individual ground motions at the numerator and denominator of Equation (3). Hence, its effect on scaling shall not be significant. We prefer retaining the simplicity of the procedure expressed by Equations (1)–(3), even though Equation (2) is strictly valid only for linear elastic systems.

3 | IMPLEMENTATION OF THE IDS METHODOLOGY: 20–STORY PLANE FRAME

A 20–story reinforced concrete building structure designed in Istanbul according to Eurocode-8[2] provisions for high ductility class (DCH) is employed in this study for testing and evaluating IDS. A second "irregular" variant of the 20 story building is also generated by increasing the first story height from 4 to 5.5 m, without revising the section designs. Elevation views of both building frames and the cross-section properties of frame members are shown in Figure 1. There are seven frames in the transverse direction spaced at every 5 m in the structure.

The 475-year design spectrum for Eurocode type B soil (NEHRP type C) is shown in Figure 2.

Given that the structures are perfectly symmetrical in plan, 2D frame models are developed by employing the structural analysis platform SeismoStruct.[28] Free vibration shapes for the first three modes of both frames are shown in Figure 3 comparatively, and their modal properties are presented in Table 1. Effective stiffnesses of RC members are employed in the linear elastic models. Total masses of the frames with the first story heights of 4 and 5.5 m are 2201 kN and 2210 kN, respectively.

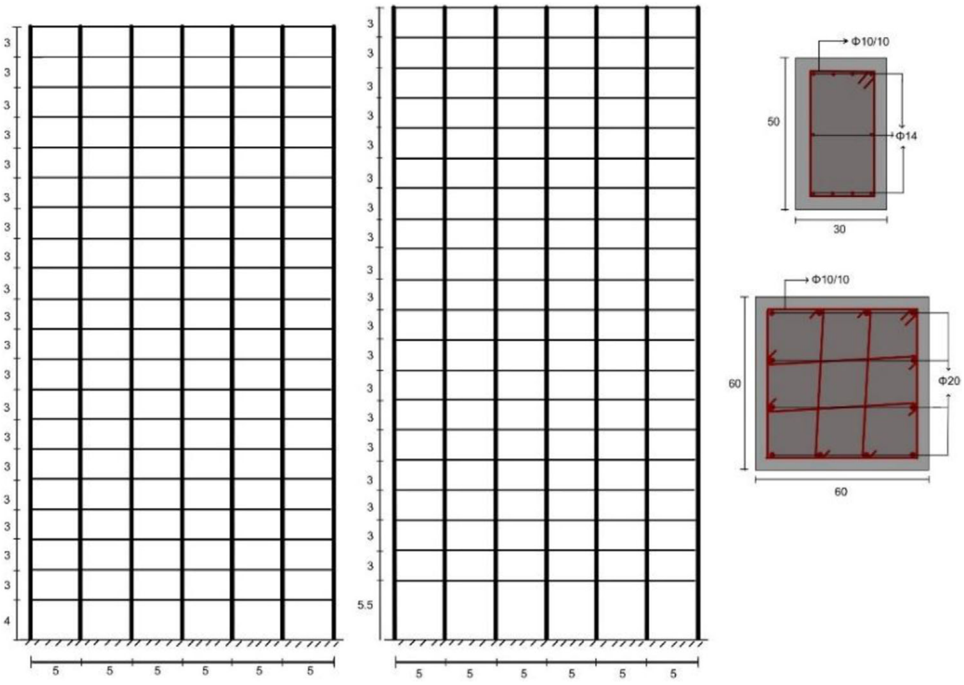

FIGURE 1 Elevation views of the regular (left) and irregular (right) variants of the 20-story frame and reinforcement details of beams and columns. Structural dimensions in m, section dimensions in cm

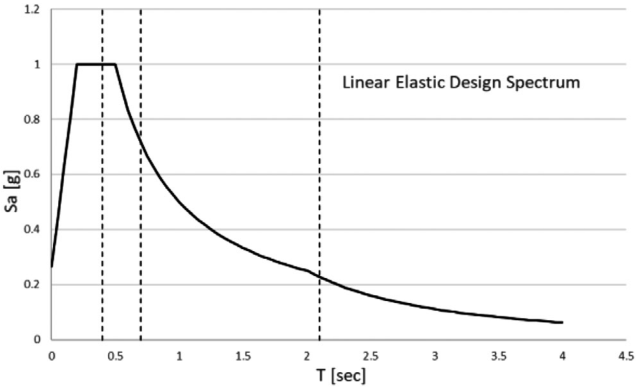

FIGURE 2 Site-specific design spectrum for 475-year return period

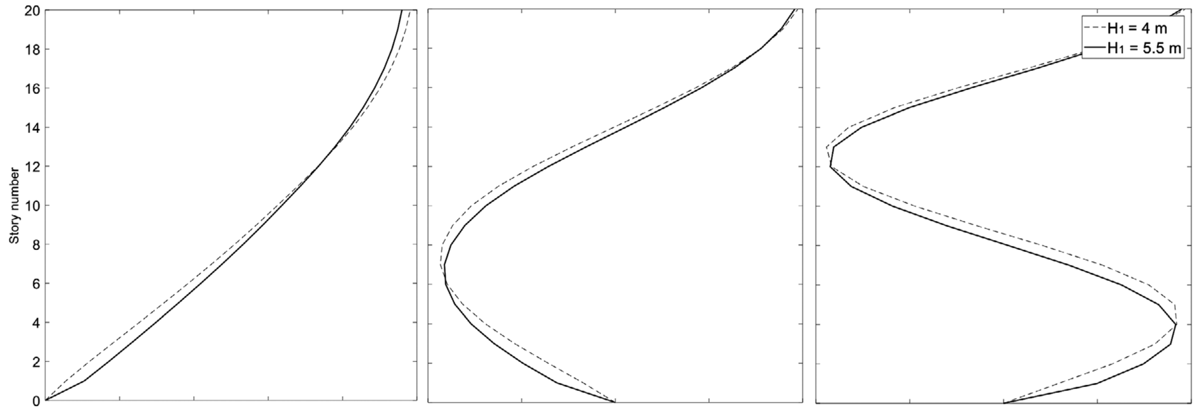

FIGURE 3 Mode shapes and modal periods for the first three modes

TABLE 1 Modal properties of the two building frames

	Regular Frame: H1 = 4 m		Irregular Frame: H1 = 5.5 m	
Mode #	Period (s)	Modal mass ratio %	Period (s)	Modal mass ratio %
1	2.10	80.6	2.49	83.6
2	0.70	10.4	0.83	10.2
3	0.40	3.5	0.48	3.5

TABLE 2 Properties of strong ground motions

GM Code	Earthquake (Year)	Station	M_w	Fault Type	R_{jb} (km)	Vs30 (m/s)	PGA (g)	PGV (cm/s)
776	Loma Prieta 1989	Gilroy Array #2	6.9	Rev. Obl.	10	271	0.30	17
778	Loma Prieta 1989	Hollister Differential Array	6.9	Rev. Obl.	25	216	0.27	44
850	Landers 1992	Desert Hot Springs	7.3	strike	22	359	0.15	21
982	Northridge-01 1994	Jensen Filter Plant Admin. Bldg	6.7	Rev.	0	373	0.41	111
1110	Kobe 1995	Morigawachi	6.9	strike	25	256	0.21	27
1158	Kocaeli 1999	Duzce	7.5	strike	14	282	0.31	59
1184	Chi-Chi 1999	CHY010	7.6	Rev. Obl.	20	539	0.17	24
1517	Chi-Chi 1999	TCU084	7.6	Rev. Obl.	0	665	0.43	48
1615	Duzce 1999	Lamont 1062	7.1	strike	9	338	0.26	18
1787	Hector Mine 1999	Hector	7.1	strike	10	726	0.33	45
3746	Cape Mendocino 1995	Centerville Beach Naval Fac	7.0	Rev.	16	459	0.32	50
4841	Chuetsu-oki 2007	Joetsu Yasuzukaku	6.8	Rev.	21	655	0.22	23
4895	Chuetsu-oki 2007	Kashiwazaki NPP Unit 5	6.8	Rev.	0	266	1.25	92
5778	Iwate 2008	Matsuyama City	6.9	Rev.	41	436	0.29	37

Reduction in the first story stiffness of the irregular variant compared to the regular frame is evident in Figure 3. First story lateral stiffness of the regular frame with a first story height of 4 m is 2.82×10^5 kN/m whereas that of the irregular frame with a first story height of 5.5 m is 1.18×10^5 kN/m. Hence, first story stiffness of the irregular frame is reduced to 42% of the first story stiffness of regular frame.

4 | STRONG GROUND MOTIONS

A suite of 14 ground motions is selected from the NGA-West2 ground motion database. They were recorded on sites within the Vs30 range of 200–800 m/s, at distances closer than 40 km from the fault, from earthquakes with moment magnitudes between 6.8 and 7.6. Magnitude and distance properties of the selected ground motions represent well the seismicity in Istanbul.[29] A constraint has not been imposed on the soil type and fault properties with the intention of having larger scatter on the intensity of ground motions, hence testing the efficiency of the IDS procedure more effectively. The properties of selected ground motions are listed in Table 2. Five-percent damped response spectra of the unscaled ground motions are shown in Figure 4, along with the mean specrum and the 475-year design spectrum. It is noteworthy to observe that these two spectra are quite close. Hence the unscaled ground motions are well representing the design spectrum in the average sense. The ground motion showing high spectral ordinates along the short period range is record 4895.

5 | SCALING OF GROUND MOTIONS FOR MATCHING THE MEAN SPECTRUM

The target spectrum is selected as the mean spectrum of unscaled ground motions here for testing the accuracy and efficiency of the IDS procedure. Three types of scaling are applied to the unscaled ground motions for comparative evaluation: IDS, ASCE 7–16, and EC 8-1 scaling. Response spectra of the scaled ground motions are compared first. Then the response

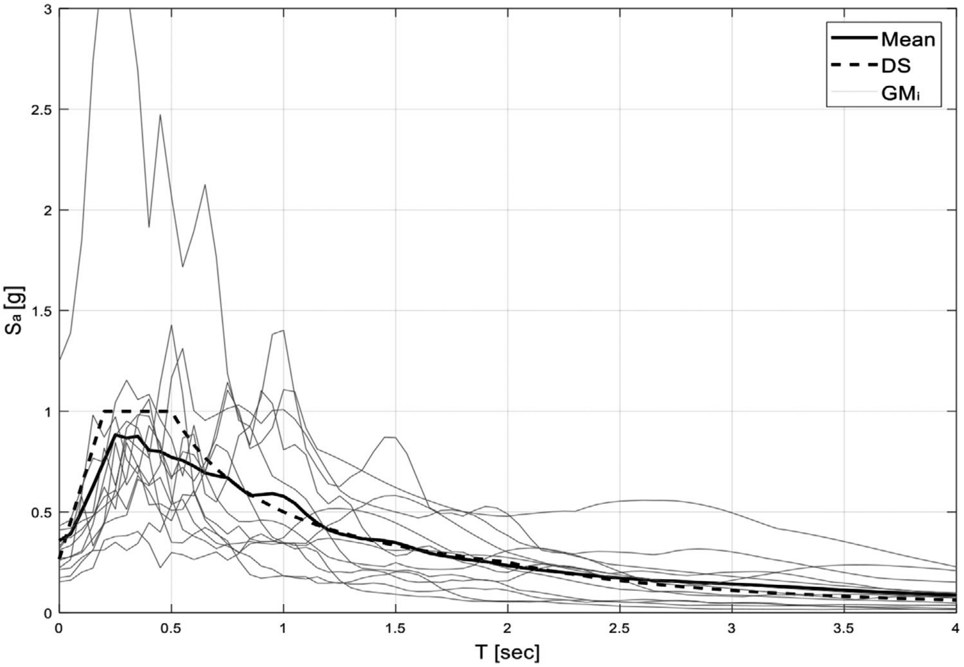

FIGURE 4 Five-percent damped response spectra of the unscaled ground motions, and design spectrum (DS)

TABLE 3 Ground motion scale factors for matching the mean spectrum

GM #	776	778	850	982	1110	1158	1184	1517	1615	1787	3746	4841	4895	5778
SF IDS	0.68	0.87	2.10	0.48	1.11	0.73	2.49	0.90	2.94	1.16	0.89	3.04	0.55	1.80
SF ASCE	0.73	1.21	2.31	0.60	1.24	1.19	2.37	0.88	2.67	1.15	1.13	2.28	0.52	1.35
SF EC8	0.97	1.33	2.32	0.87	1.67	1.15	2.05	0.83	1.38	1.09	1.12	1.60	0.29	1.21

parameters obtained under unscaled and all three sets of scaled ground motions are presented, both for the linear elastic response from RSA and for inelastic dynamic response from NRHA. Interstory drift distributions and mean beam plastic rotation distributions along the building height are the considered response parameters for accuracy and efficiency evaluation.

ASCE 7–16 amplitude scaling procedure requires a two-stage process. In the first stage, each unscaled ground motion is scaled to match the target spectrum along the $0.2T_1$–$1.5T_1$ period range as close as possible. No specific method is recommended for the first stage. Then their mean spectrum is calculated and compared with the target spectrum. If it does not fall below 90% of the target spectrum along the $0.2T_1$–$1.5T_1$ range, the second stage is not required. If it does, then an upward scaling is applied to the first-stage scaled ground motions in order to satisfy the 90% criterion. EC 8-1 procedure also requires a two-stage calculation. Each unscaled ground motion is scaled to match the target spectrum at zero period, that is, PGA. If the mean spectrum of the PGA scaled ground motions fall below 90% of the target spectrum along the $0.2T_1$–$2.0T_1$ range, an upward scaling is applied to the first-stage scaled ground motions in order to satisfy the 90% criterion.

We have determined the scale factors for the first stage scaling of ASCE 7–16 by equating the areas under the target spectrum and the ground motion spectrum along the $0.2T_1$–$1.5T_1$ range. Second stage scaling has not been necessary since the 90% criterion is satisfied. On the other hand, scale factors for the EC 8-1 procedure are directly the ratios of target PGA to the ground motion PGA. Second stage upward scaling has not been required also for the EC8 scaling. Scaling factors for the IDS procedure are determined from Equation (3). Three sets of scale factors obtained from the three procedures are presented in Table 3 for each ground motion.

Response spectra of the ground motions scaled by the three procedures are presented in Figure 5A–C. Mean spectrum of the scaled ground motions is shown with a solid black line and the target spectrum (mean of the unscaled ground motions) with a dashed black line. It is noteworthy to observe that the mean spectra of ground motions scaled by the three procedures look very close, although the associated scale factors for some GM’s in Table 3 have notable differences.

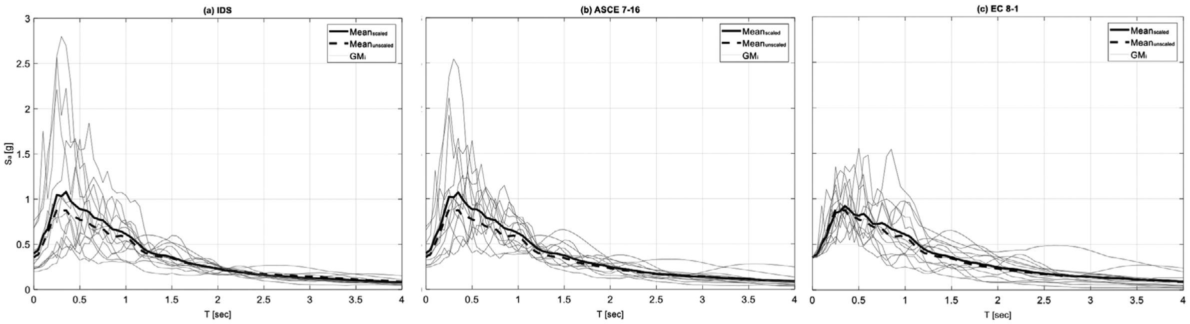

FIGURE 5 Five percent damped response spectra of the scaled ground motions. A) IDS, B) ASCE 7–16, C) EC 8-1

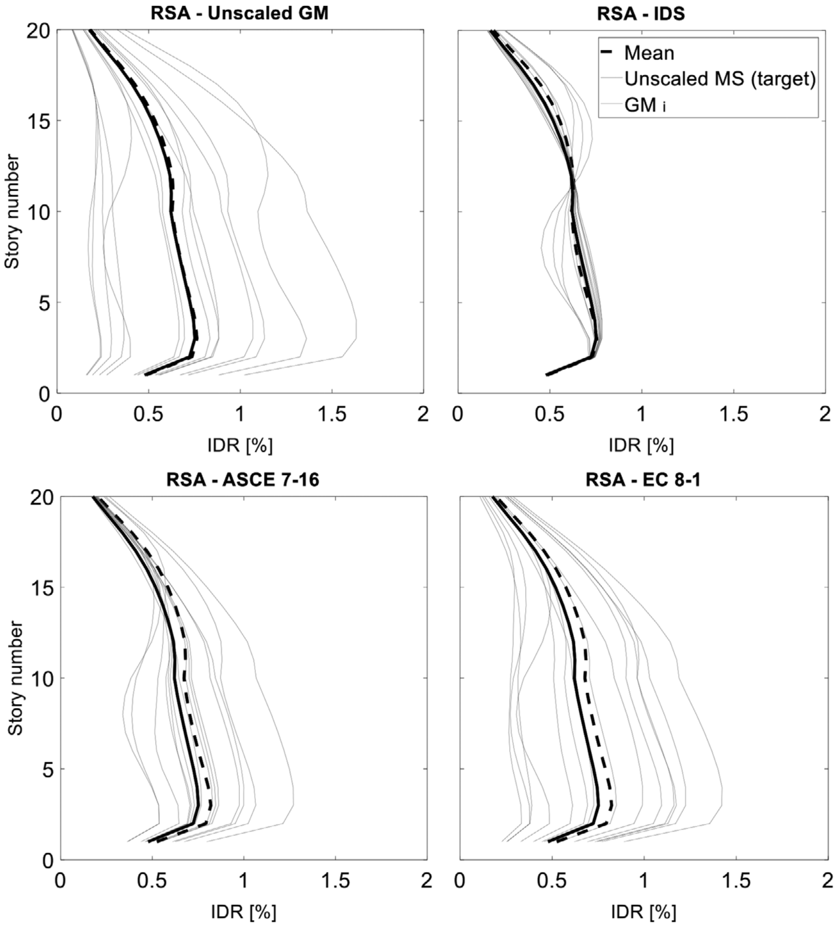

FIGURE 6 Distribution of linear elastic interstory drift ratios along building height under unscaled, interstory drift scaled, ASCE 7–16 scaled and EC 8-1 scaled ground motions for matching target mean spectrum

5.1 | Comparison of linear elastic response parameters

Interstory drift ratios are calculated by RSA under the unscaled, and two sets of scaled ground motions. The results are presented in Figure 6. It is evident that IDS procedure is very efficient in reducing the dispersion of interstory drifts. ASCE 7–16 and EC 8-1 scaling procedures are also reducing the dispersion to some extent, but their efficiency is much less compared to IDS. This outcome is not clear from the comparison of scaled response spectra in Figure 6 above, indicating that ground motions with similar spectral mean and seemingly similar dispersion around the mean may result in quite different response dispersion even for linear elastic response.

The unscaled ground motions that are producing the smallest drifts at the upper left panel of Figure 6 are the ones that increase dispersion most in the IDS, ASCE, and EC8 procedures, as expected. These are the ground motions 850, 1184, 1615, and 4841 in Table 1. They are not so weak, but their effects on the 20-story structure are weaker than the others. Accordingly, their scale factors that are displayed in Table 2 are the largest.

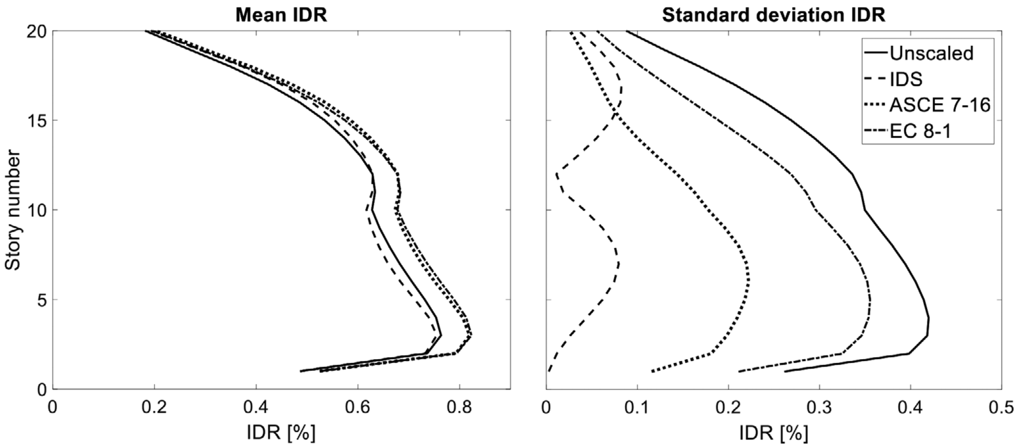

FIGURE 7 Mean and standard deviation profiles of interstory drift ratio along building height under unscaled, interstory drift scaled, ASCE 7–16 scaled and EC 8-1 scaled ground motions

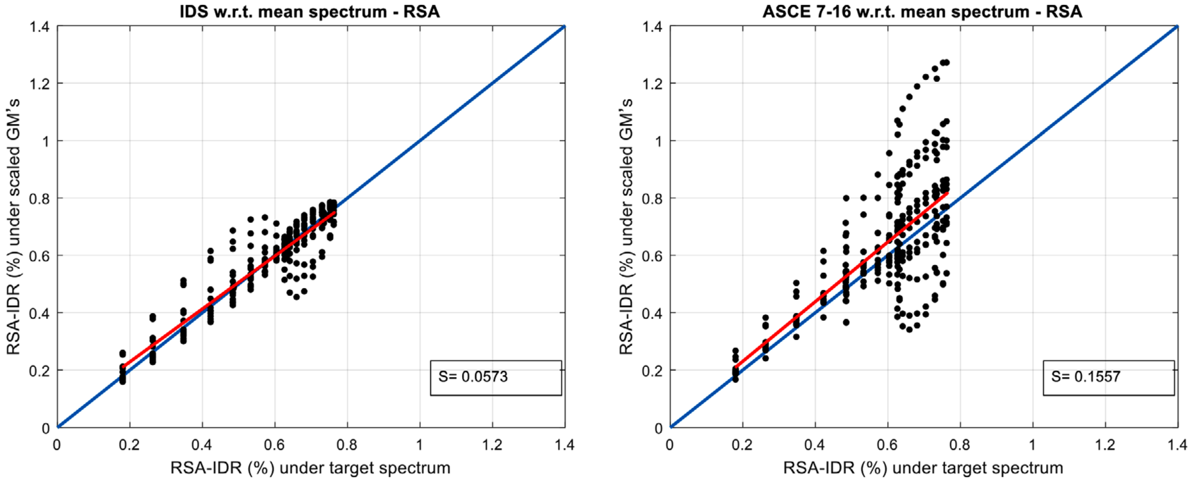

FIGURE 8 Scatter graphics of IDR under each scaled ground motion (vertical axis) versus IDR calculated under target (mean) spectrum at the associated story. Left: IDS, Right: ASCE 7–16 scaling

A scaling procedure is accurate if the mean response obtained under the scaled ground motions is similar to the response calculated under the target spectrum, that is, the procedure is unbiased. Furthermore, it is efficient if the variability of response parameters calculated under the scaled ground motions is small. Such an assessment is more reliable when the response is linear elastic, since it is not “contaminated” by the hardly predictable spread of inelasticity during nonlinear dynamic seismic response. We prefer employing linear statistics here for assessing the mean and variance of response data, and do not resort to logarithmic parameters that compress data. Mean and standard deviations of interstory drifts are displayed in Figure 7 for the sets of unscaled and scaled ground motions. Mean response results indicate that the IDS procedure is very accurate, and the ASCE and EC8 scaling procedures are fairly accurate. However, the dispersion of interstory drift responses under the ground motions scaled by IDS is much smaller, thus confirming its effectiveness. This is an expected result indeed since the IDS procedure is based on scaling factors determined from interstory drift responses.

The bias in the scaling procedure can be calculated by correlating the interstory drift ratio at each story calculated under the scaled ground motions, with the associated interstory drift ratio calculated under the target spectrum. Two scatter graphics are prepared, and presented in Figure 8, for IDS and ASCE scaling procedures through response spectrum analysis of the linear elastic system. The red line is the linear fit to the mean IDR obtained from RSA under each scaled ground motion. When this line exactly fits to the blue line, then the scaling is unbiased, that is, the mean error is zero. Both procedures produce small biases, although the bias in IDS is much smaller. This bias is introduced by the averaging operation for maximum interstory drifts in Equation (3), and the quadratic SRSS combination of modal drifts

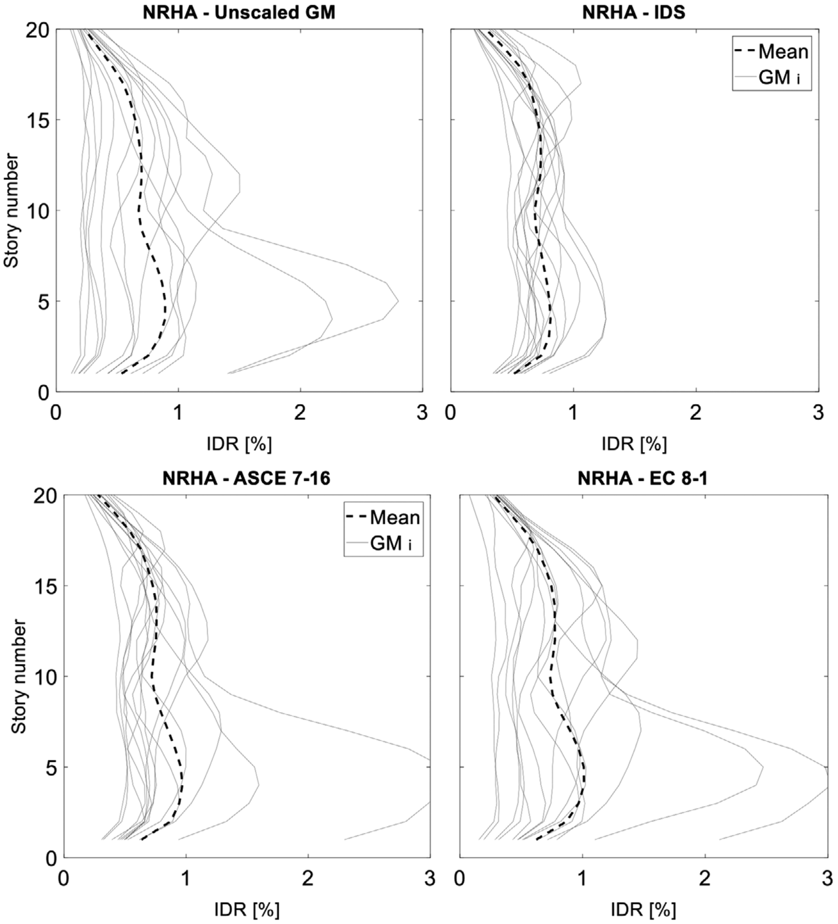

FIGURE 9 Inelastic interstory drift ratios along building height under unscaled, interstory drift scaled, ASCE 7–16 scaled and EC 8-1 scaled ground motions for matching target mean spectrum

in Equation (1). A scatter graphics for the EC8 scaling is not calculated since its bias is larger than that of ASCE scaling, which is evident in Figure 6.

The error between IDR at a given story calculated under the scaled GM's, and IDR calculated under target response spectrum is expressed by the root mean square error (RMSE), defined by S in Equation (4).

$$S = \sqrt{\frac{\sum_{n=1}^{N} \sum_{i=1}^{GM} \left(IDR_{n,i} - IDR_{n,target}\right)^2}{(NxGM)}} \tag{4}$$

Here, n is the story number, and i is the ground motion number. S values are marked at the inset of each procedure box in Figure 8. Evidently, RMSE of ASCE is 2.7 times larger than that of IDS.

5.2 | Comparison of inelastic response parameters

Inelastic response parameters are interstory drift ratios and average values of beam-end rotations in a story. Beam-end rotations are the total rotations which are the sum of elastic and plastic rotations. The distributions of inelastic drift ratios under unscaled and scaled ground motions are presented in Figure 9. As expected, dispersion increases for all ground motion sets in the case of inelastic response compared to the linear elastic response, as observed also in past research, for example,[13] However, IDS procedure still gives the least dispersion. Mean and standard deviations of interstory drift response under unscaled and scaled ground motions are shown in Figure 10. Accuracy due to scaling is not impaired much in case of inelastic response since mean profiles are still close, but standard deviations increased significantly. Yet, the dispersion under IDS ground motions is much smaller than that obtained under unscaled and ASCE scaled ground motions. It is interesting to note that ASCE scaling does not reduce dispersion when the response is inelastic. It is as inefficient as in the case where no scaling is applied.

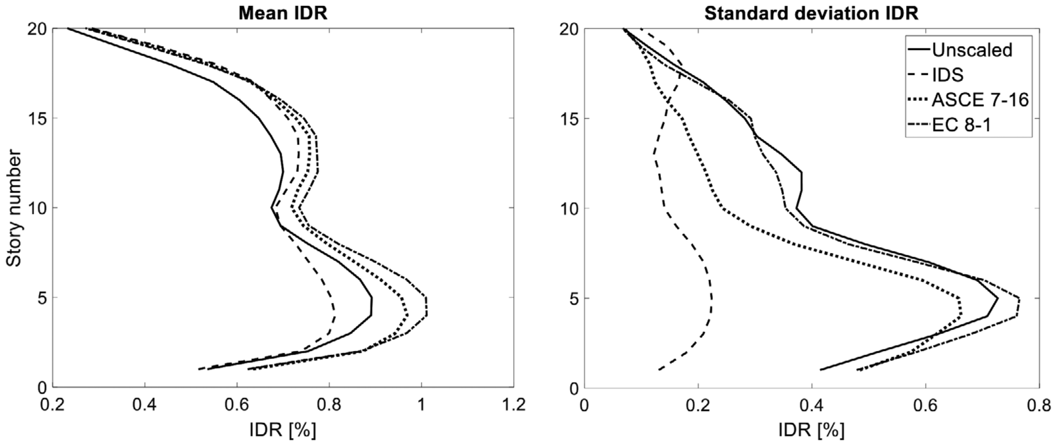

FIGURE 10 Mean and standard deviation profiles of inelastic interstory drift ratios along building height under unscaled, interstory drift scaled, ASCE 7–16 scaled and EC 8-1 scaled ground motions

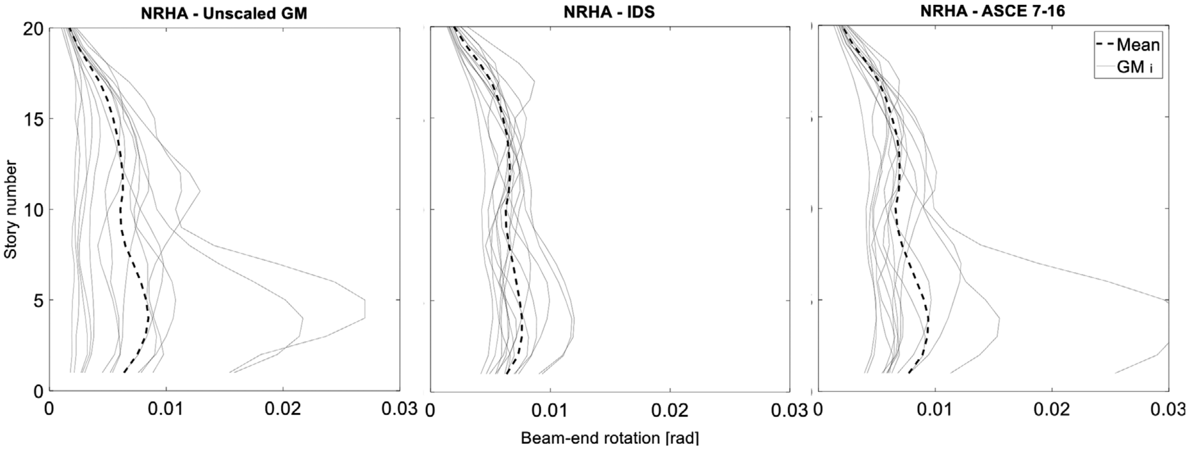

FIGURE 11 Average beam-end total rotations along building height under unscaled, interstory drift scaled, and ASCE 7–16 scaled ground motions

The distributions of average beam-end rotations are presented similarly in Figure 11. Maximum beam-end rotations are averaged along the beams of a story where the maximum rotations of beam-ends are not synchronous. Yield rotations are 0.0060 radians for the lower ten stories, and 0.0052 for the upper ten stories for all respective beam-ends. Apparently, some weak ground motions do not cause yielding at the beam ends. Some weak ground motions do not cause yielding at the beam ends. Mean and standard deviation profiles of beam-end rotations are shown in Figure 12. They are quite similar to the interstory drift distributions. The frames, designed to satisfy capacity design principles, usually display similar interstory drift and beam-end rotations under similar ground motions. This is a natural consequence of a beam response mechanism dictated by capacity design.

6 | SCALING OF GROUND MOTIONS TO MATCH THE 2475-YEAR UNIFORM HAZARD SPECTRUM

Scaling procedures are implemented to the two variants of the 20 story building frame shown in Figure 1 separately in the following sections. Only inelastic response under the scaled ground motions is considered for assessing the accuracy and efficiency of the scaling procedures. EC 8-1 scaling procedure is not further employed due to its notably lower efficiency compared to the ASCE 7–16 procedure in matching the mean spectrum of unscaled ground motions.

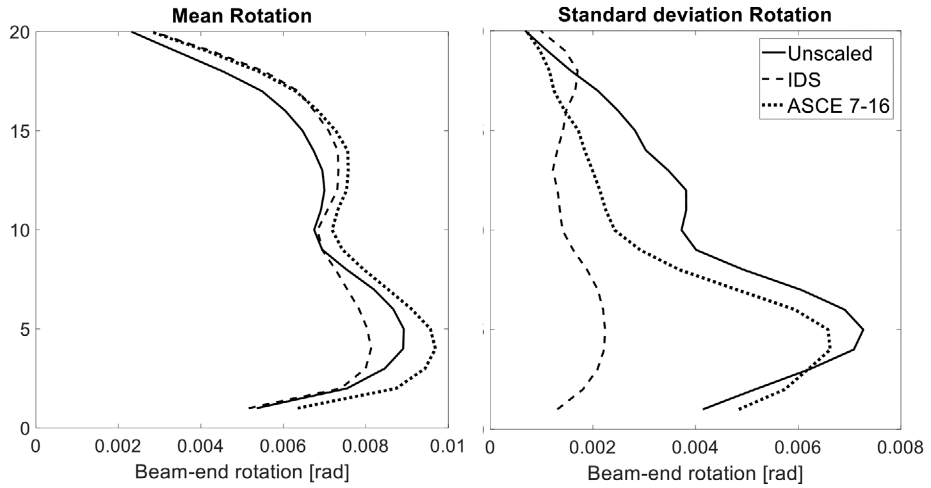

FIGURE 12 Mean and standard deviation profiles of beam-end total rotations along building height under unscaled, interstory drift scaled, and ASCE 7–16 scaled ground motions

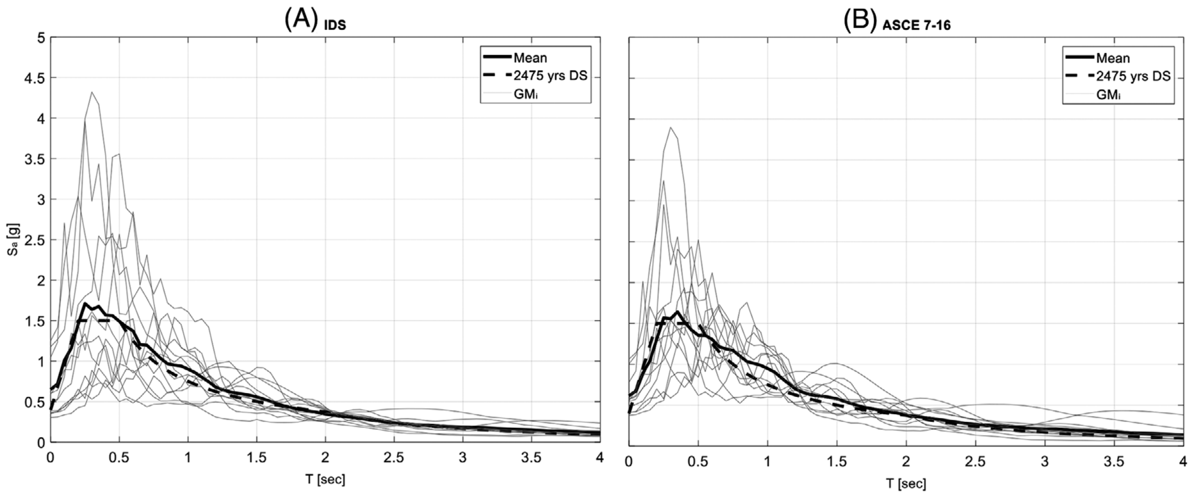

FIGURE 13 Response spectra of the scaled ground motions-2475 Year Eq. A) IDS, B) ASCE 7–16

6.1 | Comparison of inelastic response parameters: 20 story regular frame with 4 m first story height

The 2475-year uniform hazard spectrum is obtained by scaling the spectral amplitudes of the 475-year uniform hazard spectrum, presented in Figure 4 above, by 3/2. It is shown with a dashed line in Figure 13. Response spectra of the ground motions scaled by both IDS and ASCE procedures are presented in Figures 13A and B. Their mean spectra are indicated with a solid black line in the figure boxes. Mean spectra of the scaled ground motions for both procedures are again very close to each other, and very close to the target 2475-year spectrum along the entire period range.

Both sets of scale factors obtained from the two procedures are presented in Table 4 for each ground motion.

The distributions of inelastic drift ratios under scaled ground motions are presented in Figure 14. Dispersions increase again for all ground motion sets in case of inelastic response compared to the linear elastic response. However IDS procedure gives notably lower dispersion.

TABLE 4 Ground motion scale factors for matching the 2475-year uniform hazard spectrum: Regular frame

GM #	776	778	850	982	1110	1158	1184	1517	1615	1787	3746	4841	4895	5778
SF IDS	1.05	1.34	3.25	0.74	1.72	1.13	3.84	1.40	4.54	1.80	1.37	4.69	0.85	2.78
SF ASCE	1.12	1.85	3.55	0.92	1.90	1.82	3.64	1.34	4.10	1.77	1.74	3.49	0.80	2.06

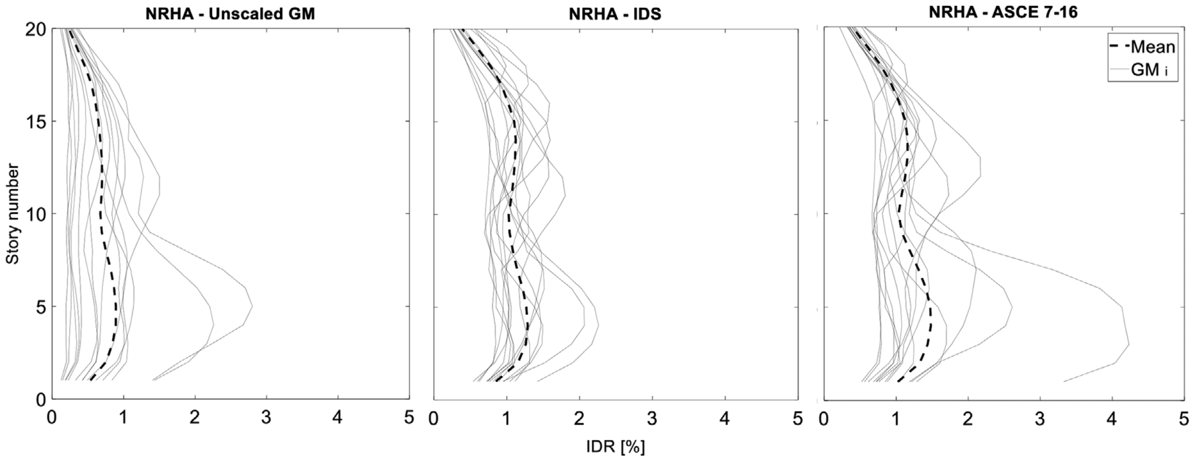

FIGURE 14 Distribution of inelastic interstory drift ratios along building height under unscaled, interstory drift scaled, and ASCE 7–16 scaled ground motions

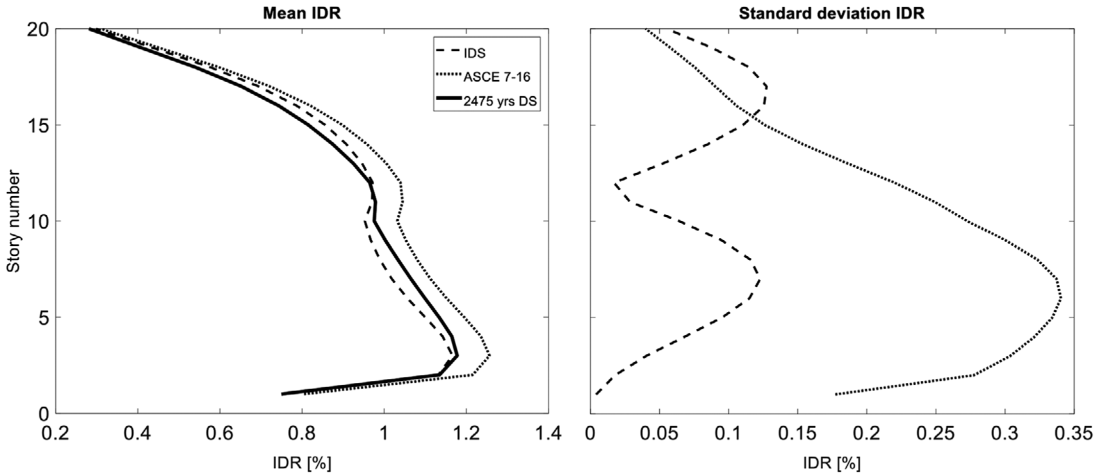

FIGURE 15 Mean and standard deviation profiles of interstory drift ratio along building height under interstory drift scaled, and ASCE 7–16 scaled ground motions

Mean and standard deviations of interstory drift response under IDS and ASCE scaled ground motions are shown in Figure 15. Mean IDR profiles of IDS and ASCE procedures are still close, but standard deviations are significantly different. The dispersion under IDS ground motions are much smaller than those obtained under the ASCE scaled ground motions.

The distributions of maximum beam-end rotations averaged along each story are presented in Figure 16, while the mean and standard deviation profiles of beam-end rotations are shown in Figure 17. These results are quite similar to those of Figures 14 and 15 in terms of dispersion.

6.2 | Comparison of inelastic response parameters: 20 story irregular frame with 5.5 m first story height

Both sets of scale factors obtained from the two procedures are listed in Table 5 for each ground motion, and the response spectra of ground motions scaled by IDS and ASCE procedures are shown respectively in Figure 18A and B.

The distributions of inelastic drift ratios under IDS and ASCE scaled ground motions are presented in Figure 19. When compared with the associated Figure 14 for the regular frame, soft story formation is evident under two unscaled ground

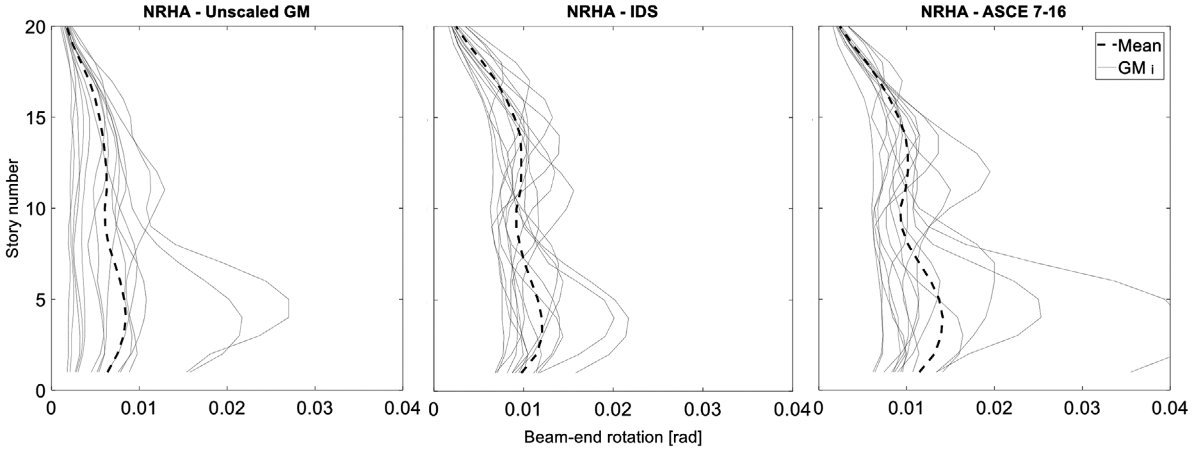

FIGURE 16 Distribution of average beam-end total rotations along building height under unscaled, interstory drift scaled, and ASCE 7–16 scaled ground motions

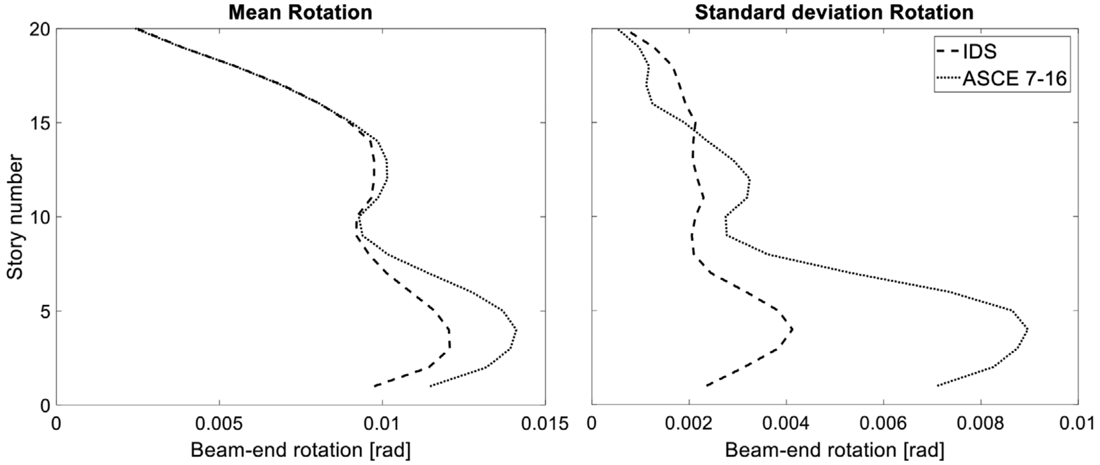

FIGURE 17 Mean and standard deviation profiles of beam-end total rotations along building height under, interstory drift scaled, and ASCE 7–16 scaled ground motions

motions, 982 and 1158. IDS reduces the first story drifts of the irregular frame under both of these ground motions, but the frame approaches soft story collapse under the ASCE scaled ground motion 1158.

Mean and standard deviations of interstory drift response under IDS and ASCE scaled ground motions are shown in Figure 20. Mean IDR profiles of IDS and ASCE procedures are still close, but standard deviations are particularly different at the lower stories. Comparison of these standard deviation profiles with those of the regular frame in Figure 15 is informative. Although the dispersions of interstory drifts from both IDS and ASCE increase at lower stories of the irregular frame, they decrease at the upper stories. Soft story response of the first story in the irregular frame serves as an isolation story, hence reduces the response of upper stories under both sets of scaled ground motions and brings them closer.

The distributions of maximum beam-end rotations averaged along each story are presented in Figure 21. These results resemble those of IDR in Figure 19 in terms of dispersion, hence their statistical parameters are quite similar.

TABLE 5 Ground motion scale factors for matching the 2475-year uniform hazard spectrum: Irregular frame

GM #	776	778	850	982	1110	1158	1184	1517	1615	1787	3746	4841	4895	5778
SF IDS	1.02	1.43	3.87	0.50	1.32	0.95	3.97	1.23	5.81	2.00	1.39	3.66	0.83	2.30
SF ASCE	0.95	1.54	3.03	0.71	1.60	1.47	3.54	1.15	4.07	1.67	1.52	3.29	0.73	1.82

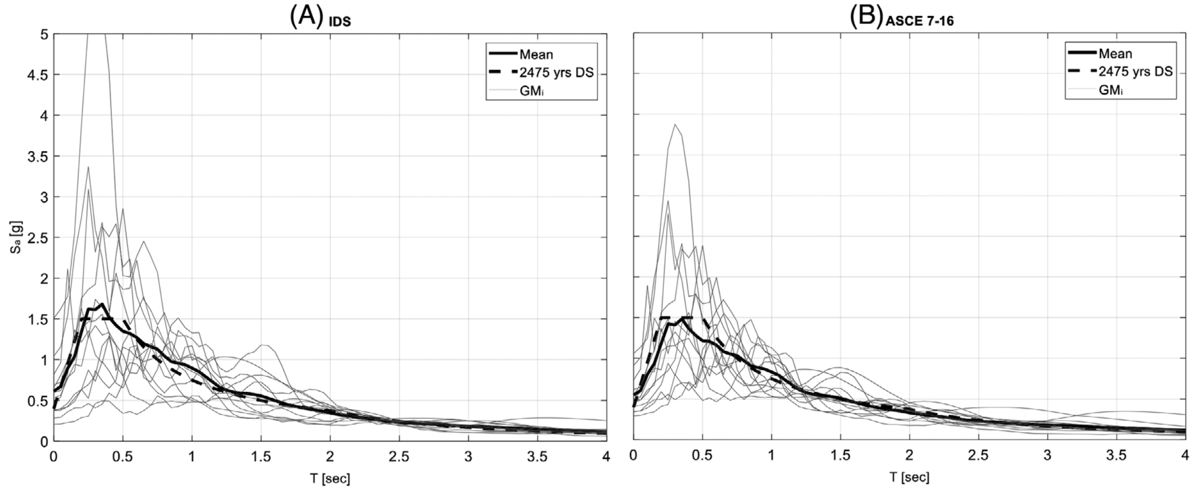

FIGURE 18 Response spectra of the scaled ground motions-2475 Year EQ, H1 = 5.5 m. (A) IDS, (B) ASCE 7–16

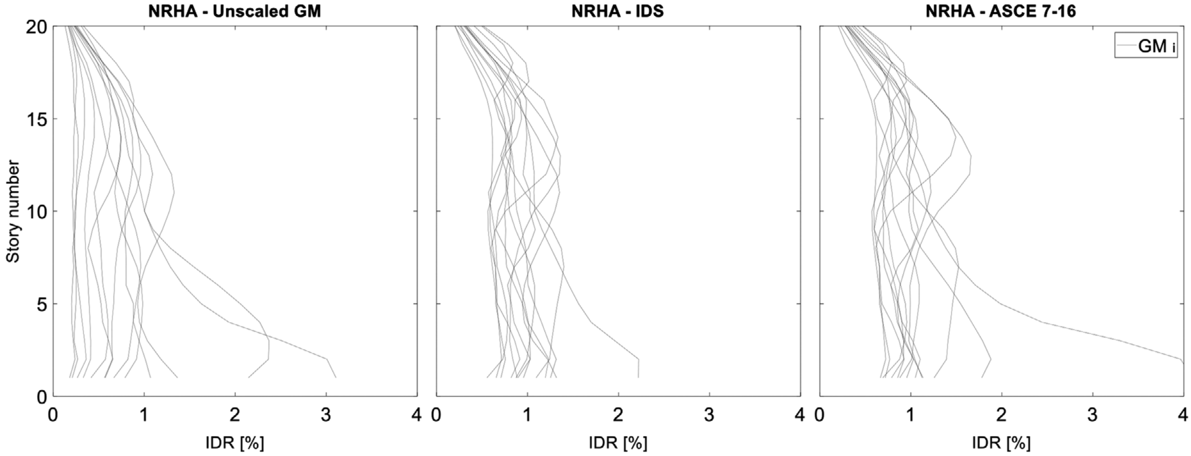

FIGURE 19 Distribution of inelastic interstory drift ratios along building height under unscaled, interstory drift scaled, and ASCE 7–16 scaled ground motions

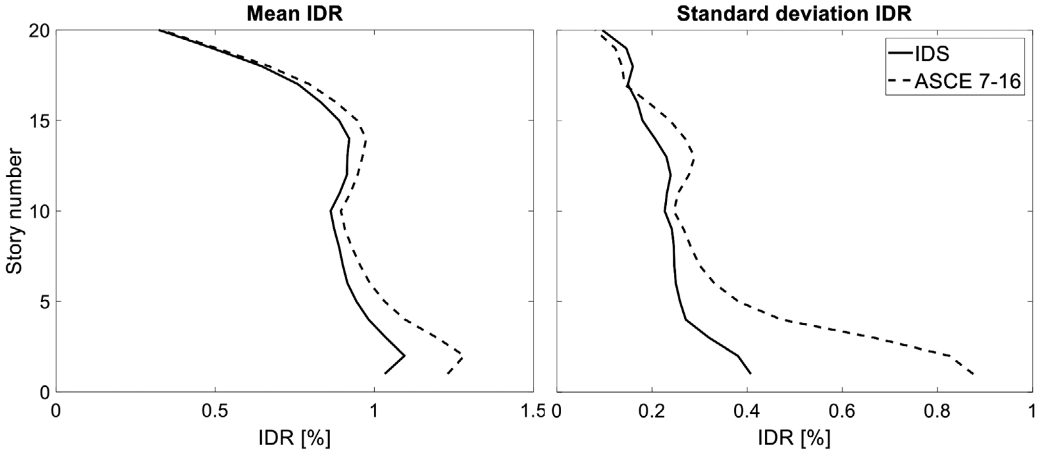

FIGURE 20 Mean and standard deviation profiles of interstory drift ratio along building height under interstory drift scaled and ASCE 7–16 scaled ground motions

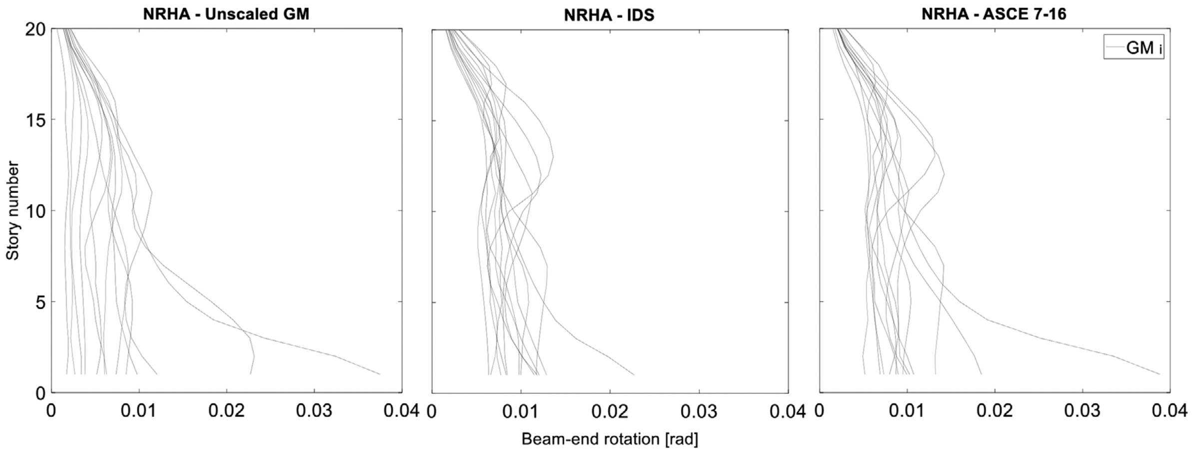

FIGURE 21 Distribution of average beam-end total rotations along building height under unscaled, interstory drift scaled, and ASCE 7–16 scaled ground motions

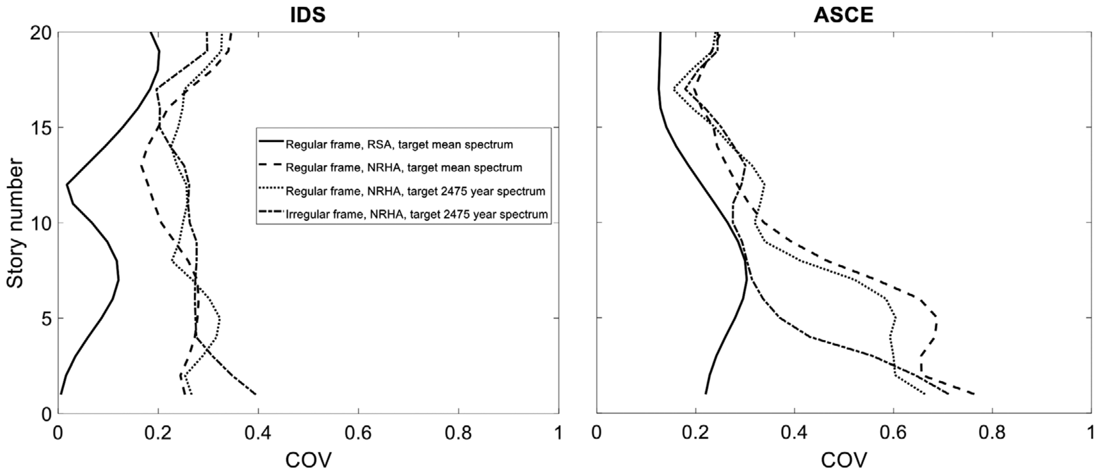

FIGURE 22 Coefficient of variation (COV) profiles of interstory drift ratio along building height under interstory drift scaled and ASCE 7–16 scaled ground motions

7 | ASSESSMENT OF SCALING PROCEDURES

Efficiency of ground motion scaling procedures where the scaling factors are calibrated based on linear elastic response are likely to be affected from the nonlinear seismic response of the object structure under scaled ground motions. Lengthening of modal vibration periods due to inelastic response is somehow accounted for indirectly in the ASCE 7–16 procedure by performing scaling along a wide period range. IDS scaling however is precisely based on the modal periods. Empirical relations can be employed for predicting the lengthening of modal periods due to inelastic response.[30] These relations however are derived for the mean values of inelastic (effective)-to-elastic periods of single degree of freedom systems under large number of ground motions. Since IDS is performed on single ground motions, lengthening of modal periods improve the scale factors for some ground motions whereas it worsens for some others. They eventually even out for the considered ground motion set.

Dispersion, which is the measure of efficiency, can be most objectively quantified by the coefficient of variation (COV), that is, the ratio of standard deviation to the mean value of data. COV is calculated for the interstory drift ratio at each story under each ground motion scaled with the IDS and ASCE procedures. The respective COV profiles are displayed in Figure 22 for the four cases studied herein:

(i) Regular frame, RSA under ground motions scaled to target mean spectrum,
(ii) Regular frame, NRHA under ground motions scaled to target mean spectrum,

(iii) Regular frame, NRHA under ground motions scaled to target 2475 year spectrum,
(iv) Irregular frame, NRHA under ground motions scaled to target 2475 year spectrum.

7.1 | The effect of inelastic response on response dispersion

Inelastic deformations increase locally or globally from case (i) to (iv). In case (i) which is performed with RSA, the COV's of IDS are much smaller than those of ASCE, particularly at the lower half of the building. These variations are inevitable even for linear elastic response since modal responses to scaled ground accelerations scale differently depending on the modal frequencies and damping ratios.[31]

There is a significant increase in the COV's of both scaling procedures as the analysis method changes from RSA in case (i) to NRHA in cases (ii-iv). Both procedures however are not significantly affected from the level of nonlinearity in these three cases. Distribution of COV is fairly uniform along the building height, around 0.25 under IDS ground motions whereas it increases from about 0.25 at the top towards 0.70 at the bottom stories under ASCE scaled ground motions.

7.2 | Limitations of scaling procedures

Limitations to ground motion scaling are generally suggested in terms of scale factors. It is advised by common sense that upward scaling factors should not depart from 1.0 significantly, because ground motions scaled with large factors would not represent the seismotectonic characteristics of the site as good as the initially selected, unscaled ground motions. A similar condition is also valid for downward scaling although ground motion scaling is usually implemented upward in practice. A practical limitation to scale factors is not easy to propose since they are case specific. Although the fourteen ground motions employed in this study represent similar seismic environment in terms of magnitude, distance and soil type, their range in Table 5 varies from 0.5 to 5.8. On the other hand, ground motions scaled with modest scale factors in the set such as those of 1158 in Table 5 may bring the system to the verge of collapse. Eliminating them from the selected set for reducing response dispersion is not reasonable because they are actually more valuable for identifying the weaknesses of the investigated structure.

The sole purpose of ground motion scaling is to bring them to a target intensity level. Spectral intensity which is employed as the common intensity measure for ground motion scaling in the Codes may not be the ideal intensity measure however. Interstory drift based scale factors proposed herein are in fact indirect intensity measures which are theoretically related with the spectral intensities. This refinement makes the interstory drift based scaling more reliable compared to direct scaling to match target spectral intensities.

8 | CONCLUSIONS

A simple interstory drift-based scaling procedure is presented in this study. The proposed methodology only requires linear elastic response spectrum analysis of a structure under both the target spectrum and the response spectra of unscaled ground motions. No further post processing is required other than calculating the ratios of interstory drifts obtained under the target spectrum and under the response spectrum of individual, unscaled ground motions. The introduced scaling procedure is implemented to the two variants of a 20-story plane frame for which the contribution of higher modes is significant. Accuracy and efficiency of the IDS procedure is assessed under a set of strong motions from large magnitude events. The results revealed that the proposed procedure is accurate and noticeably more efficient as compared to the conventional procedures suggested in recent seismic codes and in recent literature. Ultimate simplicity, accuracy and efficiency of the IDS procedure is believed to make it an attractive choice in ground motion scaling. Implementation of IDS to unsymmetrical-plan 3D structures is relatively straightforward, which is currently in progress. The main focus of this study is introducing the basic concept of interstory drift based scaling procedure and presenting its benefits as well as limitations.

DATA AVAILABILITY STATEMENT

Data available on request from the authors

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