DEVELOPMENT AND EVALUATION OF GROUND MOTION INTENSITIES FOR RECORD SELECTION AND SCALING FOR RESPONSE HISTORY ANALYSES

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Abstract

This study evaluates several possible parameters used to quantify the intensity of grouns motions and its correlation with strong nonlinear structural response and collapse. In particular, it compares the dispersion of structural collapse capacities obtained using four different ground motion intensity measures (IMs): (1) $Sa(T_1)$; (2) $Sa(T_1)$ adjusted using ε; (3) an IM consisting spectral acceleration averaged over a period range (Sa_{avg}); and (4) a new IM termed filtered incremental velocity (*FIV*). Results suggest that $Sa(T_1)$ is the least efficient IM whereas Sa_{avg} and *FIV* are the best IM parameters. Additionally, this paper investigates the influence that record scaling has on estimating probabilities of collapse of SDOF and MDOF systems. Results suggest that a systematic bias is introduced by scaling ground motions and that the bias is strongly dependent on the period of vibration and the lateral strength of the system.

Introduction

The use of nonlinear response history analyses is starting to become more common in structural engineering practice due to the adoption of Performance Based Earthquake Engineering, PBEE. This type of analysis is believed to be the most reliable analytical tool to estimate the seismic performance of a structure.

The process of selection and scaling of ground motions using an intensity measure (IM) is of paramount importance as it will influence the accuracy with which the structural response is estimated. Even when some guidelines suggested to assemble a ground motion set using records with causal parameters that are consistent with those that control the desired design spectrum, early studies conducted by Prof. Cornell and his students (Bazzurro and Cornell 1994, 2002; Bazzurro et al. 1998; Jalayer and Cornell, 2003; Luco and Cornell, 2007; Shome et al., 1998) pointed out that selecting records based on causal parameters requires a very large number of ground motions in order to provide adequate results. The reason behind this is the associated significant record-to-record variability in the structural response. Therefore, they proposed to use the five percent damped spectral acceleration at the fundamental period of the structure, $Sa(T_1)$, as the IM and to scale the records to the same spectral ordinate when computing the structural response. By following this procedure, they observed a reduction in record-to-record variability and, therefore, reduced the number of ground motions required to achieve a certain level of error in the estimate of the response. After analyzing a couple multiple-degree-of-freedom (MDOF) structures, they noted that scaling records to the same value of $Sa(T_1)$ lead to an average reduction of 40% in the dispersion of peak interstory drift ratios when compared to the results obtained from records selected based on a relatively narrow range of M_w and source-to-site distances.

One important shortcoming of the use of $Sa(T_1)$ as the intensity measure is that its efficiency rapidly decreases as the level of nonlinearity in the structure increases. Thus, several researchers have proposed alternative IMs. For example, Baker and Cornell (2005) proposed the use of a vector IM that consists of $Sa(T_1)$ and the ground motion parameter ε. The ground motion parameter ε is defined as the number of logarithmic standard deviations a pseudo acceleration spectral ordinate of ground motion deviates from the median ordinate predicted by a ground motion prediction equation (GMPE). They observed that ε could be used as a *proxy* to the spectral shape and when used together with $Sa(T_1)$ it could lead to an improved estimate of the seismic response of a structure.

Taking advantage of the bias reduction in structural responses that is obtained when ε is considered. Haselton et al. (2009) proposed a simplified procedure for correcting the collapse capacity of a structure when the spectral shape is not considered in the selection of the records by applying an ε-dependent correction factor. Their method uses a general ground-motion set, selected without regard to ε values, and then corrects the calculated structural response distribution to account for the mean ε expected for the specific site and hazard level. This procedure, which has now also been incorporated into the ATC-63 project and the FEMA P-695 document (FEMA, 2009), avoids having to consider the joint probability distribution of $Sa(T_1)$ and ε. Unfortunately, the procedure focuses on correcting the bias and not in the reduction of the variability/dispersion of the collapse intensities. As a matter of fact, and contrary to popular belief, considering ε does very little in terms of reducing the record-to-record variability and therefore the vector IM consisting on $Sa(T_1)$ and ε remains *a relatively inefficient intensity measure*. This means that it does not lead to a significant reduction in dispersion and hence, although it corrects the bias, it still requires a large number of response history analyses in order to estimate the response of the structure with an acceptable level of confidence.

The reason why the consideration of ε does not lead to a significant reduction in dispersion is because ε is not a direct measure of spectral shape but only a proxy as a single spectral ordinate relative to the intensity measured by a ground motion prediction model cannot provide a measure of spectral shape. Moreover, several studies have shown that ε is ineffective in accounting for spectral shape in the case of near-fault pulse-like ground motions (Baker and Cornell, 2008; Bojorquez and Iervolino 2011). In fact, Haselton et al. (2009) when proposing their approximate method to consider the effect of ε explicitly wrote in their paper: "*the approach proposed in this paper should not be applied to near-fault motions with large forward-directivity velocity pulses*". This is very important because this type of ground motions is precisely the one that is more likely to produce the collapse of structures.

As clearly demonstrated by Shome et al. (1998), having an intensity measure that is strongly correlated with strong nonlinear deformations and collapse of structures has enormous practical consequences for structural engineers. Namely, the level of record-to-record variability achieved in the level of structural response is related to the number of records that the engineer must use for obtaining a reliable estimate of the structural response. In particular they noted the required number of ground motions, n, required to estimate the median structural response within a factor of X (e.g., $\pm$ 0.1) with 95% confidence would be given by

$$n = 4\left(\frac{\beta}{X}\right)^2 \tag{1}$$

where β is the level of dispersion in the response when using a certain intensity measure IM expressed as the logarithmic standard deviation. From this equation it can be seen that for the same level of desired accuracy, the reduction in the necessary ground motions is proportional *to the square* of the reduction in dispersion. This is extremely important because there is a considerable computational effort involved in each nonlinear response history analysis.

Besides analyzing the efficiency of *Sa* and $Sa(T_1)+\varepsilon$, in this study we propose a couple of new intensity measures. The first one is called Sa_{avg} which is based on averaged spectral accelerations but taking into account spectral ordinates that correspond to periods that are both shorter and longer than the fundamental period of the structure. The second IM is termed *FIV* and is based on a period-dependent version of the incremental velocity (IV) originally proposed by Anderson and Bertero (1985). Note that this new IM is not based on the concept of spectral shape but rather on time-domain features of a ground motion.

The objectives of this study are: (1) the assessment of current and recently proposed intensity measures that are well correlated with strong nonlinear behavior and the collapse of structures. In particular, the proposed study develops a new ground motion intensity measure (IM) that has a better correlation with large inelastic deformations in structures and with collapse than the correlation provided by intensity measures being used today, namely, $Sa(T_1)$, or the more recently proposed vector IM consisting of $Sa(T_1)$ and ε; and (2) the evaluation of scaling bias using $Sa(T_1)$ in structural response of degrading systems, specially focusing in the estimation of the probability of collapse of a structure. In case a bias is introduced, this study will identify the situations in which it is more critical and the use of scale factors should be limited.

Structural Model and Ground Motion Records for the Efficiency Evaluation

MDOF system

The structure used in this study is a four-story steel special moment frame building with reduced beam sections designed by Lignos et al. (2012) according to the 2003 International Building Code and the 2005 AISC seismic provisions. The design base shear coefficient is V/W = 0.082. The first three modal periods of the structure are T_1 = 1.33s, T_2 = 0.43s and T_3 = 0.22.

The nonlinear behavior of the structure is characterized by concentrated plasticity elements at the ends of beams and columns whose hysteretic behavior is governed by a bilinear response with a modified version of the Ibarra-Medina-Krawinkler (IMK) deterioration model calibrated for steel moment frame structures (Ibarra et al. 2005, Lignos et al. 2010). All the nonlinear analyses are conducted using OpenSees (McKenna 2009).

Ground motion records

The ground motions were selected from the Center for Engineering Strong Motion Data (strongmotioncenter.org) and the PEER Next Generation Attenuation NGA2 database (Ancheta et al. 2014) without any special consideration on spectral shapes. The 265 selected records have magnitudes varying between 6.93 and 7.62, while the Joyner-Boore distance range is between 0 and 27km, and correspond to recordings from stations located on NEHRP site class C or D.

The ground motion set used in this study is a subset of the *MRCD137* set used by Eads et al. (2014) but some records were excluded when the scale factors that were required to trigger collapse exceeded a value of 20. Additionally, the two components of the Lamont 375 Station during the 1999 Duzce earthquake were also excluded due to extremely unusual high-frequency content. For the complete list and main information of the records used, the reader is referred to the final report of this project in the SMIP17 seminar webpage or Eads et al. (2014).

Structural Model and Ground Motion Records for the Scaling Factor Bias Evaluation

SDOF systems

Two 5%-damped SDOF systems with -3% postelastic stiffnesses were used in the analyses. The short period SDOF corresponded to a system with a period of vibration of 0.25s and the long period system corresponded to an SDOF with a period of 1.50s.

The lateral strength was varied using strength reduction factors, R, defined as

$$R = \frac{m \cdot S_a}{F_y} \tag{2}$$

where m is the mass of the system, F_y is its lateral yielding strength and S_a is the pseudo acceleration spectral ordinate. Depending on the SDOF, R factors ranged between 1.5 and 6.

MDOF systems

This study considers two MDOF systems whose structural system consists of reinforced concrete (RC) special moment frames (SMF) designed by Haselton and Deierlein (2007a). The first MDOF is a two-story building with a fundamental period of vibration T_1 = 0.63s and the second is a four-story building with a fundamental period of vibration T_1 = 1.12s. For detailed description of the design of these structures the reader is referred to Haselton et al. (2007a).

The hysteretic behavior of the ends of the beam and column connections is governed by a modified Ibarra-Medina-Krawinkler model calibrated for RC structures (Ibarra et al., 2005, Haselton et al., 2007b). All the analyses were conducted using OpenSees (McKenna 2009).

Ground motion records

The ground motions used were also selected from strongmotioncenter.org and the PEER Next Generation Attenuation NGA2 database (Ancheta et al. 2013).

SDOF systems

For each SDOF system under study, two sets of 30 ground motions were assembled depending on the scale factors that were needed to reach the intensity of the target spectrum.

This target spectrum corresponds to the MCE level from a NEHRP site class C location in downtown Palo Alto, CA (37.452°N, -122.151°W).

The first set, Set A, corresponds to ground motions whose pseudo acceleration spectral ordinate is similar to that of the target scenario, that is, the scale factors required to reach the target intensity are between 0.5 and 1.5. This set will be also called "unscaled set" and will be used as the benchmark set. The second set, Set B, corresponds to ground motions whose pseudo acceleration spectral ordinate has a value in the neighborhood of 1/10 of the spectral ordinate of the target scenario such that the scale factors required for these records to reach the target intensity are between 7.5 and 12.5. This set will be also called "scaled set".

MDOF systems

For each MDOF system under study, three sets of 50 ground motions were assembled depending on the scale factors that were needed to reach the intensity at the fundamental period of vibration of the MDOF of the same target spectrum used for the SDOF systems.

The first set, Set A, corresponds to ground motions whose pseudo acceleration spectral ordinate is similar to that of the target scenario, that is, the scale factors required to reach the target intensity are between 0.5 and 1.5. This set will be also called "unscaled set" and will be used as the benchmark set. The second set, corresponds to ground motions whose pseudo acceleration spectral ordinate has a value in the neighborhood of 1/5 of the spectral ordinate of the target scenario such that the scale factors required for these records to reach the target intensity are between 4.5 and 5.5. This set is called Set B. Finally, the third set corresponds to ground motions whose pseudo acceleration spectral ordinate has a value in the neighborhood of 1/10 of the spectral ordinate of the target scenario such that the scale factors required for these records to reach the target intensity are between 9.5 and 10.5. This set is called Set C.

For the complete list and main information of all the records used for each SDOF and MDOF systems, the reader is referred to the final report of this project in the SMIP17 seminar webpage.

Ground Motion Intensity Measures

This section evaluates the dispersion on the collapse intensities of the four-story steel structure subjected to the 265 ground motion records using different intensity measures. The intensity measures that will be considered are:

a) $Sa(T_1)$
b) $Sa(T_1)$ combined with the correction using spectral shape proxy ε
c) $Sa_{avg}(T_1)$ as proposed by Eads et al. (2015).
d) A newly developed intensity measure called *FIV3*.

The efficiency of the IMs, defined as the level of variability in the structural responses from a set of records having the same intensity level (Luco and Cornell, 2007), will be evaluated by comparing the logarithmic standard deviation, σ_{lnIM} of the estimated collapse intensities.

Sa(T₁)

Given that the most commonly used intensity measure is *Sa*(T_1), we first proceeded to compute the collapse capacities of the structure using this IM. Figure 1 shows the spectral acceleration *Sa*(T_1) by which 265 earthquake ground motions need to be scaled to in order to produce the collapse of the structure. It can be seen that the ground motions intensities, when characterized by *Sa*(T_1), exhibit a very large record-to-record variability with some ground motions producing the collapse of the structure when the record is scaled to a spectral ordinate of 0.51g at T_1 = 1.33s while others need to be scaled to spectral ordinates as large as 3.25g to produce the collapse of the structure. Also shown in the figure is the median collapse intensity which for this structure is 1.0g, the 5 percentile (ground motion intensity at which only 5% of the ground motions produce collapse in the structure) and 95 percentile (ground motion intensity at which 95% of the ground motions produce collapse). In this case the intensity corresponding to the 95 percentile (2.41g) is 4.47 times larger than the intensity corresponding to the 5 percentile (0.54g) indicating a large variability of the ground motion intensity required to produce collapse. The corresponding logarithmic standard deviation, σ_{LnSa} , equals to 0.39. This figure demonstrates the high variability that exists when one is trying to characterize the collapse potential of the structure under a large set of ground motions using a relatively inefficient intensity measure such as *Sa*(T_1).

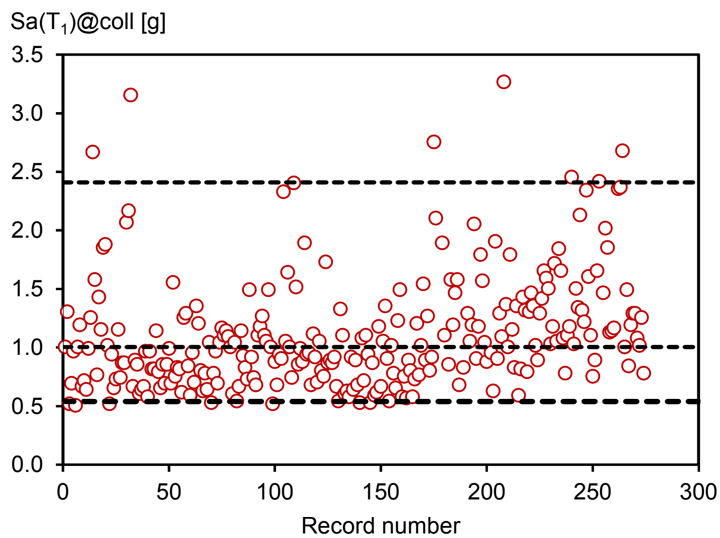

Figure 1. Spectral accelerations at the fundamental period of vibration, Sa(T_1), by which the ground motions need to be scaled to in order to produce the collapse.

Sa(T₁)* corrected by *ε

Figure 2 presents a plot of the natural logarithm of the *Sa*(T_1) by which the 265 earthquake ground motions need to be scaled to in order to produce the collapse of the building under study as a function of the corresponding ε values. Also shown in the figure is a linear fit regressed to the data. As illustrated in the figure, and as previously noted by Baker and Cornell (2005), the collapse intensity tends to increase as the ε value increases.

The collapse intensities measured using *Sa(T1)* were corrected by applying the procedure proposed by Haselton et al. (2009) to account for the effect of ε. This procedure consists in decreasing the intensity producing collapse for records with ε*'s* larger than the target ε and by increasing the intensity producing collapse for records with ε*'s* smaller than the target ε. For this structure designed for a site in Los Angeles, the target ε equals 1.8 (Eads et al., 2014) and it corresponds to the ground motion intensity that has the highest contribution to the mean annual frequency of collapse computed via a collapse deaggregation. Please note that instead of using the Haselton et al. generic slope recommendation that is based on their buildings, here we apply the slope that is specific to this structure.

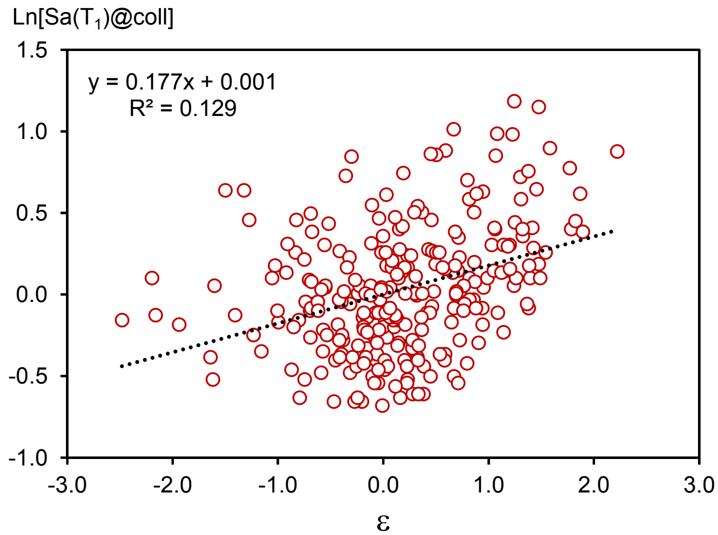

Figure 2. Natural logarithm of the spectral accelerations at the fundamental period of vibration, Sa(T_1), by which the ground motions need to be scaled to in order to produce the collapse plotted as a function of the ε of each record.

The corrected collapse intensities as a function of ε are presented in figure 3. As expected, the bias (the slope of the linear trend) has now been fully eliminated, but a large dispersion remains. Again 5, 50, and 95 percentiles, which are 0.74g, 1.34g, and 3.03g, respectively, are also plotted in the figure with horizontal dashed lines. By comparing figures 1 and 3 it can be seen that, as previously mentioned, considering ε can correct the bias in the median collapse capacity but does not lead to a significant reduction in dispersion. As a matter of fact, for this structure the ratio of corrected collapse intensities corresponding to 95 percentile to 5 percentile equals to 4.1 which is slightly smaller than the ratio of the two percentiles prior to correction for ε which was 4.47. The corresponding logarithmic standard deviation does reduce after the correction is applied to consider the effect of ε, but the reduction is minimal as it only reduces from 0.39 to 0.36. This corresponds to a reduction of approximately 6.6%.

From this results it is seen that while the vector IM comprised by $Sa(T_1)$ and ε can potentially eliminate the bias in the estimation of the median collapse capacity of the structure, it does not lead to a significant reduction in record-to-record variability/dispersion which is a desirable characteristic when nonlinear time history analyses are to be conducted.

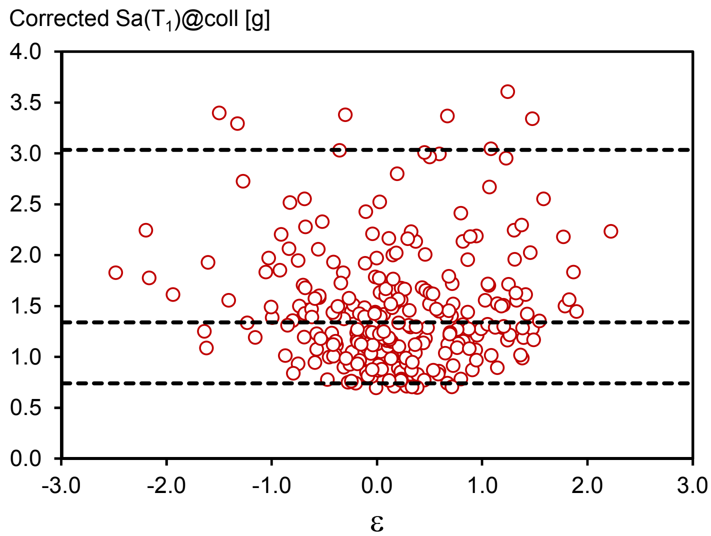

Figure 3. Spectral accelerations that produce collapse in the four-story steel building after correction to take into account the target ε of each record.

Sa_{avg}

The general idea of considering spectral ordinates in a range of periods as a way to measure the damaging potential of an earthquake can be traced back almost a century. Studies conducted by Benioff (1934) and Housner (1952) can be thought as early attempts to consider spectral ordinates from a wide range of periods as an intensity measure.

To the best of our knowledge, Kennedy et al. (1984) conducted the first study that recommended to use a period-dependent range in the averaging of spectral ordinates. They considered the average spectral value between the fundamental period of vibration of the structure (T_1) and a lengthened period. In their study, they noted that the relationship between this average value and the value of $Sa(T_1)$ had an important influence in the nonlinear response of structures. They actually observed a reduction in the variability of their results, which they attributed to the smoothing effect of averaging compared to the use of a single ordinate. More recently, several researchers (e.g. Bianchinni et al. (2009), Bojórquez and Iervolino (2010, 2011), Tsantaki et al. (2012), DeBiasio et al. 2014) have evaluated different pseudo-acceleration averaging schemes focusing on ranges between T_1 and a lengthened period based on the assumption that as the structure degrades, the period of vibration increases. All these studies found a reduction in the dispersion of structural responses when compared to $Sa(T_1)$.

Eads et al. (2014; 2015) were the first studies that recommended to consider periods shorter than T_1 in the averaging range of spectral ordinates. They proposed to use the geometric mean of Sa ordinates between $[0.2{\cdot}T_1 - 3{\cdot}T_1]$ based on the fact that pulses in the ground motion control the spectral shape of the spectrum at both sides of T_1. This report uses the Sa_{avg} definition proposed by Eads et al. (2015) to evaluate the collapse intensities of the four-story steel structure under study.

Results in figure 3 show the 265 Sa_{avg} values that produce the collapse of the four-story steel MRF structure. The 5, 50 and 95 percentiles, which are 0.49g, 0.70g and 1.08g, respectively, are also plotted in the figure with horizontal dashed lines. By comparing the record-to-record variability in this figure with that in figures 1, 5, 9, 13, and 17, it can be seen that a significant reduction in dispersion is produced when using the proposed IM. In this case the ratio of the collapse intensities corresponding to 95 percentile to 5 percentile is now 2.21 while this ratio was 4.47 for the case in which $Sa(T_1)$ alone was used as an IM or 4.10 when the vector IM comprised on $Sa(T_1)$ and ε was used. The corresponding logarithmic standard deviation for the proposed scalar IM is 0.21 which is 45% smaller and 41% smaller than the case in which $Sa(T_1)$ alone was used and when $Sa(T_1) + \varepsilon$ was used, respectively. These reductions in dispersion mean that for the same level of confidence in the structural response, one needs to use approximately 31% to 35% of the number of records that would be required when using $Sa(T_1)$ and $Sa(T_1)$ and the correction using ε, respectively.

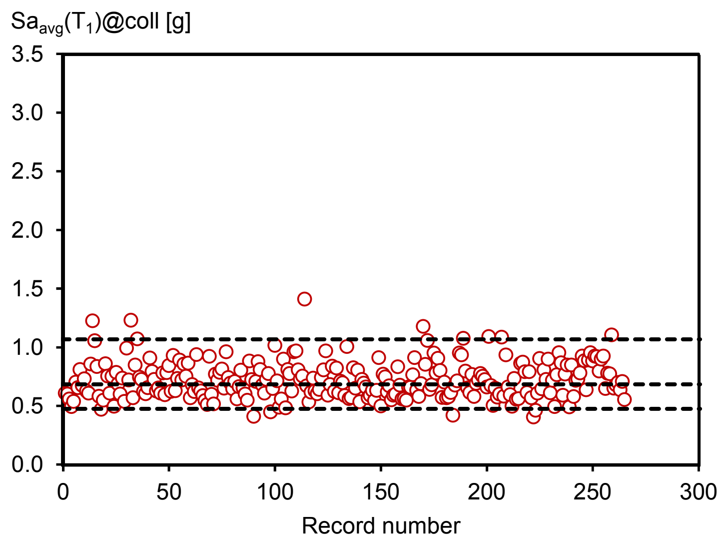

Figure 3. Sa_{avg} intensities by which the ground motions need to be scaled to in order to produce the collapse of the four-story steel structure.

FIV

The filtered incremental velocity, *FIV*, is also based on the concept of incremental velocity, but instead of just focusing on acceleration pulses with large areas, *FIV* is a period dependent intensity measure, hence capturing different intensities for structures with different periods of vibration. The fact that this IM is period dependent and computed from a filtered time acceleration time series aids *FIV* in capturing in a better way damaging pulses for different structures as it focuses on pulses with durations that can induce large inelastic incursions in the structure and disregard high frequency spikes that, depending on the fundamental period of vibration, the structure might not significantly respond to. Moreover, instead of considering only the period-dependent acceleration pulse segment with the largest area, *FIV* considers several pulse segments in the same side of the accelerogram that have the largest area and therefore are more related to large inelastic excursions and structural collapse. Note that *FIV* does not exactly capture the complete damaging acceleration pulses but rather attempts to capture damaging pulse segments. The parameters of *FIV* were determined after several iterations considering variations on the time duration used in the area summation, the number of pulses, and the type and order of the filter.

Figure 4 presents the *FIV* collapse capacities computed. The dashed lines represent the 5, 50, and 95 percentiles with correspond to 253.9cm/s, 359.6cm/s, and 567.8cm/s, respectively. The ratio of the collapse intensities corresponding to 95 percentile to 5 percentile for *FIV3* is 2.23 and the corresponding logarithmic standard deviation for the proposed scalar IM is 0.20 which is 47% smaller and 44% smaller than the case in which $Sa(T_1)$ alone was used and when $Sa(T_1) + \varepsilon$ was used, respectively. Reductions in the logarithmic standard deviation of *FIV* with respect the one computed using $Sa(T_1)$ and $Sa(T_1) + \varepsilon$ mean that by using *FIV*, one needs to use approximately only 27% to 31% of the number of records that would be required when using currently recommended IMs in order to achieve the same level of confidence.

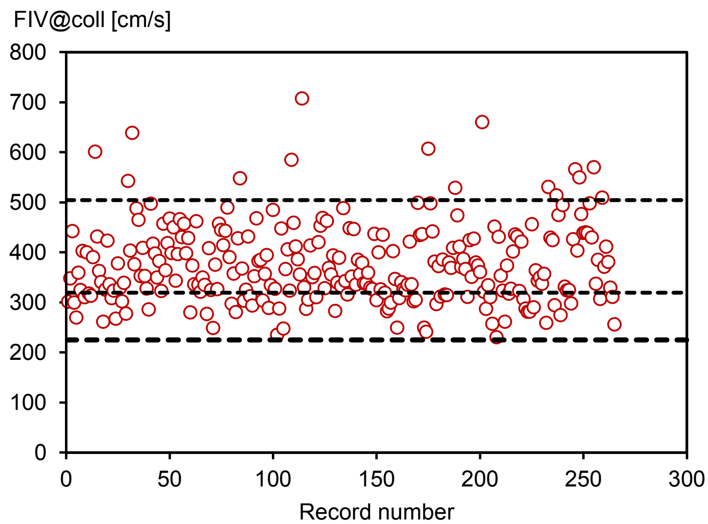

Figure 4. FIV intensities by which the ground motions need to be scaled to in order to produce the collapse of the four-story steel structure.

Figure 5 presents the normalized collapse capacities using $Sa(T_1)$, $Sa(T_1)$ adjusted by considering the spectral shape proxy ε, using Sa_{avg}, and using *FIV*. As it has been mentioned, the reduction in dispersion achieved by either Sa_{avg} or *FIV* is remarkable.

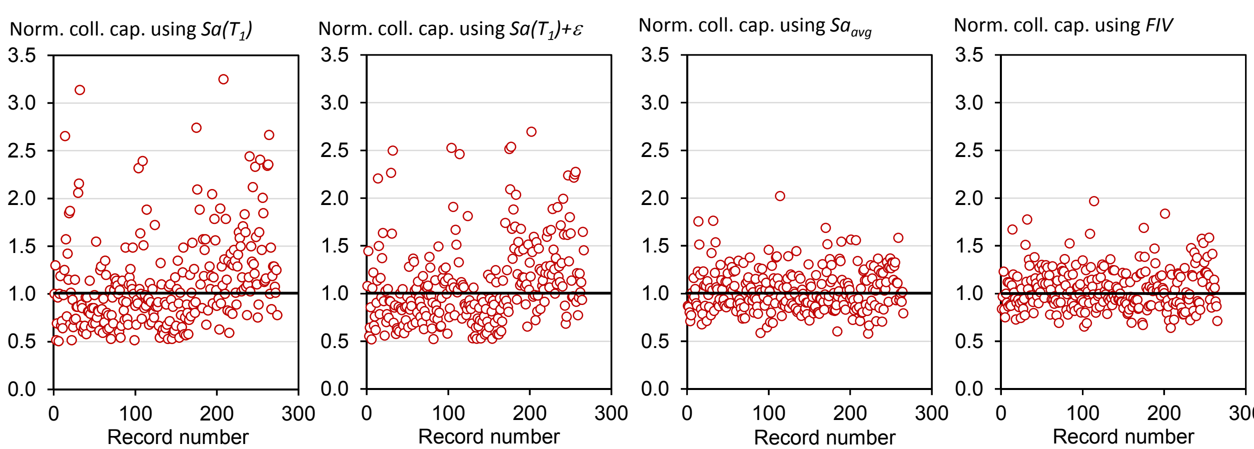

Figure 5. Normalized collapse capacities using different IMs. From left to right: $Sa(T_1)$, $Sa(T_1)$ adjusted using ε, $Sa_{avg}(T_1)$, FIV3.

Scaling factor bias evaluation

The use of scale factors is undoubtedly the most common approach to conduct nonlinear time history analyses at different intensities. The scaling process consists of scaling the acceleration time series until the desired level of the intensity measure is reached. This IM is usually the 5%-damped pseudo acceleration spectral ordinate at the fundamental period of vibration of the structure, $Sa(T_1)$.

Several studies have found contradictory conclusions regarding a possible bias in structural responses that can be introduced by the use of scaling factors. While several assert that the bias in fact exists (e.g., Watson-Lamprey and Abrahamson, 2006; Luco and Bazzuro, 2007; Baker 2007) others have found little evidence to support that claim (e.g., Shome et al., 1999; Iervolino and Cornell, 2005; Zacharenaki et al., 2014).

The following subsections evaluate the scaling factor bias using degrading SDOF and MDOF systems.

SDOF systems

Short period SDOF

The comparison of the median spectrum from the “scaled” and “unscaled” sets is presented in figure 6 which shows a clear difference in the median spectral shapes from both sets. The higher ordinates at all periods (except $T = 0.25$s) mean that, on average, there is a higher content of all frequencies in the records from Set B which might lead to larger structural responses. This observation is in agreement with those previously reported in Luco and Bazzurro (2007) and Baker (2007).

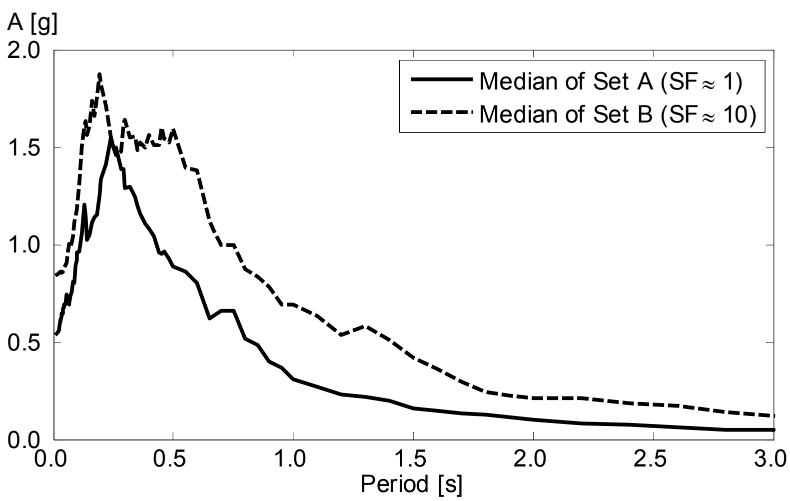

Figure 6. Median Spectra from both ground motion sets used for the T_n=0.25s SDOF

Figure 7 presents the inelastic displacements of the short period SDOF having different strength reduction factors and a positive postelastic stiffness equal to -3% subjected to all records from both sets. This negative postelastic slope is used to capture dynamic instability (Miranda and Akkar, 2003). Whenever no record caused collapse, the information presented is the same as in figure 7, but when some record triggered collapse, the corresponding probabilities of collapse of each set are reported. In these cases, the dots at the horizontal dashed red lines represent the collapsing cases. Similar conclusions can be made from the results of the degrading SDOF in the sense that the fraction of ground motions that cause collapse in the Set that requires scale factors around 10 is significantly higher than the fraction of collapses obtained using Set A (i.e., ground motions with scale factors close to one). As an example, consider the $T = 0.25$s SDOF with $R = 2.5$, if one uses the Set with scale factors close to one, the probability of collapse (*P(C))* is equal to zero whereas it corresponds to 23% if the records from Set B are used. Similarly, the probability of collapse for the $T = 0.25$s SDOF having a $R = 4$ equals 30% if the records from Set A are used and 63% if one uses the records with scale factors around 10, that is, Set B.

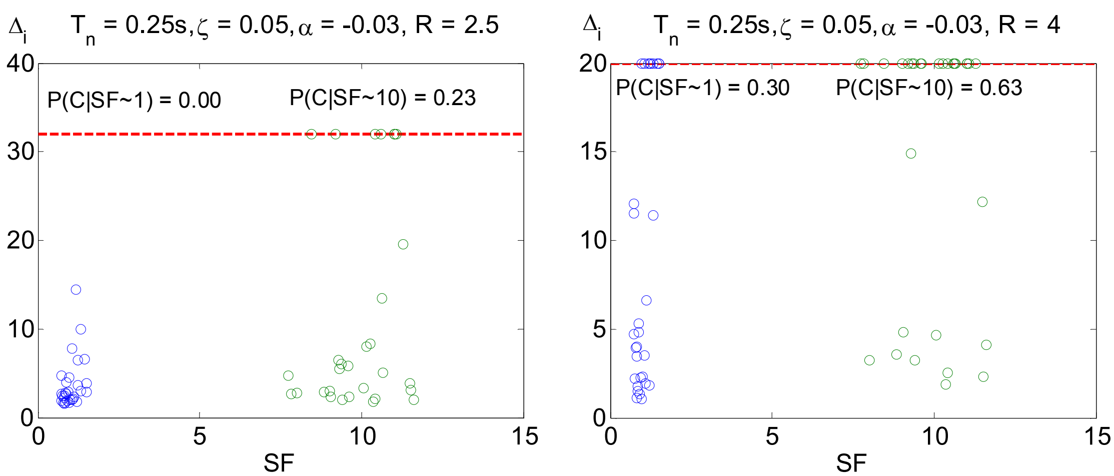

Figure 7. Inelastic displacements of a T=0.25s SDOF with several R factors and α=-3% when subjected to the MCE intensity (blue: SF between 0.5 and 1.5; and green: SF between 7 and 13). The collapse displacement is represented with a horizontal red dashed line.

Long period SDOF

The comparison of the median spectrum from each Set is presented in figure 8 where the difference in the median spectral shapes from both sets is clear. As it was the case for the shorter period SDOF, the higher ordinates at all periods (except $T = 1.5$s) mean that, on average, there is a higher content of all frequencies in the records from Set B and this might lead to larger structural responses.

The results from the degrading SDOF with $T = 1.5$s are presented in figure 9. In this case, there is a bias in the estimation of inelastic displacements and probabilities of collapse introduced by the use of scale factors. The bias in inelastic displacements seems to increase with reductions in the lateral strength of the system. As it was the case for the shorter period SDOF, important overestimations in structural responses are obtained when the Set with scale factors close to 10 is used.

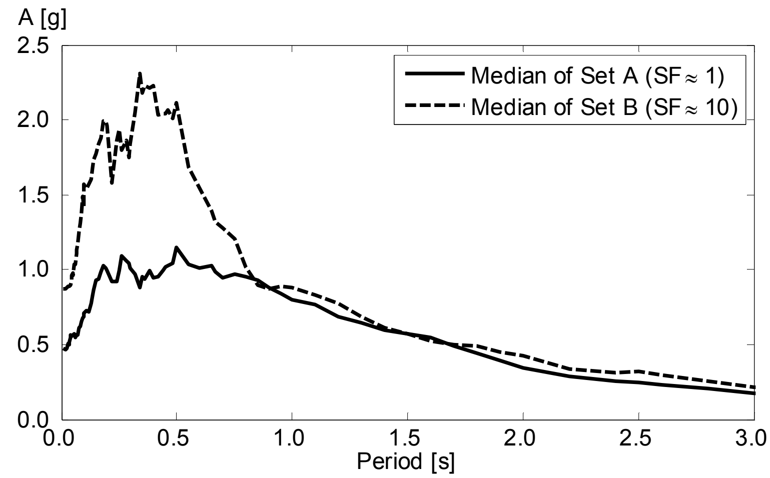

Figure 8. Median Spectra from both ground motion sets used for the T_n=1.5s SDOF

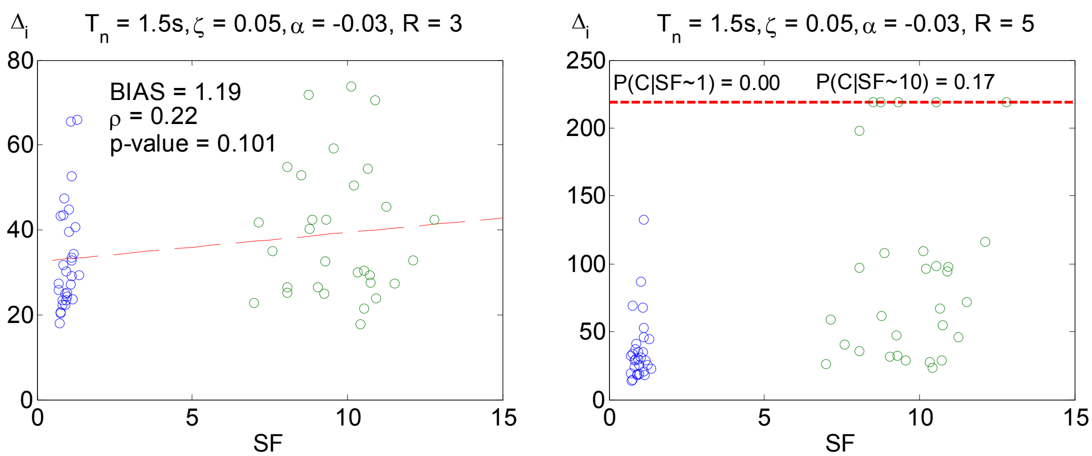

Figure 9. Inelastic displacements of a T=1.5s SDOF with several R factors and α = -3% when subjected to the MCE intensity (blue: SF between 0.5 and 1.5; and green: SF between 7 and 13). The collapse displacement is represented with a horizontal red dashed line.

MDOF systems

Figure 10 presents the median spectra of each of the three Sets used in the evaluation of a possible bias introduced by the use of scale factors. Recall that Set A requires scale factors of approximately 1, Set B scales factor of approximately 5, and Set C scale factors of approximately 10 to reach the target intensity. Panel a) presents the median spectra of each set before scaling and Panel b) presents the median spectra of each set normalized by the spectral ordinate at T_1 = 0.63s. As it was the case for the SDOF systems, these median spectral shapes also reflect the fact that records that have low spectral ordinates and therefore have to be scaled by larger factors to reach the target intensity, have a higher high- and low-frequency content than records whose intensity was already in the neighborhood of the target intensity.

Figure 11 presents the maximum interstory drift ratio (IDR) of the structure when subjected to the 50 ground motions of each set at a target intensity of $Sa(T_1)$ = 1.13g. Results plotted over the red dashed line indicate ground motions that triggered collapse. It is seen that the probability of collapse increases as the scale factors used in the ground motions increase. One could estimate that the structure has an 18% chance of collapsing at the MCE intensity if scale factors around 10 are used when the 'true' probability of collapse equals only 4%. Even when scale factors of approximately 5 are used to reach the target intensity, the probability of collapse is overestimated by more than a factor of 2.

The second MDOF under study is a four-story structure with a period of vibration of 1.12s. Figure 12 presents the median spectra of each of the three Sets used in the scaling factor bias evaluation. Panel a) presents the median spectra of each set before scaling and Panel b) presents the median spectra of each set normalized by the spectral ordinate at T_1 = 1.12s. Again, the median spectral shapes show that records that originally have low spectral ordinates end up having a higher high- and low-frequency content after scaling than records whose intensity was close to the target intensity which in this case corresponds to 0.8g.

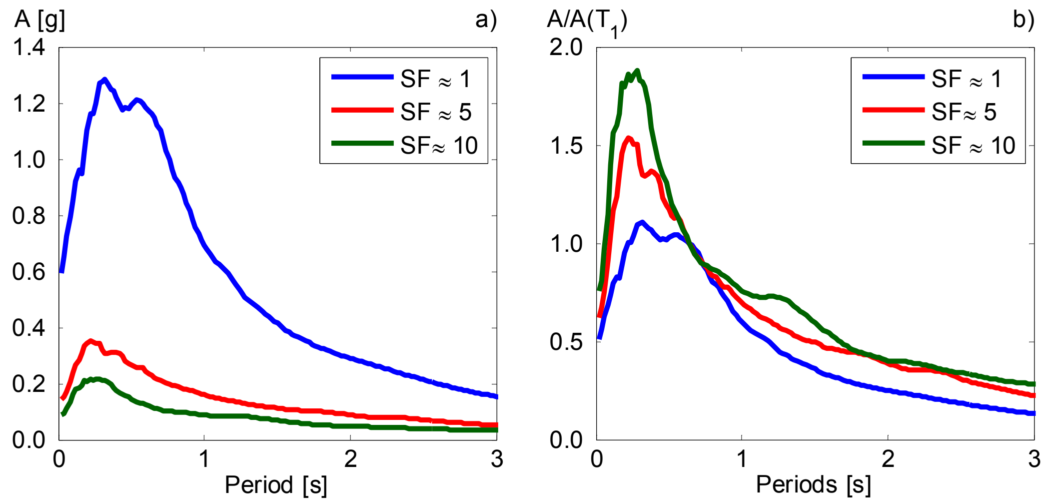

Figure 10. (a) Median spectra of the three sets used for the T_n = 0.63s MDOF without scaling; and (b) Normalized median spectra of the three sets.

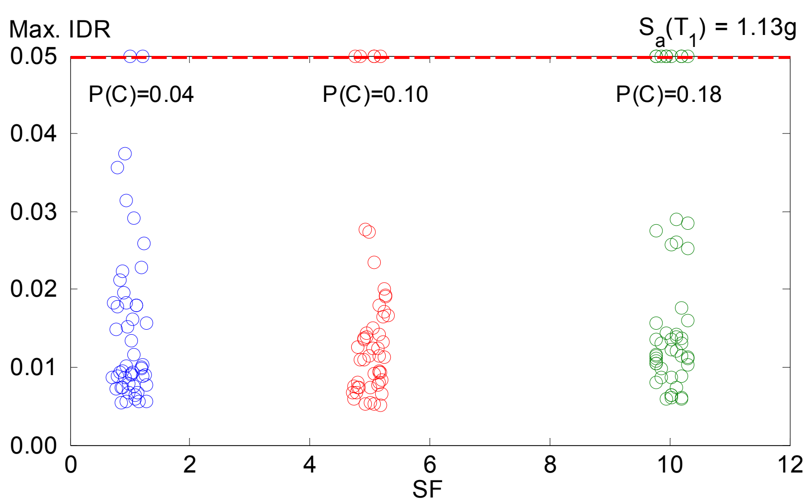

Figure 11. Inelastic displacement demands and collapse probabilities of the T=0.63s two-story MDOF when subjected to the MCE intensity (blue: SF between 0.5 and 1.5; red: scale factors between 4.5 and 5.5; and green: SF between 9.5 and 10.5). The collapse IDR is represented with a horizontal red dashed line.

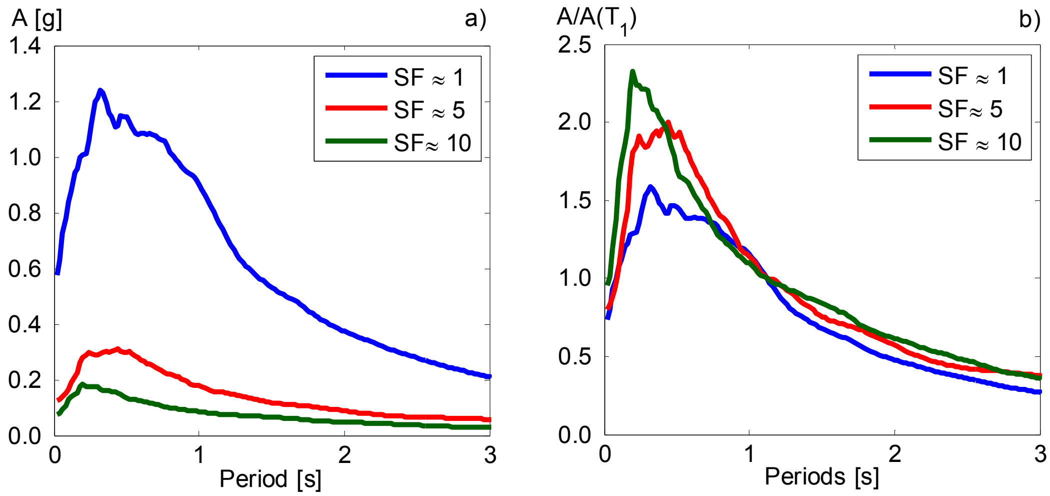

Figure 12. (a) Median spectra of the three sets used for the T_n = 1.12s MDOF without scaling; and (b) Normalized median spectra of the three sets.

The results of the maximum IDR computed with the three sets scaled to the MCE intensity are presented in figure 13. Again, results suggest that the use of scale factors introduce a bias in the collapse risk estimation. For example, using the records with scale factors of approximately 5, the probability of collapse of this structure would be 26% which corresponds to an overestimation by a factor of 2.25. In this case, this ratio is the same if the records from Set C are used.

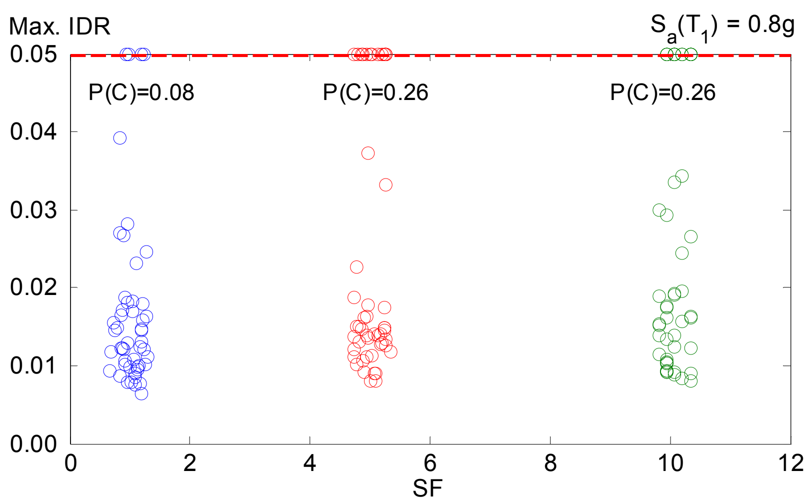

Figure 13. Inelastic displacement demands and collapse probabilities of a T=1.12s four-story MDOF when subjected to the MCE intensity (blue: SF between 0.5 and 1.5; red: scale factors between 4.5 and 5.5; and green: SF between 9.5 and 10.5). The collapse interstory drift ratio is represented with a horizontal red dashed line.

Conclusions and recommendations

Efficiency

This study presented an evaluation of the efficiency of two intensity measures that are commonly used: $Sa(T_1)$ and $Sa(T_1)$ adjusted using the spectral shape proxy ε, and two other alternate scalar IM candidates: Sa_{avg} and *FIV*.

A four story special moment frame steel structure was subjected to a set of 265 ground motions to evaluate the dispersion in the collapse capacities obtained with each of the IM candidates. From the results, the following conclusions can be drawn:

1) $Sa(T_1)$ is the IM that leads to the largest dispersion in the collapse capacities estimated, indicating that of the parameters evaluated is also the least correlated with collapse intensities.
2) Even when the bias that is introduced by ignoring the spectral shape of the records when $Sa(T_1)$ is used as the IM is partially reduced by taking into account ε, this correction does very little in reducing the dispersion in the collapse capacities. Furthermore, it is concluded that ε is not a good measure of spectral shape.
3) The scalar intensity measure Sa_{avg} proved to be a much better option than $Sa(T_1)$ and also when this parameter is combined with the spectral shape proxy ε. By considering the spectral ordinates of a wide range of periods, Sa_{avg} indirectly accounts for the underlying pulses in the ground motion record that produce the response spectrum and therefore practically eliminates the bias induced when the spectral shape is ignored. The reduction in the logarithmic standard deviation when Sa_{avg} is 45% and 41% when compared to the one computed using $Sa(T_1)$ alone or with the adjustment using ε, respectively. This reduction mean that, to obtain the desired structural response parameter with the same confidence, if Sa_{avg} is chosen as the IM, one needs to use only one third of the number of records that are required if $Sa(T_1)$ is used, hence leading to a substantial reduction in the computational effort to estimate the probability of collapse of a structure.
4) A new intensity measure termed *FIV* was proposed and it was seen that its efficiency is slightly higher than the one using Sa_{avg}. This new IM is based on a period-dependent incremental velocity computed from a low-pass filtered ground motion and considers the three pulse segments that added together have the largest area.
5) The use of either Sa_{avg} or *FIV* is strongly recommended for seismic collapse estimation as those two IM candidates gave collapse capacities with the least dispersion.

Scaling factor bias

The scaling factor bias evaluation was conducted using both, SDOF and MDOF structures with positive post elastic stiffnesses as well as degrading systems. Following common practice, the intensity measure used in this evaluation was $Sa(T_1)$. Results suggest that:

1) The use of scale factors introduces a systematic bias in the peak inelastic displacement of SDOF systems with positive postelastic stiffness. This bias tend to increase as the lateral strength of the SDOF is decreased. More importantly, the bias is clearly seen and much larger in the short period spectral region (e.g., in an SDOF with T_1 = 0.25s) than structures with long periods of vibration (e.g., SDOFs with T_1 = 1.50s).
2) In the case of the degrading SDOFs, the bias seems to appear on all SDOFs regardless of their period of vibration, but the bias is larger in SDOFs in the short period region.
3) Both MDOF studied presented a clear bias in both, inelastic displacement estimates and collapse probabilities. In general, the bias increases as the scale factor used increases. After analyzing the responses of two MDOF structures with periods of vibration of 0.63s and 1.12s at two high intensity levels, using scale factors of approximately 10 led, on average, to an overestimation of the probability of collapse of a factor of 3.65. Even when

the scale factors required to reach the target intensity are approximately 5, an overestimation of a factor of 2.8 was also be computed.

4) The bias is also higher as the structure is subjected to larger intensity levels. This means that the overestimation caused by the use of large scale factors is higher on the probability of collapse than on the estimation of inelastic displacement demands, especially in mildly inelastic systems.
5) As noted previously by some researchers, ignoring the spectral shape of the records has a major influence in the overestimation of the structural responses.
6) Based on these results, we recommend limiting scale factors to a maximum value of 2.0, recognizing that even those scale factors can introduce a small overestimation of inelastic displacements and collapse probabilities.

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