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CONDITIONAL SPECTRUM BASED GROUND MOTION RECORD SELECTION USING AVERAGE SPECTRAL ACCELERATION

Mohsen Kohrangi[1*†], Paolo Bazzurro[2], Dimitrios Vamvatsikos[3] and Andrea Spillatura[4]

[1]*Research assistant, University School for Advanced Studies IUSS Pavia, Pavia, Italy*
[2] *Professor, University School for Advanced Studies IUSS Pavia, Pavia, Italy*
[3] *Assistant Professor, School of Civil Engineering, National Technical University of Athens, Greece*
[4]*Ph.D. candidate, University School for Advanced Studies IUSS Pavia, Pavia, Italy*

SUMMARY

The use of a seismic intensity measure (IM) is paramount in decoupling seismic hazard and structural response estimation when assessing the performance of structures. For this to be valid, the IM needs to be sufficient, i.e., the engineering demand parameter (EDP) response should be independent of other ground motion characteristics when conditioned on the IM. Whenever non-trivial dependence is found, such as in the case of the IM being the first-mode spectral acceleration, ground motion selection must be employed to generate sets of ground motion records that are consistent vis-à-vis the hazard conditioned on the IM. Conditional spectrum (CS) record selection is such a method for choosing records that are consistent with the site-dependent spectral shape conditioned on the first-mode spectral acceleration. Based on a single structural period, however, the result may be suboptimal, or insufficient, for EDPs influenced by different period values, e.g., peak interstory drifts or peak floor accelerations at different floors, potentially requiring different record suites for each. Recently, the log-average spectral acceleration over a period range, *AvgSA*, has emerged as an improved scalar IM for building response estimation whose hazard can be evaluated using existing ground motion prediction equations. Herein, we present a recasting of CS record selection that is based on *AvgSA* over a period range as the conditioning IM. This procedure ensures increased efficiency and sufficiency in simultaneously estimating multiple EDPs by means of a single IM.

KEY WORDS: Record selection; Conditional Spectrum; Average spectral acceleration

1. INTRODUCTION

Ground motion record selection is the link between seismic hazard and probabilistic seismic demand analysis of a structure. Record selection is commonly carried out based on the following procedure: first, Probabilistic Seismic Hazard Analysis (PSHA [1]) is performed for one or more ground motion Intensity Measures (IMs) at the site; second, the characteristics of the events (e.g., magnitude, rupture-to-site distance, and fault type) most contributing to a given rate of exceeding or "equaling" any desired level of one of the selected IMs are

* Correspondence to: Mohsen Kohrangi, Istituto Universitario di Studi Superiori – IUSS Palazzo del Broletto - Piazza della Vittoria 15, 27100 Pavia, Italy

† E-mail: Mohsen.kohrangi@gmail.com

obtained using disaggregation analysis (Bazzurro and Cornell [2]); third, based on these events' characteristics and using an appropriate Ground Motion Prediction Equation (GMPE) for their rupture mechanisms, a target spectrum, or in general a joint distribution of ground motion characteristics, is defined for the scope at hand; fourth and last, a set of records to be used for structural response estimation is selected to "match" this spectrum or joint distribution. The first and second steps of this procedure are fairly standard and will not be discussed further. The focus is on steps three and four, and in particular on whether there is an advantage to using a scalar IM that incorporates spectral ordinates at multiple periods vis-à-vis a conventional single-period spectral acceleration.

The procedure to define the target spectrum and, once defined, to choose ground motion records that "match" it, is not unique. One such a procedure utilizes the Uniform Hazard Spectrum (UHS) for spectral accelerations as the target and then uses either real or synthetic records selected or generated in such a way that, *on average*, their spectra match the target within a given tolerance (say, ±5%). The matching is enforced either for every oscillator period of the UHS or, more commonly, for a period range of interest. The records are often, but not always (see REXEL [3]), chosen without an explicit use of disaggregation analysis. This UHS-based approach provides sets of records that, when used as input to structural analysis, tend to produce probabilistically conservative estimates (Baker and Cornell [4]) of the mean response of the structure for the selected ground motion hazard level unless the structure exhibits only elastic first-mode response. The going explanatory argument for this conservatisms states that real records do not usually have energy content as broad as that of the UHS and, therefore, records that match the UHS are "unnaturally" aggressive. This UHS-based approach has been used since the 1980s mostly for design of new structures or requalification of existing ones for hazard levels corresponding to the distinct limit states (e.g., serviceability or ultimate limit states) specified in design codes [5-7]. This approach was not intended to be used for risk estimation purposes.

A suitable and more recent approach for risk calculations is based on the Conditional Mean Spectrum (CMS) (Baker and Cornell [4]) or, better, on the Conditional Spectrum (CS) (Jayaram et al. [8]). The former considers only the mean acceleration response spectrum for a given scenario event (e.g., magnitude, rupture-to-site distance, and fault mechanism) conditional on a spectral acceleration at a given period, T^*, whereas the latter accounts for the variability around the CMS of the spectral accelerations at all oscillator periods except for T^* at which, by design, such a variability is zero. Along the same lines, Bradley [9] proposed the Generalized Conditional Intensity Measure (GCIM) approach, which is a straightforward generalization of the CS method for cases where non-spectral ground motion IMs (e.g., record duration or Arias intensity) are important to the prediction of structural response. The focus of CS is on improving the *sufficiency* with respect to spectral shape while the focus of GCIM is the same but conceptually broader since the sufficiency improvement is sought with respect to all ground motion characteristics that affect the response. Sufficiency here simply means that two different sets of records that correspond to a given conditioning value of the IM and have the same spectral shape in the CS framework or, say, the same spectral shape and Arias Intensity in the GCIM framework, but different distributions of other characteristics (e.g. cumulative absolute velocity) generate statistically indistinguishable estimates of the Engineering Demand Parameters (EDPs) chosen to gauge the response of the structure. In another effort, Iervolino et al. (2010) [10] found the conditional distribution of the so-called Cosenza and Manfredi index (ID), given peak ground acceleration (PGA) in order to generate a conditional hazard map for ID. Such hazard map was intended to be used for a more refined ground-motion record selection as an input for nonlinear dynamic analysis of structures

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conditional on the code design values of PGA. Computational algorithms for selecting ground motions for these methods are publically available ([8] for CS; [11] for GCIM; [3, 12] for ID conditional on PGA). Here, we will not further discuss methods other than CS since they are conceptually similar to the CS method and their inclusion does not significantly contribute to the main argument presented in this paper.

In the CS approach, the pivotal ground motion IM is the elastic spectral acceleration at the conditioning period, *SAT**, where *T** is selected such that *SAT** is a good predictor of the EDP of choice. For a specific *SAT** level (e.g., *SAT*=0.5g, where *T*=1s), a suite of records is selected and scaled to "match" the target CS. Note that for hazard levels of engineering interest, the spectral acceleration values of the mean CS (i.e., the CMS) at periods other than *T** are lower than the corresponding ordinates of the UHS.

Is the selection of a suitable value of *T** important for engineering analyses record selection? To answer this question one needs to consider the two types of assessment typically used in earthquake engineering. The first is the so-called "risk-based" assessment, whereby structural response is evaluated at multiple levels of intensity and the results are convolved with a seismic hazard curve to determine the MAR of exceeding a limit-state of interest. On the other hand, "intensity-based assessment" is akin to standard engineering practice whereby structural response is assessed at a single level of seismic intensity and the results are used to (approximately) determine compliance with (or non-exceedance of) a given limit-state. Lin et al. [13] showed that when using the CS method for *risk-based assessment* of a structure, the estimates of the annual rate, λ_{ij}, of exceeding any different level *j* of EDP *i* (e.g., 1% interstory drift ratio) are relatively insensitive to the choice of the anchoring period *T**. Lin et al. [14] pointed out, however, that the choice of *T** can have a substantial impact on the estimates of the rate, $\lambda_{ij,h}$, of exceeding any different level *j* of EDP *i* for a *given hazard level*, *h* of the IM . Namely records that match two different CS anchored at two different ordinates of the same UHS may, and usually do, generate vastly different estimates of λ_{ih}. In the latter case, i.e., *intensity-based assessment*, the choice of a suitable conditioning period *T** is, therefore, crucial for obtaining robust estimates of the $\lambda_{ij,h}$ for the EDP of interest. Kwong et al. [15] in fact, recommends that the engineer iteratively select an appropriate value of *T** during the design process when the dynamic characteristics of the structure are not yet finalized.

Although not as fundamental for risk-based assessment as it is for intensity-based assessment, an unwise choice of *T** may lead to undesired consequences in probabilistic demand and risk computations, as we will see later. Lin et al. [13] points out that the choice of a suitable conditioning period *T** (or of a better conditioning IM altogether, in the GCIM method), can certainty help to achieve a more precise response prediction (this relates to the sufficiency issue discussed above). In addition, it should always be kept in mind that, besides the issue of sufficiency, a judicious choice of *T** leads to the selection of an *efficient SAT** (i.e., the response variability is limited to relatively low values for a given *SAT** value, an issue which is called *efficiency* in the literature [38]) and, consequently, the following estimates of the $\lambda_{ij,h}$'s for the EDP *i* of choice obtained with a fixed, and in real applications usually limited, number of nonlinear dynamic analyses are less likely to be biased.

What should then an engineer interested in risk assessment do if he/she is unsure about the value of *T** and is concerned about the potentially inaccurate risk estimates caused by a weak *T** choice? Selecting an appropriate value of *T** is everything but trivial and the selection depends on the objective of the analysis. If the interest is, for example, in assessing the collapse probability of a building perhaps a value of *T** that is 1.5 or 2 times the fundamental period, T_1, of the structure may be a good choice. This is because *SAT** for $T^*=1.5\cdot T_1$ or $2.0\cdot T_1$ is a good predictor for the maximum (along the height) of the peak (in time) interstory

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drift ratio, MIDR, which is an EDP well correlated with collapse (Kohrangi et al. [16]).

However, usually the motivation for performing such a challenging exercise is broader than assessing the ultimate response of a building. The engineer may also want to assess *with the same set of analyses* whether the serviceability limit state of the building, namely when the structure behaves in the linear elastic regime or close to it, is met. In that case, T_1 may be a better choice for T^*. Or, again, using the same set of analyses, he/she may also want to estimate the risk of experiencing economic losses due to damage to structural (e.g., beams and columns) and non-structural (e.g., elevators, suspended ceilings, piping) components and to contents (e.g., bookcases, TV sets). Some of the non-structural components and contents are not sensitive to structural deformation but to story-specific peak floor acceleration (PFA), which is a completely different EDP than MIDR. Therefore, in complex but frequent performance assessment cases, the choice of T^* based on simplistic considerations about the fundamental period of vibration of the structure is no longer adequate.

A conceptually straightforward but less practical solution would be to repeat the same intensity-based assessment using CS, for multiple choices of T^* (Baker and Cornell [4]) and adopt for each EDP the most conservative estimates obtained using the different values of T^*. This approach, which is consistent with the seismic hazard at the site, is, however, not only time consuming but also conservative (i.e., biased). For example, consider an ensemble of records that is consistent with a CS anchored at SAT^* with $T^*=T_1$ from a severe hazard level at the site (e.g., 10% in 50yrs probability of exceedance). This set of records tends to generate large peak interstory drift ratios (IDRs) but relatively low PFA values in a building. On the other hand, a second ensemble of CS-based records anchored at SAT^* with $T^*=0.2\cdot T_1$ at the *same hazard level* as above tends to generate higher PFA values and lower interstory drift ratios [11]. The first ensemble of records would estimate higher structural damage and lower non-structural damage than the second ensemble but both sets have the same occurrence rate at the site. Should the engineer perform both analyses and select the worse damage/loss estimate of the two? This example clearly shows that a conservative approach, which is often sought during design, would be undesirable for intensity-based seismic assessment.

An alternative, practical and arguably unbiased approach might involve the selection of an IM that is a good predictor for the ensemble of *all* the EDPs of interest but perhaps not the best for any single one. Following this insight, many researchers have considered using as the conditioning IM various versions of a log-average of spectral acceleration, *AvgSA*, over a range of periods bracketing the fundamental period T_1 [4, 16-25]. In this approach, it could be argued that the issue of *efficiency* would be addressed by an IM choice that is a "good" predictor for all the EDPs of interest and the issue of *sufficiency* would be addressed by performing a careful record selection based on that IM.

As in the literature cited above, we explore the use of different definitions of *AvgSA* as the pivotal IM of choice in probabilistic seismic demand analysis but here we go one step further. Although it is possible to perform the record selection based on one conditioning IM (e.g., SAT^*) and use a different IM (e.g., SAT' where $T'\neq T^*$) for response prediction (Vamvatsikos and Cornell [18] and Kohrangi et al. [16]), it is certainly preferable to be consistent by keeping the same conditioning IM in both aspects of the analysis. Hence, to ensure this consistency, we introduce here the CS-based record selection conditioned on *AvgSA*. Using a general term of CS(*IM*) to denote the conditional spectrum variant based on a given IM, we shall proceed to discuss the definition and detailed application of CS(*AvgSA*) for performance assessment.

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2. CONDITIONAL SPECTRUM BASED ON *AVGSA*

We consider the average spectral acceleration, *AvgSA*, defined as the mean of the log spectral accelerations at a set of periods of interest, to be used for the estimation of multiple EDPs that are crucial for risk assessment and loss estimation of a structure of interest. These periods, for example, could be equally spaced in the $0.2 \cdot T_1$ to $1.5 \cdot T_1$ range, where T_1 is the first mode elastic period of vibration of the structure. This array of periods could cover higher mode response and also the "structural period elongation", whereby periods higher than the elastic ones gain predictive power due to the accumulation of damage [16]. Alternatively, and perhaps more effectively, it could be defined as the mean of log spectral accelerations at relevant elastic vibration periods of a 3D structure, such as T_{1x}, T_{1y}, T_{2x}, T_{2y}, $1.5 \cdot T_{1x}$ and $1.5 \cdot T_{1y}$, where x and y refer to the two main orthogonal directions of the building and the indices 1 and 2 refer to the first and second modes of vibration of the structure in those directions. Mathematically, *AvgSA* is defined in Equation (1) and, more conveniently, by Equation (2) where the natural logarithm has been applied to both sides of Equation (1):

$$AvgSA = \left[\prod_{i=1}^{n} SAT_i \right]^{1/n} \tag{1}$$

$$\ln AvgSA = \left(\frac{1}{n} \right) \cdot \sum_{i=1}^{n} \ln SAT_i \tag{2}$$

The quantity n refers here to the number of *SAT*'s being averaged. Therefore, from Equation (2) the mean and variance of ln*AvgSA* could be calculated as:

$$\mu_{\ln AvgSA|\text{rup}} = \left(\frac{1}{n} \right) \cdot \sum_{i=1}^{n} \mu_{\ln SAT_i|\text{rup}} \ , \tag{3}$$

$$\text{var}(\ln AvgSA \mid \text{rup}) = \left(\frac{1}{n} \right)^2 \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} \rho_{\ln SAT_i, \ln SAT_j} \cdot \sigma_{\ln SAT_i|\text{rup}} \cdot \sigma_{\ln SAT_j|\text{rup}} \ , \tag{4}$$

Where $\mu_{\ln SAT_i|\text{rup}}$ and $\sigma_{\ln SAT_i|\text{rup}}$ are the logarithmic mean and standard deviation of the spectral acceleration at the *i*-th period in the selected range for a given rupture scenario as obtained from a standard GMPE. $\rho_{\ln SAT_i, \ln SAT_j}$ is the correlation coefficient between $\ln SAT_i$ and $\ln SAT_j$. The CMS conditioned on $\ln AvgSA=x$, i.e. without consideration of the variance in the spectrum, was first introduced by Baker and Cornell [4]. The logarithmic mean and variance of CS(*AvgSA*) at all periods of the spectrum can be computed as follows:

$$\mu_{\ln SAT|\ln AvgSA=x,\text{rup}} = \mu_{\ln SAT|\text{rup}} + \rho_{\ln SAT, \ln AvgSA} \cdot \sigma_{\ln SAT|\text{rup}} \cdot \varepsilon_{\ln AvgSA|\text{rup}} \tag{5}$$

$$\sigma_{\ln SAT|lnAvgSA=x,\text{rup}} = \sigma_{\ln SAT|\text{rup}} \cdot \sqrt{1-\rho^2_{\ln SAT, \ln AvgSA}} \tag{6}$$

In these equations, $\mu_{\ln SAT|\ln AvgSA=x,\text{rup}}$ and $\sigma_{\ln SAT|lnAvgSA=x,\text{rup}}$ are the logarithmic mean and standard deviation of the spectral acceleration at the generic period T conditioned on $\ln AvgSA=x$ for a given rupture scenario. The quantity $\varepsilon_{\ln AvgSA|\text{rup}}$ is the number of standard deviations that the ln*AvgSA* value of a record is away from the mean of ln*AvgSA* predicted by a GMPE for the same rupture characteristics (e.g., magnitude, source-to-site distance and fault type). $\rho_{\ln SAT, \ln AvgSA}$ is the correlation coefficient between ln*SAT* and ln*AvgSA*, which can be computed according to Equation (7) below:

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$$\rho_{\ln SAT,\ln AvgSA} = \frac{\sum_{i=1}^{n} \rho_{\ln SAT,\ln SAT_i} \cdot \sigma_{\ln SAT_i}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n} \rho_{\ln SAT_i,\ln SAT_j} \cdot \sigma_{\ln SAT_i} \cdot \sigma_{\ln SAT_j}}}. \tag{6}$$

Of course, this is not the only possible definition of a spectral acceleration average that could be considered as a conditioning IM. In fact, we also investigated another version of *AvgSA*, called I_{NP} [21], that is a normalized version of *AvgSA* to SAT_1 that, at least in its original definition, does not consider periods shorter than T_1 (higher modes). The investigation of CS(I_{NP}) and related record selection, however, did not bring any advantage over CS(*AvgSA*) and, therefore, its treatment is omitted herein. The interested reader can find the derivation of CS(I_{NP}) and the results obtained using it in Kohrangi [26]-Appendix E.

3. UNIFORM HAZARD AND CONDITIONAL MEAN SPECTRA

As examples of the proposed record selection procedure that utilizes CS(*AvgSA*), we carry out both risk- and intensity-based assessments of four buildings located at a highly seismic hazard site close to Istanbul. OpenQuake [27], the open-source software for seismic hazard and risk assessment developed by the Global Earthquake Model (GEM) Foundation, was used to perform the seismic hazard computations. The analysis is based on the SHARE Project [28] and the GMPE proposed by Boore and Atkinson [29]. The selected site is similar to what adopted in [24]. For further details of the hazard analysis and information about the selected site, interested reader is referred to the latter study. The building characteristics will be presented in the next section. To compare and contrast advantages and disadvantages of this procedure we also perform the analysis using other more conventional IMs, such as SAT_1.

For illustration purposes only, Figure 1(b) shows the CMS for *AvgSA* and SAT_1, called CMS(*AvgSA*) and CMS(SAT_1), respectively, for three different hazard levels of 2%, 10% and 50% probability of exceedance in 50 years at the selected site along with the corresponding UHS. The UHS and CMS are computed using the GMPE of Boore and Atkinson [29] and the three CMS are based on the mean scenario contributing to each hazard level obtained via seismic hazard disaggregation. Hazard levels and mean scenarios for the site are reported in Table 1. Note that hazard disaggregation results in this example (and anywhere else in this study) are based on the disaggregation of equaling rather than exceeding; a thorough discussion on this issue is presented in [47]. SAT_1 in this example is the spectral acceleration at T_1=1.0s and the *AvgSA* is defined as the combination of *SAT*'s at the seven periods that go from $T_{min}=0.2\cdot T_1$ to $T_{max}=1.5\cdot T_1$ with an increment of 0.2s. We used the work of Baker and Jayaram [30] to estimate the correlation coefficient between spectral ordinates at any pair of periods T_i and T_j. Figure 1(a) compares the hazard curves at the selected site for SAT_1, *AvgSA* and spectral acceleration at the seven periods in the range considered in *AvgSA*. Note in Figure 1(b) that almost everywhere in the T_{min} to T_{max} period range, CMS(*AvgSA*) lies between the corresponding UHS and CMS(SAT_1) and, as expected, the differences between UHS and CMS(*AvgSA*) are larger for the rarer hazard level (e.g. 2% in 50yrs). The shape of CMS(*AvgSA*) is strongly dependent on the weight of the spectral accelerations. For an *AvgSA* with more weights on spectral ordinates lower than T_1, the spectral shape of CMS(*AvgSA*) would be more skewed towards those periods and vice versa for an *AvgSA* with more weights on spectral ordinates higher than T_1. In a risk-based assessment where the spectral ordinates higher and lower than T_1 are of uttermost importance, the user should pay attention in providing a balance between those period ranges by considering equivalent weights for the spectral ordinates on both sides of T_1.

Table 1. Summary of mean disaggregation results for three different hazard levels

Event	SAT_1				$AvgSA$			
	IM Level [g]	$\bar{\varepsilon}$	$\bar{M}$	$\bar{R}$	IM Level [g]	$\bar{\varepsilon}$	$\bar{M}$	$\bar{R}$
2% in 50 yrs	0.48	2.2	6.8	16.3	0.55	2.3	6.7	14.9
10% in 50 yrs	0.30	1.8	6.7	21.0	0.36	1.9	6.7	19.0
50% in 50 yrs	0.15	1.3	6.6	28.6	0.18	1.3	6.6	25.0

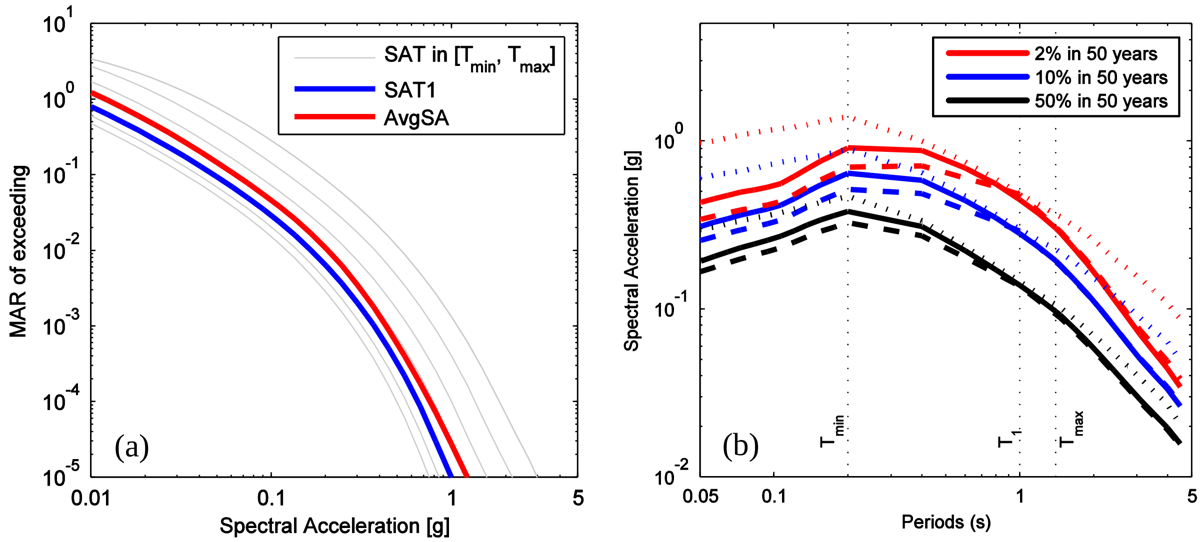

Figure 1. (a) Site seismic hazard curves, in terms of the mean annual rate (MAR) of exceedance, for *AvgSA*, for SAT_1 at T_1=1.0s, and for the six intermediate periods considered in the T_{min} to T_{max} range, (b) Comparison between UHS, CMS(*SAT*1) and CMS(*AvgSA*) for the 2%, 10% and 50% in 50 years hazard levels. (Dotted lines: UHS, dashed lines: CMS(SAT_1), Solid lines: CMS(*AvgSA*)).

Table 2. The conditioning IMs used for record selection and structural response estimation. The periods are expressed in seconds. The notation "a:s:b" signifies a discretization of [a, b] in steps of "s".

	SAT_1	SAT_2	$SATH$	$AvgSA$
	T_1	T_2	$1.5 \cdot T_1$	Period range
4-story	1.82	0.57	2.73	0.57:0.2:2.77
7-story	1.60	0.52	2.40	0.52:0.2:2.52
12-story	2.10	0.73	3.15	0.73:0.2:3.13
20-story	2.85	0.92	4.28	0.92:0.2:4.32

4. CASE STUDY AND GROUND MOTION SELECTION

4.1. *Building example and modeling assumptions*

To test our methodology, we developed 2D centerline models using OpenSees (McKenna et al. [31]) of four plan-symmetric reinforced-concrete moment-resisting frames with 4-, 7-, 12- and 20-stories. They are modern structures built to post-1980 seismic design provisions for high-seismicity regions (site class D). The behavior of the structural members was modeled using lumped-plasticity elements for both beams and columns. The plastic hinge rotational springs have a moment-rotation relationship with a quadrilinear backbone incorporating

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moderate pinching hysteresis, in-cycle strength and stiffness degradation together with an ultimate fracturing rotation. Geometric nonlinearities in the form of P-Δ effects were considered. The details of the building modeling can be found in [22]. The relevant periods of vibration of these four structures are shown in Table 2.

4.2. IMs used for record selection and response prediction

To illustrate the procedure, we selected ground motion ensembles to match two different definitions of CS: CS(*SAT*) and CS(*AvgSA*). CS(*SAT*) was computed for three single-period conditioning spectral accelerations: SAT_1, SAT_2, and *SATH*, where T_1 and T_2 are the periods at first and second mode of vibration of each building and $TH = 1.5 \cdot T_1$. The average spectral accelerations considered here for computing CS(*AvgSA*) are defined with period increments of 0.2s in the $T_{min}=T_2$ and $T_{max}=TH$ range (see Table 2). In all these CS realizations, 13 IM levels were considered, corresponding to mean return periods (MRPs) of exceedance for the site ranging approximately from 10 to 10^6 years. All versions of the CS were derived using the GMPE of Boore and Atkinson [29], which has also been used for performing the PSHA calculations. The period range considered for matching in record selection is 0.1s to 4.5s.

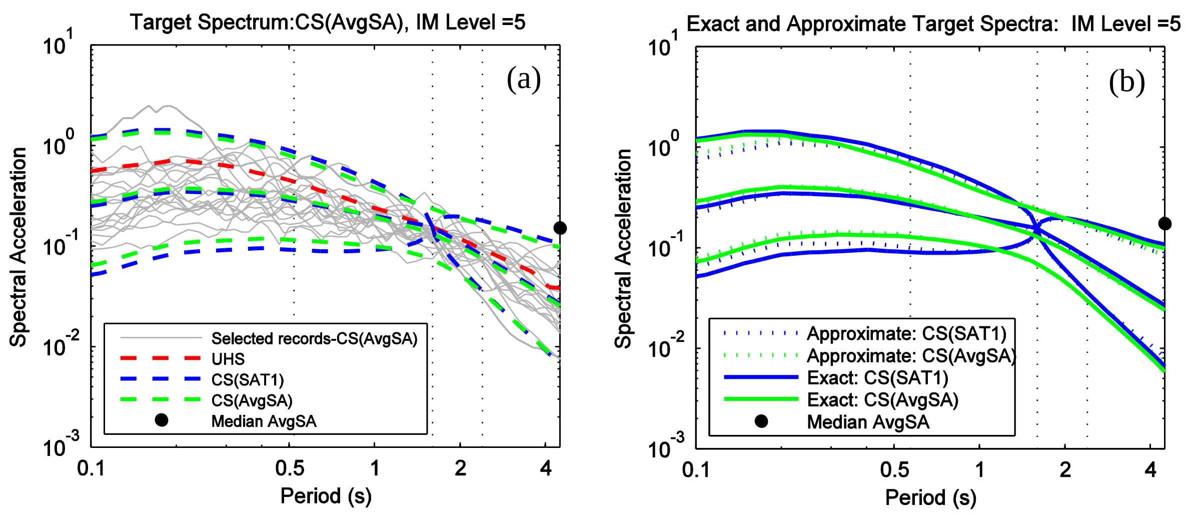

Figure 2. Conditional Spectrum based record selection for IM level 5 corresponding to 10% in 30 years for the 7-story building with first mode of vibration equal to 1.6s: (a) Target CS for different conditioning IMs and the 20 individual records selected for CS(*AvgSA*), (b) comparison between the exact and approximate CS target for CS(SAT_1) and CS(*AvgSA*). (Note: the dots in the right side of each figure represent the median value of the conditioning *AvgSA*).

Figure 2(a) shows the CS target spectra for CS(SAT_1) and CS(*AvgSA*) obtained using the procedure presented in the previous section. Figure 2(b) shows instead a comparison between the "exact" and "approximate" CS, conditioned on *AvgSA* and SAT_1 (Lin et al., [13]). In the exact method all the causative scenarios are incorporated in the generation of the target CS, whereas the CS in the approximate method is based on only one scenario, usually the mean hazard-contributing scenario, as done here. These two CS may differ significantly in those cases when the hazard is not controlled by a single scenario. Here the difference between the approximate and exact CS versions is not large and mostly noticeable in their conditional mean (of the log) plus and minus one-standard deviation lines, especially at spectral ordinates of periods far removed from the conditioning one. Of course, the variability is higher in the

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exact method of CS. The mean conditional spectra, however, are very similar. All the record sets used in the response analysis of the buildings are based on the “exact” CS method.

4.3. Selection procedure of ground motion record ensembles

The suite of ground motions to match the three CS(*SAT*) were selected according to the algorithm developed by Jayaram et al. [8]. This algorithm was then modified (see Kohrangi [32]) to select records that match the CS(*AvgSA*) computed according to Equations (1) to (7). In both cases the algorithm extracts and scales arbitrarily chosen horizontal components of ground motions from the PEER NGA West database. Note that in this record selection exercise we did not distinguish records with and without pulse-like characteristics. The applicability of the original CMS method, i.e. CMS(*SAT*), for pulse-like characteristics is addressed in [33] and is beyond our scope.

In order to avoid potential bias in structural responses from overly-scaled records, we intended to limit scaling factors to a maximum value of four (Luco and Bazzurro [34]). This goal was achieved for all the 13 *AvgSA* hazard levels and for the lower hazard levels of SAT_1, SAT_2 and *SATH*. In extreme cases corresponding to very high SAT_1, SAT_2 and *SATH*, scale factors up to 10 were necessary for a good CS(*SAT*) match. Therefore, and not surprisingly, records that are hazard consistent with CS(*AvgSA*) can be scaled, on average, less than records that are hazard consistent with CS(*SAT*). This outcome is general and can be considered as a highly positive feature of using *AvgSA* instead of single-period spectral accelerations for CS record selection. For illustration purposes, Figure 2(a), introduced earlier, shows also the response spectra of 20 ground motions selected and scaled to match the CS(*AvgSA*) corresponding to 10% in 30 years probability of exceedance (i.e., IM level 5 in this study).

The consistency of the response spectra of all the selected ground motion ensembles with the four target CS is explored in Figure 3(a) and 3(b). The target CS conditional mean ($\mu_{\ln SAT\,|\,\ln IM*}$) and standard deviation ($\sigma_{\ln SAT\,|\,\ln IM*}$) are compared with those of the selected records for different conditioning IMs, represented by IM^* in notation. The agreement is excellent. The four CS shown in this figure refer, again, to the IM hazard level 5 but the agreement is equally good for all other IM levels.

Since CS(*AvgSA*) provides, as expected, a compromise between the CS conditioned on SAT_2, SAT_1 and *SATH*, the records selected according to CS(*AvgSA*), as far as spectral content is concerned, are neither very aggressive nor very benign in any period range. This is another positive feature of using CS(*AvgSA*) for record selection. As mentioned in the introduction, when records are selected using CS(*SAT*), as usually done, the systematically different spectral content at periods away from the conditioning one generates very different intensity-based assessments depending on which conditioning period T^* is chosen. For example, records selected according to CS(SAT_2) have, on average, spectral accelerations significantly lower than those of records selected based on *AvgSA* at periods shorter than T_2 and, conversely, spectral accelerations significantly higher at periods longer than T_2 (i.e., at periods close to T_1 and *TH*). Thus, the records selected based on CS(SAT_2) tend to yield lower values of displacement-sensitive EDPs, such as the peak IDR at the lower floors, and higher demands for acceleration-sensitive EDPs, such as PFA at the mid-height of the building. Of course, an opposite trend holds in the case of records selected according to CS(*SATH*). These discrepancies can be significantly curtailed by selecting records based on CS(*AvgSA*) for intensity-based assessments.

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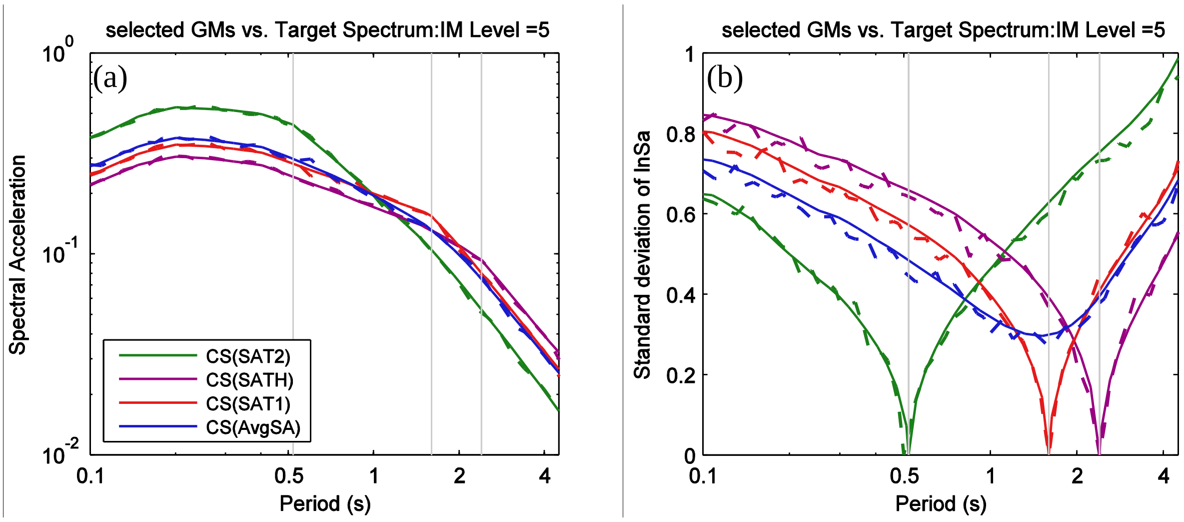

Figure 3. Comparison between the four target spectra and the corresponding empirically derived conditional spectra of the selected record ensembles (solid line: target, dotted line: selected records) based on CS(SAT_2), CS(SAT_1), CS($SATH$) and CS($AvgSA$): (a) mean (of the log), and (b) standard deviation (of the log) of the record-based spectra for the ensemble corresponding to IM Level 5.

Another positive aspect of using CS($AvgSA$) for record selection is its capability to provide records with moderate conditional variability at all spectral ordinates as opposed to no variability at the conditioning period and large variability at periods far from it, as is the case for CS(SAT). Loosely speaking, the “butterfly” look of the ensemble of the response spectra of records selected to match the CS at a given hazard level is greatly reduced if CS($AvgSA$) is used (see Figure 3b). This is intuitive to understand because the variability in $AvgSA$ for a given period range caused at a given site by a specific earthquake is lower than the variability of any spectral ordinate at any specific period included in the averaging operation (Figure 4). The red curve shows the value of $\sigma_{IM|\text{rup}}$ of the GMPE at any IM = lnSAT_1 for any specific period T_1, while the blue curve is the value of $\sigma_{IM|\text{rup}}$ of the GMPE for IM = ln$AvgSA$ (see Equations 3 and 4) computed for periods ranging from $0.2 \cdot T_1$ to $1.5 \cdot T_1$. The values shown were computed for the IM of an arbitrary horizontal component of a ground motion using the GMPE of Boore and Atkinson [29]. Figure 4 shows clearly the significant gain in the predictability of $AvgSA$ with respect to SAT_1 regardless of the value of T_1.

The lower the variability in the IM for a given earthquake rupture ($\sigma_{IM|\text{rup}}$ in the GMPE), the lower the uncertainty in the estimate of the response, measured by an EDP for the same rupture (e.g. Kramer and Mitchell [35]; Bradley et al. [36]). This reduction in $(\sigma_{\ln EDP})_{\text{total}}$ can be easily appreciated by considering the following equation (Shome et al. [37]):

$$\sigma_{\ln EDP|\text{rup}} = \sqrt{\sigma^2_{\ln EDP|IM} + b^2 \cdot \sigma^2_{IM|\text{rup}}}\ , \tag{7}$$

which was derived assuming that the EDP–IM relationship is linear in log-log space, namely $EDP = a + b \cdot \ln IM + \varepsilon_r$, in which a and b are the regression coefficients and ε_r is the regression residual with a standard deviation of $\sigma_{\ln EDP|IM}$. Cornell et al. [38] and Vamvatsikos and Cornell [39], showed that b is often equal to one (e.g., for long and medium period oscillators with no in-cycle strength degradation); therefore, the total uncertainty dispersion is simply the square root sum of square of $\sigma_{IM|\text{rup}}$ and $\sigma_{\ln EDP|IM}$. According to Equation (7), if $\sigma_{\ln EDP|IM}$ does not increase with the change to a new IM, this being the case with $AvgSA$, then the higher predictability of the new IM will cause the overall dispersion to drop.

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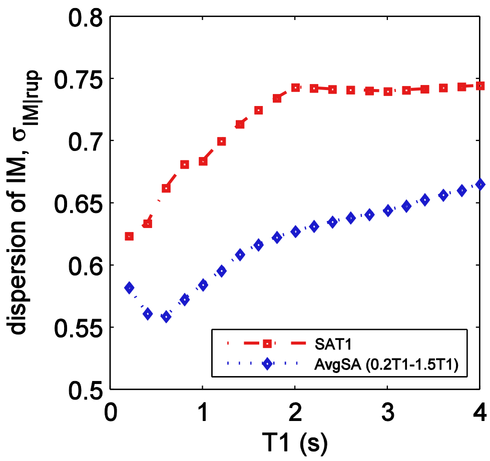

Figure 4. Comparison between the values of $\sigma_{\ln EDP|\mathrm{rup}}$ in the Boore and Atkinson (2008) GMPE for IM=lnSAT_1 and IM=ln*AvgSA* defined for different oscillator periods T_1.

Finally, as a result of the lower conditional variability of CS(*AvgSA*) explained earlier, lower dispersion in various EDPs that are sensitive to different spectral ordinates is expected. This is another positive aspect of selecting records based on CS(*AvgSA*) rather than CS(*SAT*), as it will be clear in the following sections, *AvgSA* is also reasonably efficient (as per the definition of efficiency in [40]) in predicting *at all stories* the different EDP types (e.g., IDR and PFA) that are used for loss estimation (see [16], for details). This means that when *AvgSA* is used as predictive IM, $\sigma_{\ln EDP|IM}$ is also low at all stories and, therefore, the loss estimates are more accurate than if period-specific spectral accelerations are used as EDP predictors. Of course, an even more efficient, but certainly more complicated approach would be to use as predictors a vector of these spectral accelerations without averaging them in a single IM of *AvgSA*. This vector approach was investigated in a different study (Kohrangi et al. [16]) and it has been found to be of considerable advantage for 3D structures, especially when plan asymmetry is involved.

5. HAZARD CONSISTENCY

The interface between the hazard and the structural response in the PBEE approach utilized in this study is limited to ground motion spectral quantities. Hence, for ensuring that the building response estimates computed via nonlinear dynamic analysis are representative of those that could be experienced in the future by the considered structure, it is important that the selected records used for response estimation are consistent with the hazard at the site [13, 41]. More precisely, a set of records are said to be ”hazard consistent” for a given IM if the rates of exceedance of that IM are similar if not identical to those extracted from the hazard curve computed using PSHA at that site for that IM. Figure 5 show that the ensembles of records selected based on CS(SAT_1) and CS(*AvgSA*) are indeed consistent with the PSHA-based hazard curves for this site. This good consistency is due to the adoption of the “exact” approach to CS calculation and to the usage of a common GMPE for both hazard and CS calculation. The hazard consistency for SAT_2, however, is somewhat poorer. It should be noted that, strictly speaking, the hazard consistency should also be checked (or, better, enforced) with respect to other characteristic of the earthquake-site specific combination, such as magnitude, source-to-site distance, Vs_{30}, etc. To do so one could use hazard disaggregation and site soil characteristics to inform the choice of records to be included in the ensembles

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that meet the CS specifications [42]. This is not done here, however, because we assumed that response spectrum consistency with site hazard is adequate.

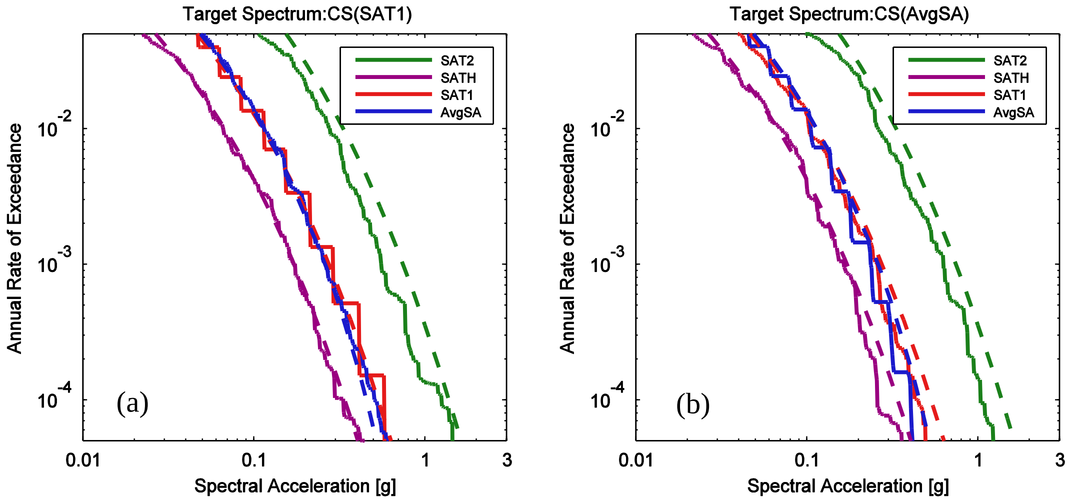

Figure 5. Hazard consistency checking with respect to spectral shape for the sets of records selected to be compatible with (a) CS(SAT_1); and (b) CS($AvgSA$). (Dashed line: hazard curve from PSHA, solid line: empirical hazard from selected record sets).

6. STRUCTURAL ANALYSIS

6.1. Intensity-based assessment

The ensembles of records selected based on the different conditional spectra discussed in the previous sections were used as input for nonlinear response history analysis of the 4-, 7-, 12- and 20-story frame buildings. For simplicity and space constraints, only results from the 7-story building are presented. However, similar findings apply to all the examined structures (Kohrangi [26]-Appendix E).

Figure 6 summarizes for the overall 7-story building the intensity-based analysis results for each one of the 13 IM levels for which record selection was done. More specifically, Figure 6(a) and 6(b) show the median and logarithmic standard deviation of MIDR. It is worth noting that, even though hazard-consistent record selection using the exact CS approach (i.e. considering all contributing causal earthquake ruptures in the hazard of the conditioning IM) was applied, the responses conditional on different IMs with same MRP at the site are quite different. These findings are in line with those obtained in other studies as well (NIST [43]; Lin et al. [13]; Bradley [44]). Again, since MIDR is more dependent to spectral content of the records at T_1 than, say, at T_2, when records based on CS(SAT_1) are used the median MIDR for a given MRP tends to be higher than when CS(SAT_2)-based records at the same MRP are used instead. The latter ensemble of records tend to have response spectrum values at T_1 that are, on average, lower than the single conditioning SAT_1 value of the former ensemble of records especially for long-MRP, high-*IM* levels. Hence, it follows naturally that the median of MIDR generated by records that are selected based on CS(SAT_2) at a given MRP is lower than the median of MIDR generated by records that are selected based on CS(SAT_1) at the same MRP. In this respect note that the median of MIDR for the CS(SAT_1) ensemble for the highest IM level 13 is missing in the figure (i.e., this means collapse) while it is about 0.05 for the CS(SAT_2) ensemble (i.e., no collapse).

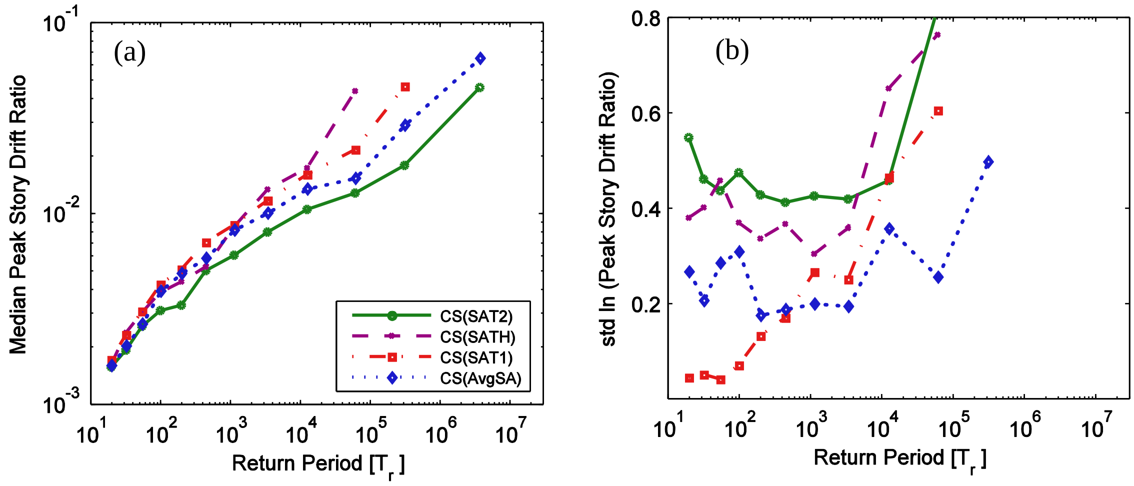

Figure 6. Structural analysis results for the 7-story building for 13 different amplitude levels of different IMs of same MRP at the site: (a) Median of the MIDR; (b) logarithmic standard deviation of the MIDR.

As Bradley [45] mentioned, by conditioning the response on a single IM and at a given IM level, despite all possible events being included in the calculation, it is those that dominate the hazard for that IM that are weighted most while those that may dominate the hazard for other IMs tend to be weighted less. When the single IM is related to a specific oscillator period, such as SAT_1, SAT_2 and *SATH*, this means that events most contributing to hazard at this period will be favored (e.g., short-distance events for high frequencies and long-distance ones for lower frequencies) and subsequently, will favor high epsilon (extreme) events for that particular period. Instead *AvgSA,* whose reach is wider than a single period, can intuitively better represent such different events by more equally distributing the weight. In fact, the median estimates of MIDR given *AvgSA* tend to be bracketed by the estimates given SAT_1 and SAT_2 for all MRPs. Hence, the use of *AvgSA* instead of SAT_1 could remove some of the conservativism that was mentioned in the introduction regarding the estimate of the rate, $\lambda_{ij,h}$, of exceeding any level *j* of EDP *i* for a given hazard level *h*. We will discuss this positive feature of *AvgSA*-based response estimates in more detail when discussing the risk-based calculations.

As expected, Figure 6(b) shows that for all MRPs the dispersion of MIDR is lower for SAT_1 and *SATH* than it is for SAT_2, which is not a good predictor of this EDP. Furthermore, the dispersion of MIDR is, of course, much smaller at low hazard levels for *SAT*1 than it is for *SATH* because the structure responds almost linearly for low amplitude ground motions and the contribution of the first mode of vibration is high. These two estimates of the MIDR dispersion tends to become similar at high hazard levels when the fundamental oscillator periods "lengthen" from T_1 to periods close to or larger than *TH* and, therefore, *SATH* predictive power increases. It is interesting to note that the dispersion of MIDR given *AvgSA* is in between the dispersion of MIDR given SAT_1 and given *SATH* for the low hazard levels but lower than both for the high hazard levels. Again, we will revisit this issue later when discussing the findings of risk-based calculations.

Finally, note that here, unlike in the aforementioned studies [14, 44], we do not always detect a negative correlation between the median and dispersion of an *EDP|IM* (i.e. the higher the median, the lower the dispersion and vice versa) when hazard consistent records are used. For instance, both the estimates of the median and of the dispersion of MIDR obtained for

AvgSA are lower than those obtained for SAT_1 for the high amplitude stripes corresponding to long MRPs. This could be explained by the characteristics of *AvgSA* that, by design, is sensitive to the spectral content of the records at periods both shorter and longer than T_1.

As a foreshadow to risk-based calculations, where the ability of accurately assessing story-specific measures of response in addition to overall ones such as MIDR is of paramount importance, we shift our focus here to IDR and PFA. The median and logarithmic standard deviation values of the IDR at each floor for IM level 5 are displayed in Figure 7(a) and 7(c) while Figure 7(b) and 7(d) show the same for PFA. When the records selected according to CS(SAT_1) are used, the median of IDR is maximized for this IM level (Figure 7(a)) at many floors but not all. For this building (and the other 3 analyzed but omitted here) the ensemble of CS(SAT_2)-based records instead always maximize the median of PFA at all IM levels at least when compared with the medians computed from records selected using CS(SAT_1) and CS(*SATH*). As mentioned in the introduction, Lin et al. [14] and Bradley [45] suggest performing multiple record selections based on different IMs for intensity-based assessment at a given hazard level involving one or more EDPs and use, conservatively, the worst-case scenario for each EDP. In plain words, this translates into picking the IM that predicts the highest median value of the EDP at the hazard level of interest. For this building this approach could be implemented for PFA since the ensemble of records based on CS(SAT_2) always predict higher median PFA values. However, given that neither SAT_1 nor *SATH*, nor any other period-specific *SAT* for that matter, provide always the highest median values of IDR at all floors even for the same IM level (Figure 7(b)), this suggestion would require multiple CS-selected record sets to implement in practice. A vector of spectral values at multiple such periods would offer better predictive power but at the cost of added complexity [16].

Even if SAT_1 were to predict the highest values of IDR at all floors, it would perhaps be acceptable and even preferred for *design* purposes to pick always the IM that provides the highest EDP estimates for each EDP. Such a "worst-case scenario" or "enveloping" approach was recently adopted in [46] for design purposes. However, as discussed earlier, this would not be appropriate for seismic *assessment* calculations. The highest values of all the EDPs as estimated using this worst-case scenario approach are not achievable when record selection is conditioned on a CS hinging on a single period, namely they cannot be simultaneously caused by the same set of *CS(SAT)-selected* records. For example, if T_2 is far from T_1, the very extreme hazard levels of SAT_2 among the 13 considered here cause very high PFA values but very low IDR values. The opposite holds for CS(SAT_1)-based records for high SAT_1 values that bring the structure close to collapse (i.e., high IDR) but cause relatively low levels of PFAs. The conservativism of picking the worst-case scenario for estimating all the EDPs IM level of interest is obviously unacceptable if applied to seismic assessment. CS(*AvgSA*)-based records, however, provide median values of *both* IDR and PFA that are moderately high *at all stories for all* IM *levels.* Therefore, the results shown here may suggest an alternative solution to the problem of selecting a single IM to provide joint estimates for all EDPs. The medians of IDR and PFA based on CS(*AvgSA*)-based records for all hazard levels are not the maximum observable but they are inherently consistent since they have been caused by the same set of response analyses that used the same set of ground motion records as input. In our opinion, when performing intensity-based assessment, each of these suites of records conditioned on different IMs is a legitimate representation of different events with different characteristics (i.e., magnitude, site-to-rupture distance, etc., and consequently different spectral shapes), therefore, we might expect to see differences in the structural response.

In addition, Figure 7(c) and (d) show that CS(*AvgSA*)-based records also provide, again *for*

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both MIDR and PFA along the entire height of the building, values of dispersion that are almost as low as, and sometimes lower than, the values provided by the records based on CS(SAT_1) for IDR and on CS(SAT_2) for PFA. This relatively low variability for all 13 hazard levels (not shown here besides IM level 5) and for all stories, enables the prediction of IDR and PFA at all stories for any given hazard level more efficiently and more practically than the worst-case scenario approach discussed above. This robustness is clearly not shared by CS(SAT)-based records regardless of the specific oscillator period utilized. In this case, ensembles of records based on SAT_1, SAT_2 and $SATH$ may yield low dispersion in the IDR and PFA at some IM levels and high at other IM levels, or high at some floors and low at other floors for the same IM level. Based on these premises, the use of CS($AvgSA$) to select ground motion record ensembles for risk-assessment purposes involving multiple EDPs and multiple hazard levels seems a plausible and, arguably, superior alternative that is investigated in the next section.

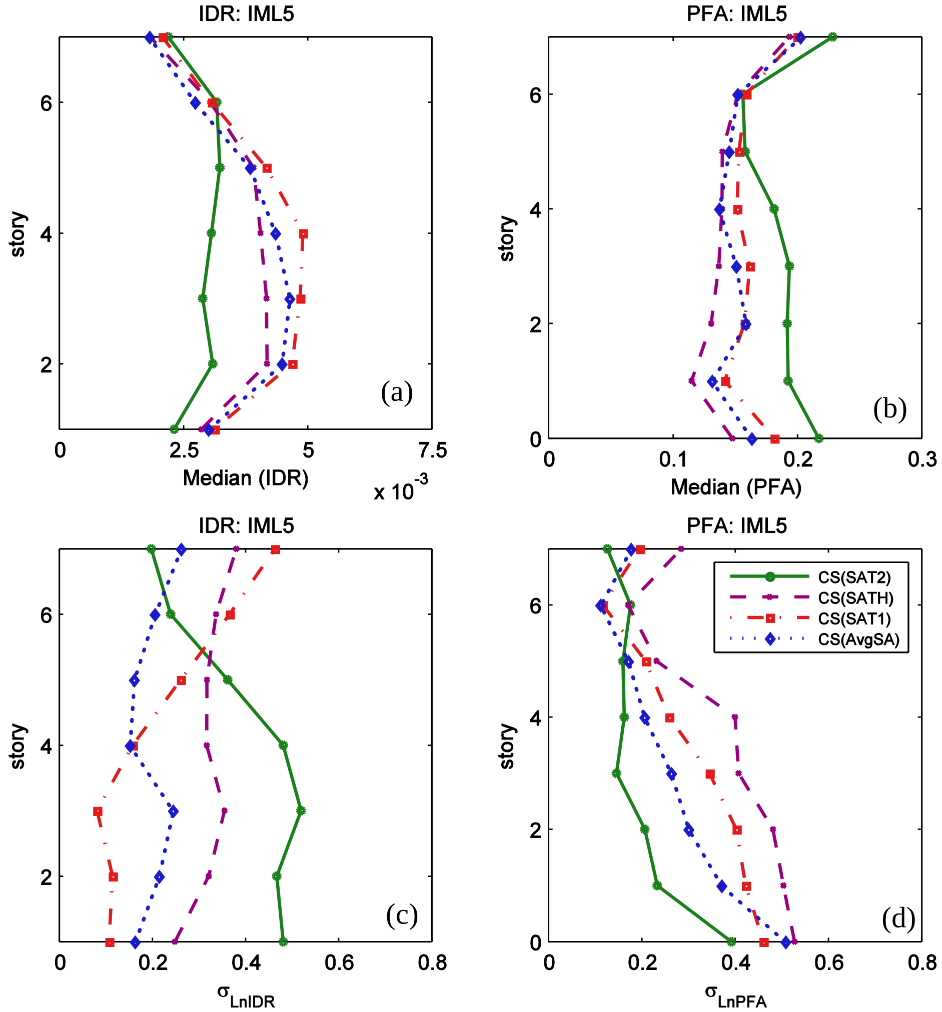

Figure 7. The median and logarithmic standard deviation profile along the height for the 7-story building based on four record selection approaches, CS(SAT_1), CS(SAT_2), CS($SATH$), and CS($AvgSA$): (a) Median IDR, (b) Median PFA, (c) IDR dispersion, and (d) PFA dispersion computed at IM level 5.

6.2. Risk-based assessment

The response hazard curves for MIDR and PFA at the 5-th floor of the 7-story building computed using different CS record selections are shown in Figure 8(a) and (b), respectively.

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It is apparent that the response hazard curves, especially for PFA, are not as similar as one may have expected. Although theoretically the choice of the conditioning variable would not matter if we had an infinite database of ground motion records appropriate for the site under consideration (and thus no need for a GMPE). In practice we do not and, therefore, it does matter as discussed in [44]. In that study, it was shown that in a practical context, if hazard consistent record selection is used (i.e., based on CS or GCIM), the estimate of the response hazard curve is prone to inaccuracies mainly because of the (i) poor interpolation of the response distribution (i.e. *EDP|IM*) and (ii) limited number of ground motion records used to obtain the response distribution. In our case, both of these clauses are valid, yet we believe that there are additional factors that have come into play.

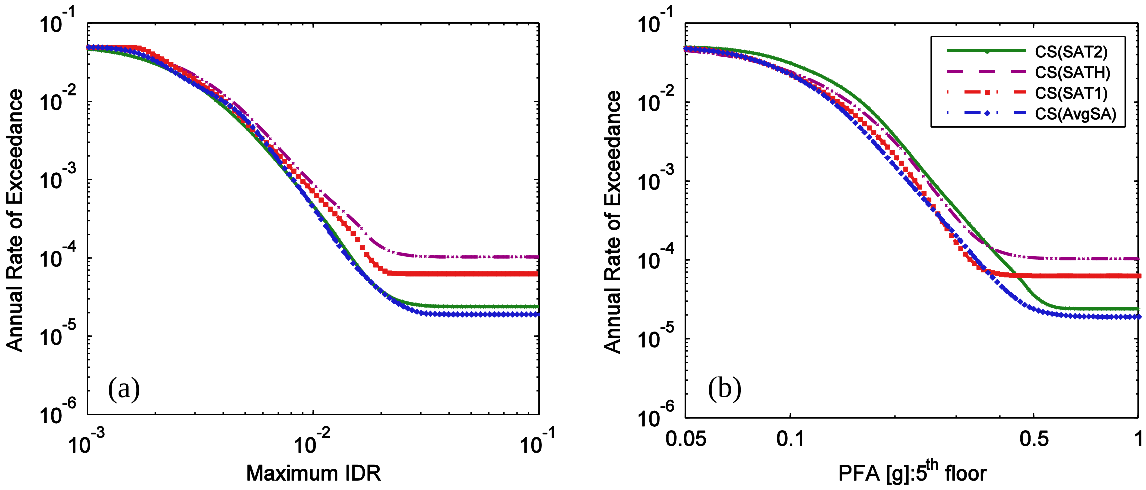

Figure 8. Response hazard curves for the 7-story building. Comparison between different record selection approaches: (a) Maximum inter story drift ratio along the height (MIDR); (b) Peak Floor Acceleration at the 5th floor.

Firstly, by inspecting the hazard consistency in Figure 5 it is evident that at exceedance rates around 10^{-4}, SAT_1 is nearly hazard consistent for all four IMs, while *AvgSA* slightly under-represents the amplitudes of all four IMs. Correspondingly, *AvgSA* produces lower risk-based estimates of demands in Figure 8 at exceedance rates of about 10^{-4}. This might be a potential reason for the differences observed in the response hazard curves especially at exceedance rates around 10^{-4}. We emphasize that, as mentioned earlier, in all selected CS-based records, we used the exact method of CS (and not the approximate one), and as claimed in [13], the hazard consistency should be verified in this case. In that study, the authors used the approximate approach and observed hazard inconsistency especially when lower periods (such as the T_2 of our study) were used. Subsequently, assuming that this inconsistency was imposed due to the application of the approximate CS-method, they inflated the conditional variance of their CS, to reach a better hazard consistency. The final result of such inflation of the variance of the target spectrum was that the drift hazard curves of various IMs was closer (but not exactly the same). This raises the question, what might be the cause for such inconsistency as we observe in Figure 5. One possible reason might come from the correlation coefficients for spectral acceleration at different periods, shown to be magnitude-dependent (dependence not accounted for in computing CS here) by Azarbakht et al. [47] and Carlton and Abrahamson [48].

Secondly, another potential issue might be the dissimilar predictive ability of each IM for various EDPs due to the different conditional spectral period(s) employed. As an example, the

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response hazard curves shown in Figure 8 are affected by the predicted response distribution (i.e., mean and variance of EDP given IM) and the corresponding probability of collapse. For both PFA and IDR, the probability of global collapse is defined essentially on MIDR, either by observing numerical non-convergence or by exceeding a given drift threshold. Therefore, the distribution of collapse-inducing values of the IM is fixed and influences the right tail of the response hazard curve for any EDP of interest. In analysis of the buildings in this study, we observed that when using CS(SAT_2), similar to [13], systematically fewer collapses are observed compared to the record sets of CS(SAT_1) or CS($SATH$) for any given return period. This is because the record sets selected based on CS(SAT_2) are lower in median spectral acceleration around the periods that most influence structural collapse, i.e. periods between T_1 to TH (see Figure 3a). This results in lower probability of collapse for CS(SAT_2) for any given return period and consequently an overall lower MAR of collapse. A similar pattern was also observed based on CS($AvgSA$) in comparison with CS(SAT_1). Hence, the corresponding response hazard curves for CS(SAT_2) and CS($AvgSA$) are lower in the right tail for both PFA and IDR in Figures 8(a), (b). Similarly, for example, CS(SAT_2) is focused on the high frequency spectral content and thus predicts higher PFA values for practically any MAR level in the left side of Figure 8(b), i.e., before collapse and MIDR influence take over. This is in full agreement with the considerations made in Section 6.1 of this article.

7. DISCUSSION

It is worth distinguishing the results presented here which uses CS-based selection with a single-period IM versus the "classical" single period IM assessments. The former actually considers target values of a range of *SAT* values and aims to match all those targets via careful record selection. The latter uses only the IM when selecting records. In that sense, CS-selection shares features with Vector PSHA using the "indirect method," [24] in that it uses disaggregation to obtain target values of different IMs. Therefore, CS approach based on single-period *SA* values are not "ignoring" other spectral periods but rather addressing them via record selection rather than in the IM. This study goes one step forward compared to the CS-based selection with a single-period IM by changing the conditioning IM to *AvgSA*, in order to bring the integration of multiple periods closer to the conditioning IM and benefit from associated improvements and error reductions down the line.

After observing the difference in the results presented in the previous sections, the question remains, "is one of these record sets superior to others in seismic assessment?" Notwithstanding, all versions of CS selection presented could be considered valid choices for performing assessment. Hence, why should we prefer CS($AvgSA$) instead of the simpler option of CS conditioned at a single period, such as SAT_1? One might claim that any hazard inconsistency, such as appearing in Figure 5 may make any comparison more difficult. Yet, we find several reasons to favor a CS($AvgSA$)-based approach:

- *AvgSA* has a lower GMPE dispersion (i.e., lower $\sigma_{IM|\mathrm{rup}}$, which implies higher predictability) compared to any singe spectral acceleration (e.g. Figure 4). This is an advantage in reducing the total uncertainty of the PBEE procedure, as seen by inspecting Equation (7). Note that we observed here, in agreement with Bradley et al. [36], that this dispersion is generally the dominant one in assessing the total dispersion of the EDP.
- *AvgSA* is an IM with an efficient prediction power, namely low $\sigma_{\ln EDP|IM}$, for very different EDPs such as IDR and PFA that are instrumental in risk assessment and loss estimation. This does not occur for spectral accelerations at any single oscillator period.
- The dispersion $\sigma_{\ln EDP|IM}$ is also more constant along the height of the building at different

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IM levels than for other IMs (such as SAT_1, for example). This means that the level of accuracy in estimating IDR and PFA *at each story* is comparable. When using SAT_1 to predict IDR, for example, the accuracy is usually much higher at the lower stories than it is at the higher stories of tall structures and vice-versa for PFA.

- Given that $\sigma_{IM|\mathrm{rup}}$ and, on average, $\sigma_{\ln EDP|IM}$ tend to be lower when *AvgSA* is used than the corresponding values for single spectral accelerations, it is reasonable to expect that the total uncertainty in the EDP estimate (see Equation (7)) and, in turn, in loss estimates, are more accurate. For example, Figure 9 compares at IM level 5 the total dispersion of IDR (Panel a) and of PFA (Panel b) along the height of the 7-story building computed using different record selection approaches. The advantage of using the CS(*AvgSA*) approach is clear. Similar results can be found for other IM levels, stories or buildings.
- The estimate of losses caused by earthquakes at any floor of a building are due to damage to both deformation-sensitive components, whose extent is well predicted by IDR, and acceleration-sensitive components, whose extent is instead well predicted by PFA. Only an accurate prediction of both can ensure an accurate prediction of the total losses. *AvgSA* is a relatively good predictor of both EDPs, unlike any other single spectral accelerations considered here. Therefore, records based on CS(*AvgSA*) can be efficiently used to predict losses. Other proposals found in the literature suggested using multiple sets of analyses for assessing each EDP, with an evident waste of resources.
- Again with focus on the loss estimation, as discussed in the text using a set of analyses employing, say, CS(*SATH*)-based records for estimating IDR and, from it damage to drift-sensitive components and a separate set of analyses using CS(SAT_2)-based records for estimating PFA may lead to biased loss estimates. High IDR values and high PFA values do not occur for the same record. CS(*SATH*)-based records tend to emphasize IDR estimates and, therefore, IDR-related damage and losses. On the other hand, CS(SAT_2)-based records tend to emphasize PFA-related damage and losses. Summing the former losses with the latter for each IM level is likely to lead to overestimating the total losses. Record selected based on CS(*AvgSA*) do not have this negative feature provided that the spectral ordinates averaged are not skewed towards either long periods, such as *TH*, or shorter ones, such as T_2.

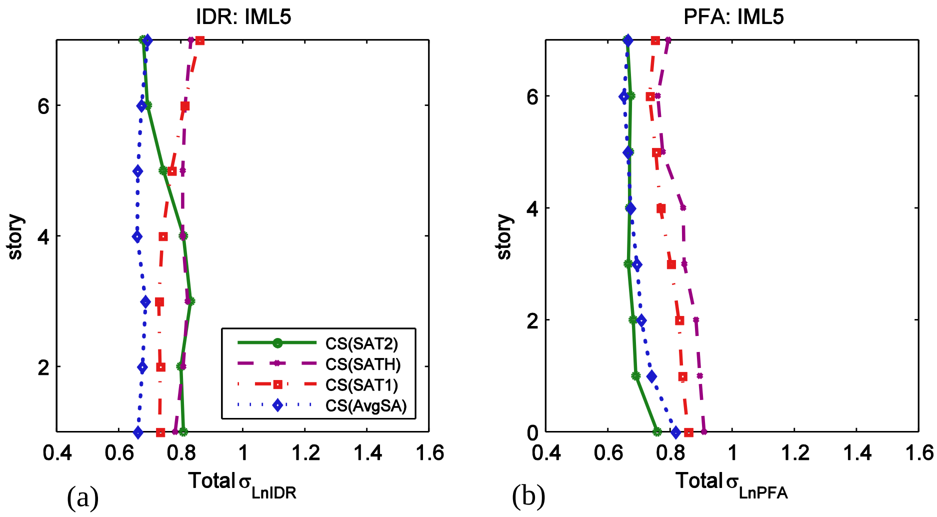

Figure 9. Comparison between the total logarithmic standard deviation of the response based on different record selection approaches based on Equation (8): (a) PFA; (b) MIDR dispersion profiles for IM level 5.

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- When using a CS(*AvgSA*) approach to record selection, the hazard consistency at high IM levels (i.e., rarer, high-amplitude spectral ordinates) can be achieved with lower scale factors than when using a CS(SAT_1) or other single-period CS methods. Scaling records to very high IM levels is necessary when assessing the collapse capacity of modern structures given the scarcity of records that naturally have such high spectral ordinates. Since over-scaled records may cause biased responses, limiting the scale factors while maintaining the hazard consistency is certainly advantageous. Scale factors and the spectral mismatch with CS(SAT_1) of records that were observed for high IM levels are documented in Kohrangi [26]-Appendix E.
- The CS(*AvgSA*)-based record selection combines different causal earthquakes from all possible scenarios contributing to the site hazard for different spectral ordinates of interest into the target spectrum. While CS(*SAT*) approaches are based on the same premise, it could be intuitively argued that by using *AvgSA,* events that are more relevant for the risk of structure investigated are better weighted and thus more efficiently incorporated in the record selection compared to an *SAT*-based scheme.
- One of the features of the *AvgSA,* as an advanced IM, is its practicality compared to some other complicated advanced IMs. In other words, we can perform the hazard computations for this IM, using the available GMPEs for spectral accelerations and the corresponding correlation coefficients (*indirect* method), recall Equations (3) and (4). Note that, this, however, is an assumption that requires verification using actual GMPEs obtained directly from record data (*direct* method). In this study, in lines with the previous similar studies we accept the legitimacy of the indirect method, nevertheless, we recall the necessity to thoroughly investigate this assumption.

8. CONCLUSIONS

We explored the use of an alternative approach to probabilistic seismic demand analysis that uses ground motion records selected from a conditional spectrum based on the average spectral acceleration, *AvgSA*, in the period range that matters for the response of the considered building. *AvgSA* has already been shown in previous studies to be an efficient and sufficient IM for building response prediction but *AvgSA* has not been used so far both for informing hazard analysis and also for selecting ground motion records to be used as input to structural response assessment. Here *AvgSA* is utilized in the implementation of an extension of the single-period based conditional spectrum, called here CS(*AvgSA*), to explicitly hinge on the average of multiple spectral accelerations, and also in the probabilistic hazard calculations. The entire chain of probabilistic seismic demand analysis, which is the first step to loss estimation, is thus internally fully consistent.

The proposed methodology was tested for four 4-, 7-, 12- and 20-story steel and RC buildings located in a highly seismic site in south of Marmara Sea in Turkey. The 2D structural models of such buildings were subject to both *intensity-based* and *risk-based assessment* calculations by using ground motions selected according to CS(*AvgSA*) and CS(*SAT*) at multiple periods ranging from T_2 to $1.5 \cdot T_1$, where T_1 and T_2 are the first two fundamental frequency of the linear elastic building. *AvgSA* is an intensity measure that has many qualities that range from a higher predictability vis-a-vis single-period spectral accelerations to an overall a superior prediction power for both EDPs that control the building seismic losses, namely the peak in time interstory drift (IDR) and the peak floor acceleration (PFA) at each story. This holds for different IM levels, both weak and intense.

The efficiency of *AvgSA for both IDR and PFA* is essential in risk-based assessment where

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their distribution at all IM levels is necessary. In this respect, it is advantageous to work with the conditioning IM that performs moderately well for different EDPs at all stories and at all IM levels rather than identifying the very best IM that is only efficient for estimating a single EDP and perhaps not even at all stories of a building (e.g., SAT_1 is not a good predictor for IDR at high stories of a tall building) and not for all IM levels (e.g., *SATH* is very good for estimating IDR at high ground motion intensity levels but poor at weak ones).

In an intensity based assessment context, on the other hand, it has been advocated (Lin [12], Bradley [43]) to use multiple IM predictors as conditioning IM and use the envelope of the obtained results from multiple analyses. This approach requires response analyses for multiple sets of records selected according to different IMs. This may be fine for design purposes [46], but not for assessment, as such it would not only be wasteful and less practical but also potentially conservative. Instead, utilizing CS(*AvgSA*) seems to be advantageous compared to this enveloping approach by both reducing the analysis effort and removing the unneeded conservatism.

Finally, the use of CS(*AvgSA*) showed more flexibility during record scaling to match the CS amplitude levels than the use of CS conditioned on single period spectral accelerations. A good hazard consistency to CS(*AvgSA*) for the severe hazard levels necessary to test the ultimate capacity of these buildings was ensured by limiting the scale factors to four while scale factors up to 10 were necessary when using the CS(SAT_1). The potential for overscaling and, therefore, of using records with unrealistic characteristics that may cause biased EDP estimates is greatly reduced when CS(*AvgSA*)-based records are utilized.

The results presented in this study are performed for four difference building examples using 2D structural models. We did not distinguish between different record types (such as pulse-like versus ordinary), seismic source types, etc. and we only considered the spectral shape as the dominating characteristic of the ground motion. As such, further research on verifying the superior qualities observed herein for CS(*AvgSA*) and extending its application to different building types, 3D models, different seismic regions, etc. should be conducted.

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REFERENCES

1. Cornell CA. *Engineering seismic risk analysis.* Bulletin of Seismological Society of America, 1968. **58**:1583–1606.
2. Bazzurro P, Cornell CA. *Disaggregation of Seismic Hazard.* Bulletin of Seismological Society of America, 1999. **89**(2):501–529.
3. Iervolino I, Galasso C, Cosenza E. *Computer aided record selection for code-based seismic structural analysis. REXEL.* Bulletin of Earthquake Engineering, 2010. **8**(2):339–362.
4. Baker JW, Cornell CA. *Spectral shape, epsilon and record selection.* Earthquake engineering and structural dynamics, 2006. **35**(9):1077–1095.
5. ICC, *International building code*, 2003: Interntational Code Council.
6. ASCE. *Minimum Design Loads for Buildings and Other Structures*, in *American Society of Civil Engineers/Structural Engineering Institute*2010: Reston, VA.
7. Eurocode8. *design of structures for earthquake Resistance,* in *—Part 1: general rules, seismic actions and rules for buildings*2004, Comité Européen de Normalisation: Brussels, Belgium.
8. Jayaram N, Lin T, Baker JW. *A Computationally Efficient Ground-Motion Selection Algorithm for*

Matching a Target Response Spectrum Mean and Variance. Earthquake Spectra, 2011. **27**(3):797–815.

9. Bradley BA. *A generalized conditional intensity measure approach and holistic ground-motion selection.* Earthquake Engineering and Structural Dynamics, 2010. **39**(12):1321–1342.
10. Iervolino I, Giorgio M, Galasso C, and Manfredi, G., *Conditional hazard maps for secondary intensity measures.* Bulletin of the Seismological Society of America, 2010. **100**(6): 3312–3319.
11. Bradley BA. *Ground motion selection algorithm based on the generalized conditional intensity measure approach.* Soil Dynamics and Earthquake Engineering, 2012. **48**:48–61.
12. Iervolino I, Chioccarelli E, and Convertito V, *Engineering design earthquakes from multimodal hazard disaggregation.* Soil Dynamics and Earthquake Engineering, 2011. **31**(9): 1212–1231.
13. Lin T, Haselton CB, Baker JW. *Conditional spectrum-based ground motion selection. Part I: Hazard consistency for risk-based assessments.* Earthquake engineering and structural dynamics, 2013. **42**(12):1847–1865.
14. Lin T, Haselton CB and Baker JW. *Conditional spectrum-based ground motion selection. Part II: Intensity-based assessments and evaluation of alternative target spectra.* Earthquake engineering and structural dynamics, 2013. **42**:1867–1884.
15. Kwong NS, Chopra AK, McGuire RK. *A framework for the evaluation of ground motion selection and modification procedures.* Earthquake Engineering and Structural Dynamics, 2015. **44**(5):795–815.
16. Kohrangi M, Bazzurro P, Vamvatsikos D. *Vector and Scalar IMs in Structural Response Estimation: Part II–Building Demand Assessment.* Earthquake Spectra, 2015.
17. Cordova PP, Deierlein GG, Mehanny SS and Cornell CA. *Development of a two-parameter seismic intensity measure and probabilistic assessment procedure*. in *2nd US–Japan Workshop on Performance-based Earthquake Engineering Methodology for RC Building Structures, Sapporo, Hokkaido, 2000.* 2000.
18. Vamvatsikos D, Cornell CA. *Developing efficient scalar and vector intensity measures for IDA capacity estimation by incorporating elastic spectral shape information.* Earthquake Engineering & Structural Dynamics, 2005. **34**:1573–1600.
19. Mehanny SSF. *A broad-range power-law form scalar-based seismic intensity measure.* 2009. **31**(7):1354–1368.
20. Bianchini M, Diotallevi P, Baker JW. *Prediction of Inelastic Structural Response Using an Average of Spectral Accelerations*. in *10th International Conference on Structural Safety and Reliability (ICOSSAR09), Osaka, Japan*. 2009.
21. Bojórquez E, Iervolino I. *Spectral shape proxies and nonlinear structural response.* Soil Dynamics and Earthquake Engineering, 2011. **31**(7):996–1008.
22. Kazantzi AK, Vamvatsikos D. *Intensity measure selection for vulnerability studies of building classes.* Earthquake Engineering and Structural Dynamics, 2015:DOI: 10.1002/eqe.2603.
23. Eads L, Miranda E, Lignos DG. *Average spectral acceleration as an intensity measure for collapse risk assessment* Earthquake Engineering and Structural Dynamics, 2015.
24. Kohrangi M, Bazzurro P and Vamvatsikos D. *Vector and Scalar IMs in Structural Response Estimation: Part I–Hazard Analysis.* Earthquake Spectra, 2015.
25. Adam C, Kampenhuber D, Ibarra LF and Tsantaki S. *A new spectral acceleration based intensity measure for seismic collapse assessment of P-delta vulnerable frame structures,* 2016. *(under review)*
26. Kohrangi M. *Beyond scalar Intensity Measures in seismic risk assessment*, in *UME School/ROSE Programme* 2015, IUSS-Pavia.
27. Monelli D, Pagani, M, Weatherill G, Silva V, Crowley H. *The hazard component of OpenQuake: The calculation engine of the Global Earthquake Model*. *15th World Conference on Earthquake Engineering, Lisbon, Portugal*, 2012.
28. Giardini D. et al. *Seismic Hazard Harmonization in Europe (SHARE).* Online data resource, Swiss Seismological Service, 2013: ETH Zurich, Zurich, Switzerland, [Available at: http://www.efehr.org:8080/jetspeed/].
29. Boore DM and Atkinson GM. *Ground-Motion Prediction Equations for the Average Horizontal*

Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s. Earthquake Spectra, 2008. **24**(1):99–138.
30. Baker JW, and Jayaram N. *Correlation of spectral acceleration values from NGA ground motion models.* Earthquake Spectra 2008. **24**:299–317.
31. OpenSEES. Open system for earthquake engineering simulation. Pacific Earthquake Engineering Research Center, 2011. (Available from: http://opensees.berkeley.edu).
32. Kohrangi M. *CS(AvgSA) software, https://drive.google.com/open?id=0B6og4ZbhkXLSVnlad19udXdWaTA.* 2015.
33. Almufti I, Motamed R, Grant DN, Willford, M. *Incorporation of Velocity Pulses in Design Ground Motions for Response History Analysis Using a Probabilistic Framework.* Earthquake Spectra, 2015. **31**(3):1647–1666.
34. Luco N, Bazzurro P. *Does amplitude scaling of ground motion records result in biased nonlinear structural drift responses?* Earthquake Engineering and Structural Dynamics, 2007. **36**(13):1813–1836.
35. Kramer, SA, Mitcell RA. *Ground motion intensity measures for liquefaction hazard evaluation.* Earthquake Spectra 2006. **22**(2):413–438.
36. Bradley BA, Dhakal RP, MacRae GA, Cubrinovski M. *Prediction of spatially distributed seismic demands in specific structures: Structural response to loss estimation.* Earthquake Engineering and Structural Dynamics, 2009. **39**:591–613.
37. Shome N, Cornell CA, Bazzurro P, Carballo JE. *Earthquakes, records, and nonlinear responses.* Earthquake Spectra, 1998. **14**(3):469–500.
38. Cornell AC, Jalayer F, Hamburger RO, Foutch DA. *Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines.* Journal of Structural Engineering, 2002. **128**(4):526–533.
39. Vamvatsikos D, Cornell CA. *Direct estimation of the seismic demand and capacity of oscillators with multi-linear static pushovers through Incremental Dynamic Analysis.* Earthquake Engineering and Structural Dynamics, 2006. **35**(9):1097–1117.
40. Luco N, Cornell CA. *Structure-Specific Scalar Intensity Measures for Near-Source and Ordinary Earthquake Ground Motions.* Earthquake Spectra, 2007. **23**(2):357–392.
41. Iervolino I. *Design earthquakes and conditional hazard, in Protection of Built Environment Against Earthquakes, M. Dolsek (Ed.).* Springer-Verlag New York. ISBN-13: 9789400714472; ISBN: 9400714475, 2011.
42. Spillatura A, et al., *Use of Site-Specific Magnitude-Distance Distributions in Record Selection,* 2016. *(Under review)*
43. NIST. Selecting and scaling earthquake ground motions for performing response-history analyses, NIST GCR 11-917-15. *Technical Report*, prepared by the NEHRP Consultants Joint Venture for the National Institute of Standards and Technology: Gaithersburg, Maryland, 2011.
44. Bradley BA. *The seismic demand hazard and importance of the conditioning intensity measure.* Earthquake Engineering and Structural Dynamics, 2012. **41**(11):1417–1437.
45. Bradley BA. *A comparison of intensity-based demand distributions and the seismic demand hazard for seismic performance assessment.* Earthquake Engineering and Structural Dynamics, 2013. **42**:2235–2253.
46. BSSC. *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. FEMA P-1050*, ed. W. Building Seismic Safety Council, D.C., 515p. 2015: available at: https://www.fema.gov/media-library/assets/documents/107646.
47. Azarbakht A, Mousavi M, Nourizadeh M, Shahri M. *Dependence of correlations between spectral accelerations at multiple periods on magnitude and distance.* Earthquake Engineering and Structural Dynamics., 2014. **43**:1193–1204.
48. Carlton B, Abrahamson N. *Issues and Approaches for Implementing Conditional Mean Spectra in Practice.* Bulletin of the Seismological Society of America, 2014. **104**(1):503–512.
49. Fox MJ, Stafford PJ, Sullivan T. *Seismic hazard disaggregation in performance‐based earthquake engineering: occurrence or exceedance?* Earthquake Engineering and Structural Dynamics, 2015.

