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A record selection methodology for vulnerability functions consistent with regional seismic hazard for classes of buildings

M. Kohrangi[(1)], D. Vamvatsikos[(2)], P. Bazzurro[(3)]

[(1)] *Research assistant, University Institute for Advance Studies (IUSS), Pavia, Italy. mohsen.kohrangi@gmail.com*
[(2)] *Assistant Professor, School of Civil Engineering, National Technical University of Athens, Greece. divamva@mail.ntua.gr*
[(3)] *Professor, University Institute for Advance Studies (IUSS), Pavia, Italy. paolo.bazzurro@iusspavia.it*

Abstract

Earthquake loss estimation studies for portfolios of buildings are performed routinely for a variety of applications, ranging from risk evaluation and mitigation to post-event emergency assessment. Essential ingredients of such analyses are the vulnerability functions appropriate for different building classes representing the regional inventory. When abundant empirical data are absent, which is often the case, these vulnerability functions are obtained numerically via dynamic analyses informed by sets of ground motion records, usually selected without specific criteria. The implicit assumption is that the vulnerability function of two identical buildings located at different sites in the region would be identical. However, the structural response estimates even of identical buildings are sensitive to the characteristics of the earthquakes that control the hazard at each site in the region. Hence, strictly speaking, vulnerability functions should be both structure- and site-specific. This consideration is always neglected in portfolio loss assessment where identical vulnerability functions are used for buildings in the same class regardless of where they are located. Developing a set of different, site-specific vulnerability functions for like buildings in the same class is, however, impractical. To address this complexity, a record selection scheme is proposed that employs the conditional spectrum (CS) method but uses as a conditioning Intensity Measure (IM) the spectral acceleration (geometrically) averaged over a period range. This conditioning IM is more in sync with the response of a class of buildings rather than with the response of any single one. In addition, this method modifies the standard CS approach by incorporating within a single target CS the variation of the target spectra at multiple sites. An example of this method illustrates the development of a vulnerability function that is consistent with the regional hazard for a class of tall buildings.

Keywords: Regional loss assessment; building response site-dependence; record selection; conditional spectrum

1. Introduction

Vulnerability functions are commonly obtained based on: 1) empirical methods, 2) analytical methods, 3) engineering judgment; and 4) hybrid methods. In the first approach, the data related to the structural damages observed in a site after an earthquake are collected and used for generation of the vulnerability functions [1-4]. This method, if enough data is available, is perhaps the most reliable of all. When enough empirical data is not accessible, numerical analyses (analytical approach) could be used. This approach is based on structural modeling and simulation and it is arguably the most widely used [5-8]. The next method is collecting data based on the opinion of a group of engineers regarding the damage of different types of structures and relying on their experience as in ATC-13 [9]. In the hybrid method, a combination of all other three methods is employed [10-13].

When analytical methods are used, the structural models of different building types should be generated and different analysis methods could be applied for the assessment, such as capacity-spectrum based method using pushover analysis [14, 15], displacement-based methods [16, 17] or Nonlinear Dynamic Analysis, NDA, [18] depending on the desired level of accuracy. When NDA is performed for vulnerability assessment, one challenge is the record selection. Unlike previous methods, in an analytical approach, the analyst has control of the collected data by choosing the IM type and the IM levels at which the analysis will be performed. The structural response is, generally, dependent on the structural characteristics, the site conditions and location of the building. For instance, the same reinforced concrete buildings with the same characteristics and design would have different vulnerability functions at two different sites within the same country. The site seismicity, the closest fault rupture distance to the building, the soil type, etc. can alter the building response and consequently the predicted damages. This suggests that the record selection, which links the seismic hazard of the site to the building seismic response, should be representative of the characteristics of that specific site. In addition, in a portfolio analysis, different classes of buildings (e.g. steel, reinforced concrete, masonry) with different properties (e.g. low-rise, mid-rise and high-rise) should be analyzed. The record selection, therefore, should be also building-specific. In recent years several record selection approaches for building- and site-specific record selection such as Conditional Mean Spectrum (CMS) [19], Conditional Spectrum (CS) [20] and Generalized Conditional Intensity Measure (GCIM) approach [21] have been proposed.

When the vulnerability of a portfolio at multiple sites with different seismic characteristics is of interest, it is common that one set of records regardless of its consistency with the hazard of the site is used and Incremental Dynamic Analysis [22] or some other form of stripe or cloud analysis [23] is performed. This will result in identical damage functions for the buildings located in different sites. Ideally, however, one should perform multiple record selections for each site and building, separately, to obtain appropriate damage functions specific to the site and the building. Although this method is the most precise approach for such problems, it is cumbersome and might not seem appealing in practice.

To address this, Haselton et al. [18] noticing the significance of the spectral shape in site-specific collapse assessment of building structures in a portfolio, proposed a simplified method for adjustment of epsilon [24] accounting for spectral shape in order to be able to use a single set of records for collapse assessment of a class of buildings (by avoiding a careful record selection). Kazantzi and Vamvatsikos [25] proposed using the (geometrically) averaged spectral acceleration [26, 27, 28] for a range of periods (*AvgSA*) as Intensity Measure (IM) for a class of buildings in vulnerability studies. It was concluded in that study that even without a careful record selection, *AvgSA* is a good structural response predictor for a group of buildings compared with spectral acceleration at the first mode of vibration of the building, SAT_1, while it has also a higher sufficiency. Eads *et al*. [29] using *AvgSA* for collapse assessment of a group of 700 buildings with different heights and types, showed that, in general, this IM, if an appropriate period range is selected, can be a sufficient and efficient IM for building collapse risk assessment. Kohrangi *et al*., [30] proposed a method based on the extension of the conditional spectrum based record selection approach conditioned on spectral acceleration at single period, CS(*SAT*), [20], by changing the conditioning IM from spectral acceleration at a single period to *AvgSA*, CS(*AvgSA*). This selection scheme provides a suite of records that matches the mean and variation of the spectrum, maintaining the hazard consistency at the site.

Here a record selection approach for portfolio seismic assessment is proposed by re-engineering both CS(*SAT*) and CS(*AvgSA*) to incorporate multi-site effects. It stands on the idea of the "exact" CS method where multiple causal earthquakes and multiple Ground Motion Prediction Equations (GMPEs) are incorporated [31]. As a result, a single set of records is selected to be consistent (to the extent possible) with the hazard at all the sites. This way, even though identical fragility/vulnerability functions are still obtained for identical buildings located at different sites, they are arguably characterized by a fair mean (and perhaps even variability of) response of the buildings at all the sites by systematically considering the inherent site-to-site variability in a single shot. In addition, the CS(*AvgSA*) approach also allows the use of a single scalar IM that can remain common throughout an entire class of buildings, thus facilitating the summarization of results for the generation of vulnerability curves while retaining high sufficiency and efficiency for structural demand [25], something impossible to achieve with the single-period-dependent SAT_1. In the following, the details of the methodologies are described, together with their application in an illustrative example.

1. Problem definition

Perhaps the most accurate and robust way of generating building fragility functions at multiple sites for which the hazard seismicity is significantly different is to derive them to be building- and site-dependent and use the same specific fragilities for each site and building separately in the cost and loss estimations. This approach might not be appealing in practice because, firstly, deriving building specific fragility functions for each site means performing site-specific record selection for multiple IM levels and nonlinear dynamic analysis multiple times corresponding to each building, each site and each IM level. Secondly, when using the fragilities in the loss estimation procedure, it is an easier task to consider one fragility curve for a class of buildings everywhere within the region to avoid heavy bookkeeping. Therefore, an effort to define a single fragility curve for multiple sites, on one hand, and further avoid deriving multiple fragility functions for multiple-sites is of interest. Two methodologies are introduced here to achieve this objective:

i) *incorporating multiple fragility functions* related to multiple-sites into a single function (the multi-run approach);

ii) *incorporating multiple sites in record selection* to perform record selection and nonlinear dynamic analysis only once (he single-run approach).

In the following, both methodologies are explained.

1.2 Fragility function definition

There are different ways to derive the fragility functions to be used in regional loss estimation. In this study, we are focused on the analytical approach. There are a number of ways to estimate parameter values for a fragility function which are consistent with the observed data, depending on the procedure used to obtain structural analysis data [32]. The fragility functions are commonly defined as lognormal cumulative distribution functions, $\Phi(\cdot)$, by means of the logarithmic mean (θ) and logarithmic standard deviation (β) of the IM*s* causing exceedance of a specific limit state (LS):

$$P(\mathrm{LS} \mid IM = x) = \Phi\left(\frac{\ln(x/\theta)}{\beta}\right) \tag{1}$$

where $P(\mathrm{LS} \mid IM = x)$ is the probability of exceedance of a certain limit state (LS) given the *IM* being equal to *x*. This fragility function could be called a building fragility function and is meant to relate the overall damage state of a building with a ground motion IM. This is generally different than the ones defined for building components that are used for detailed building-specific loss estimation. Two main approaches for the estimation of fragility parameters (θ,β) are the method of moments and the method of maximum likelihood. In this study, we use the method of moments for IDA and the method of maximum likelihood for the multi-stripe analysis (MSA). Unlike IDA, when MSA is used, the analysis may not be performed up to IM amplitudes where all ground motions exceed the predefined LS (e.g. collapse), offering some reduction in computations at the cost of some potential bias. In this case, using the method of moments is not applicable.

1.3 Multiple fragilities from multiple sites

With the assumption of lognormal distribution of the fragilities, when the parameters of multiple fragility functions, using one of the methods, is estimated, multiple fragility functions could be incorporated into a single function using the *law of total variance*. The logarithmic mean and standard deviation of such a fragility function is obtained based on the following expressions:

$$\theta_{tot} = \exp\left[\sum_{s=1}^{n} P_s \cdot \ln(\theta_{IM,s})\right], \tag{2}$$

$$\beta_{tot} = \sqrt{\sum_{s=1}^{n} P_s \cdot \left[\beta^2_{\ln IM,s} + \left(\ln\left[\frac{\theta_{tot}}{\theta_{IM,s}}\right]\right)^2\right]}\ , \tag{3}$$

θ_{tot} and β_{tot} are the median and logarithmic standard deviation of the IM, respectively, i.e., the estimated parameters of the incorporated fragility. P_s, is the weight considered for site *s*, which is dependent on the significance of each site or could be defined in proportion to the number of buildings in each site, for instance. $\theta_{IM,s}$ and $\beta_{IM,s}$ are the median and logarithmic standard deviation of the fragility function obtained for site *s*. Here we use this multi-run method as a benchmark for examining the accuracy of the simpler single-run methodology explained in the following section.

2. Multi-Site Conditional Spectrum record selection

2.1 Original single causal earthquake, single-site approach

A computationally efficient algorithm has been proposed by Jayaram et al. [20] to compute the CS target that considers both the mean and variance of the spectral accelerations at different spectral ordinates for a single site. The procedure for a single scenario is summarized as follows. The conditional mean spectral ordinates at periods T_1 to T_n (i.e., vector of {ln$SA(T_1)$,…,ln$SA(T_n)$}) conditioned on IM^* is defined as:

$$\mu = \begin{bmatrix} \mu_{\ln SAT_1} + \rho_{\ln SAT_1,\ln IM^*} \cdot \varepsilon(IM^*) \cdot \sigma_{\ln SAT_1} \\ \mu_{\ln SAT_2} + \rho_{\ln SAT_2,\ln IM^*} \cdot \varepsilon(IM^*) \cdot \sigma_{\ln SAT_2} \\ \vdots \\ \mu_{\ln SAT_n} + \rho_{\ln SAT_n,\ln IM^*} \cdot \varepsilon(IM^*) \cdot \sigma_{\ln SAT_n} \end{bmatrix} \tag{4}$$

in which $\mu_{\ln SAT_i}$ and $\sigma_{\ln SAT_i}$ are the logarithmic mean and standard deviation of the spectral acceleration at period T_i, obtained from the GMPE for a given scenario (e.g., magnitude, rupture-to-site distance and fault type). $\rho_{\ln Sa(T_i),\ln IM^*}$ is the correlation coefficient between the spectral acceleration at period T_i and IM^*. The epsilon value $\varepsilon(IM^*)$ is the number of standard deviations by which a given lnIM^* of a recorded ground motion differs from the mean predicted by a GMPE. In general, epsilon can be defined as:

$$\varepsilon(IM) = \frac{\ln IM - \mu_{\ln IM}}{\sigma_{\ln IM}} \tag{5}$$

where lnIM is a given (unscaled) ground motion recorded value of IM. The covariance matrix of the spectral accelerations at multiple ordinates conditioned on IM^* is therefore defined as:

$$\mathbf{\Sigma} = \mathbf{\Sigma}_0 - \frac{1}{\sigma^2_{\ln IM^*}} \cdot \mathbf{\Sigma} \cdot \mathbf{\Sigma}_1' \tag{6}$$

where prime denotes transposition of a matrix. $\mathbf{\Sigma_1}$ is defined as

$$\Sigma_1 = \begin{bmatrix} \rho_{\ln SAT_1, \ln IM*} \cdot \sigma_{\ln SAT_1} \cdot \sigma_{\ln IM*} \\ \cdots \\ \rho_{\ln SAT_n, \ln IM*} \cdot \sigma_{\ln SAT_n} \cdot \sigma_{\ln IM*} \end{bmatrix} \tag{7}$$

$\mathbf{\Sigma_0}$ denotes the (unconditional) covariance matrix of the vector $\{\ln SAT_1, \ldots, \ln SAT_n\}$:

$$\Sigma_0 = \begin{bmatrix} \sigma^2_{\ln SAT_1} & \cdots & \rho_{\ln SAT_1, \ln SAT_2} \cdot \sigma^2_{\ln SAT_1} \cdot \sigma^2_{\ln SAT_n} \\ \vdots & \ddots & \vdots \\ \rho_{\ln SAT_n, \ln SAT_1} \cdot \sigma_{\ln SAT_n} \cdot \sigma_{\ln SAT_1} & \cdots & \sigma^2_{\ln SAT_n} \end{bmatrix} \tag{8}$$

The diagonal elements of $\mathbf{\Sigma}$, denoted by $\Sigma_{i,i}$ can be expressed as:

$$\Sigma_{i,i} = \sigma^2_{\ln SAT_i} - \frac{1}{\sigma^2_{\ln IM*}} \cdot \rho^2_{\ln SAT_i, \ln IM*} \cdot \sigma^2_{\ln SAT_i} \cdot \sigma^2_{\ln IM*} \tag{9}$$

The standard deviation of SAT_i conditioned on $IM*$ is therefore defined by:

$$\sigma_{\ln SAT_i | \ln IM*} = \ln SAT_i \cdot \sqrt{1 - \rho^2_{\ln SAT_i | \ln IM*}} \tag{10}$$

2.2 Incorporating multiple causal earthquakes, GMPEs and sites

Lin et al. [31] proposed a formulation for computing a conditional spectrum incorporating multiple causal earthquakes and GMPEs at a single site. This method is adopted here and extended to incorporate the hazard disaggregation for multiple sites. Such a CS target could be used for selecting a single set of records for analyzing an archetype building at different sites. We can consider the "exact" solution for multiple causal earthquakes, GMPEs and sites, weighing all the scenarios (numbered by *j*), GMPEs (numbered by *k*), and sites (numbered by *s*) to estimate the conditional mean and standard deviation of the spectrum:

$$\mu_{\ln SAT_i | \ln IM*} = \sum_s \sum_j \sum_k p_{s,j,k} \cdot \mu_{\ln SAT_i, s, j, k | \ln IM*}, \tag{11}$$

$$\sigma_{\ln SAT_i | \ln IM*} = \sqrt{\sum_s \sum_j \sum_k p_{s,j,k} \cdot \left[\sigma^2_{\ln SAT_i, s, j, k | \ln IM*} + \left(\mu_{\ln SAT_i, s, j, k | \ln SAT*} - \mu_{\ln SAT_i | \ln IM*} \right)^2 \right]}, \tag{12}$$

where $\sigma_{\ln SAT_i | \ln IM*}$ is the *i*-th element of the co-variance matrix and $p_{s,j,k}$ is the probability of the *j*-th scenario, *k*-th GMPE and *s*-th site, as it applies to the logarithmic mean value of the conditional spectral accelerations.

3. Case study description

Four plan-symmetric moment-resisting frames are employed as case-studies, namely a 4-story steel frame, and three reinforced-concrete frames of 7, 12 and 20 stories. These are modern structures built to post-1980 seismic design provisions for high-seismicity regions (NEHRP site class D). A 2D centerline idealization of each building was modeled using OpenSees [33]. The behavior of the structural members was modeled by lumped-plasticity elements to increase speed of computation and to improve numerical convergence for large deformations. Geometric nonlinearities in the form of P-Δ effects were considered. Further details on the building properties and modeling approach appear in Kazantzi and Vamvatsikos [25]. The first modal periods of the buildings are 1.82, 1.60, 2.10 and 2.85s for the 4-, 7-, 12- and 20-story buildings, respectively.

We intend to derive fragility and vulnerability functions for three different sites with latitude and longitude of [32.76°, 32.76°], [28.96°, 41.02°] and [39.49°, 39.74°], representing the Turkish cities of Ankara, Istanbul and Erzincan, respectively. The OpenQuake [34], 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 [35] source model and the GMPE proposed by Boore and Atkinson [36]. The hazard curves corresponding to the spectral acceleration at T = 1.6s and *AvgSA*(0.4:0.2:4.0s) for the three sites are shown in Fig. 1.

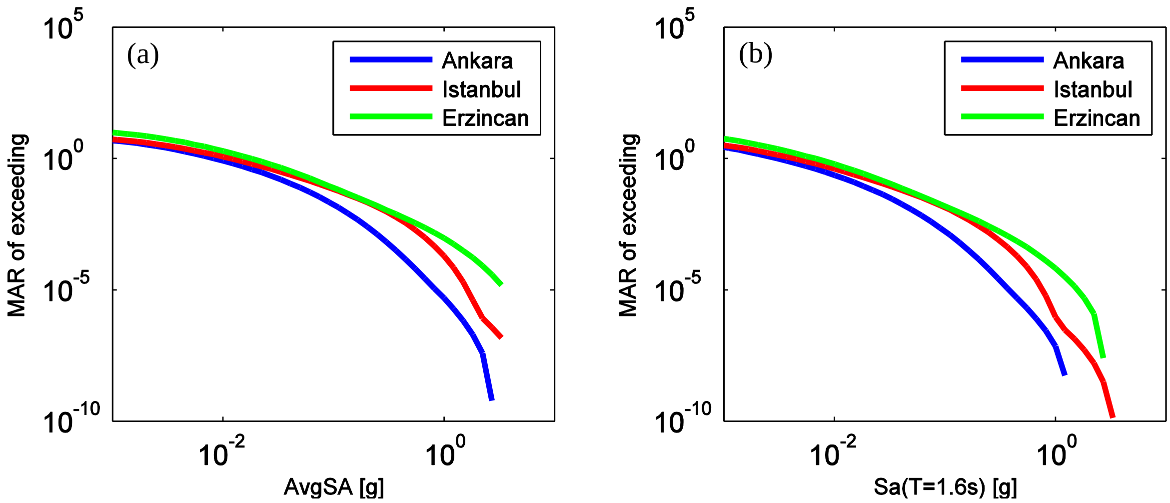

Fig. 1 – Hazard curves for Ankara, Istanbul and Erzincan for (a) *SA*(1.6s) and (b) *AvgSA*(0.4:0.2:4.0s). Legend: MAR=mean annual rate. (Note: the shorthand notation of 0.4:0.2:4.0s will be used to denote a set of periods ranging from 0.4s to 4.0s with an increment of 0.2s).

In order to show the site sensitivity of the global and local EDP response conditioned on the IM (and the corresponding fragility curves) of a given building model, multiple nonlinear dynamic analyses are performed according to the IDA [22] and MSA [23] paradigms. In IDA a fixed suite of ground motions is appropriately scaled to evaluate response at each IM level. Although MSA was originally cast to use a fixed record set, having little difference from IDA, we shall exploit instead the flexibility it allows to employ a different ground motion set at each IM level, selected each time according to the hazard of each site of interest. Of course, such flexibility comes at a price. Changing the conditioning IM in IDA is a simple, practical matter of post-processing. On the other hand, in MSA (as applied herein) the choice of the IM when selecting the records is critical since the same IM should also be used for the structural response estimation (and later the convolution with the hazard) to maintain the benefit of hazard-consistent record selection.

The fixed IDA record set comprises the 22 pairs of motions of the FEMA P695 [37] far-field ground motion set. These are strong ground motions originating from relatively large magnitude events appropriate for collapse prediction of modern structures. Record selection for MSA was performed at each IM level using two target spectra, namely CS(SAT_1) conditioned on the first mode of the vibration of each building, and CS(*AvgSA*) computed for the spectral ordinates at periods T = 0.4:0.2:4.0s. For each building, target spectrum and IM level, four record sets of equal size (44 accelerograms) were chosen. Three sets to match the hazard at each of the three sites, and the fourth record set to represent the hazard at all three sites together assuming equal weighting. We emphasize here that when *AvgSA* is adopted as the conditioning IM a single period range may often be chosen to investigate the response of multiple buildings. This is the case herein, where the four buildings examined have fundamental periods T_1 = 1.6s – 2.85s. The period range of 0.4:0.2:4.0s used for *AvgSA* is meant to cover both the "elongation" of T_1 (say by a factor of about 1.5) due to damage and the periods shorter than T_1 corresponding to the higher modes affecting response. Thus, as we will see, one does not need to differentiate among the different buildings when performing CS(*AvgSA*), significantly reducing the computational burden.

For both CS approaches, records from NGA-West1 ground motion database were selected and scaled to collectively match the entire distribution of the CS. To do so, we used the original algorithm developed for CS(*SAT*) [20] and its extended version for CS(*AvgSA*) [30]. For CS record sets, each consisting of 44 records, 10 IM levels were adopted, having fixed values of 0.01, 0.05, 0.08, 0.15, 0.25, 0.35, 0.50, 0.65, 0.80 and 0.95g to cover all ranges of the building response from linear to nonlinear until collapse. The target spectra were defined based on the mode (i.e., the most probable scenarios) of the M-R distributions from disaggregation results of the hazard. It is emphasized, however, that these 10 fixed IM levels, although used for both IM types, have different return periods when associated with different IMs. More specifically, they tend to correspond to higher hazard levels (longer return periods) for *AvgSA* than for SAT_1. Fig. 2 shows the target spectra for CS(*SAT*) and CS(*AvgSA*) at IM level 5 for each individual site and for the multi-site approach together with the 44 individual records selected for the multi-site target. The mean (in log-space) and 2.5th, 97.5th percentiles lines of the FEMA P695 records used for IDA are also shown for comparison, scaled to SAT_1 and *AvgSA* corresponding to the IM level 5. This IM level (0.25g), for example, in Ankara corresponds to a return period of 6.2×10^{-5} for SAT_1 at 1.6s and of 1.3×10^{-3} for *AvgSA* in the period range of 0.4:0.2:4.0s.

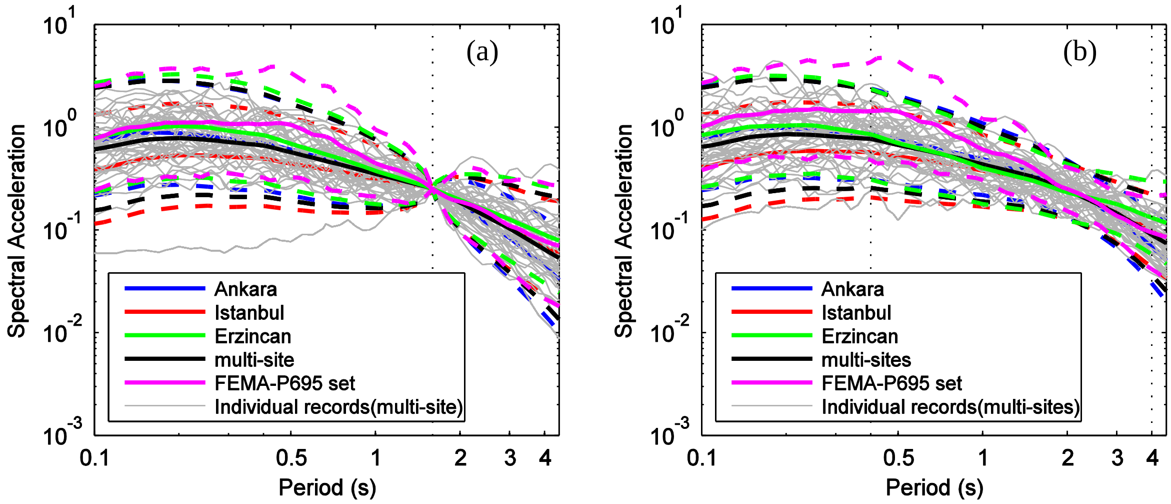

Fig. 2 – Record selection corresponding to the IM level 5 of 0.25g for the 7-story building for three sites using conditional spectra-based records versus the FEMA P-695 far-field set used for IDA: (a) CS(SAT_1), (b) CS(*AvgSA*). Thick solid lines indicate medians and dashed lines mark the 2.5th and 97.5th percentiles. The individual records shown in grey correspond to records selected via the multi-site method.

4. Analysis results

4.1 Local response

The nonlinear dynamic analysis results based on IDA and MSA for the site of Ankara are shown in Fig. 3. Fig. 3(a) and (b) show the IDA curves corresponding to the maximum IDR along the height (MIDR) based on the conditioning IMs of SAT_1 and *AvgSA*, respectively. As observed, the dispersion in IDA when *AvgSA* is used as the conditioning IM is lower than that when SAT_1 is used instead. This suggests a higher efficiency of *AvgSA* compared to SAT_1, in line with the findings of previous studies (e.g. [26], [30]). Fig. 3(c) and (d) display the MIDR response based on MSA and the conditioning IMs of SAT_1 and *AvgSA*, respectively. Each stripe consists of 44 data points related to the MIDR response, each one obtained from one nonlinear dynamic analysis. As was previously observed in Kohrangi et al. [30], the results obtained from the record set of CS(*AvgSA*) tend to maintain a uniform dispersion at different IM levels, which is a desirable feature, whereas the counterpart set of CS(SAT_1) produces less dispersed results for MIDR in the lower IM levels and more dispersed results at higher IM levels (i.e., at higher nonlinearity). This is because, SAT_1 is naturally a good (better) predictor for elastic response compared to *AvgSA* and it loses its efficiency at higher IM levels. *AvgSA*, on the other hand, is remains an adequate IM at all IM levels from linear to nonlinear state of the structure (see [30] for more details). The MIDR results, however, present only a partial, although important, view about the building response. For a comprehensive loss assessment, an IM should predict an EDP well at different IM levels and at different locations within the building and also should perform well in estimating different EDP types (i.e., acceleration- and displacement-based).

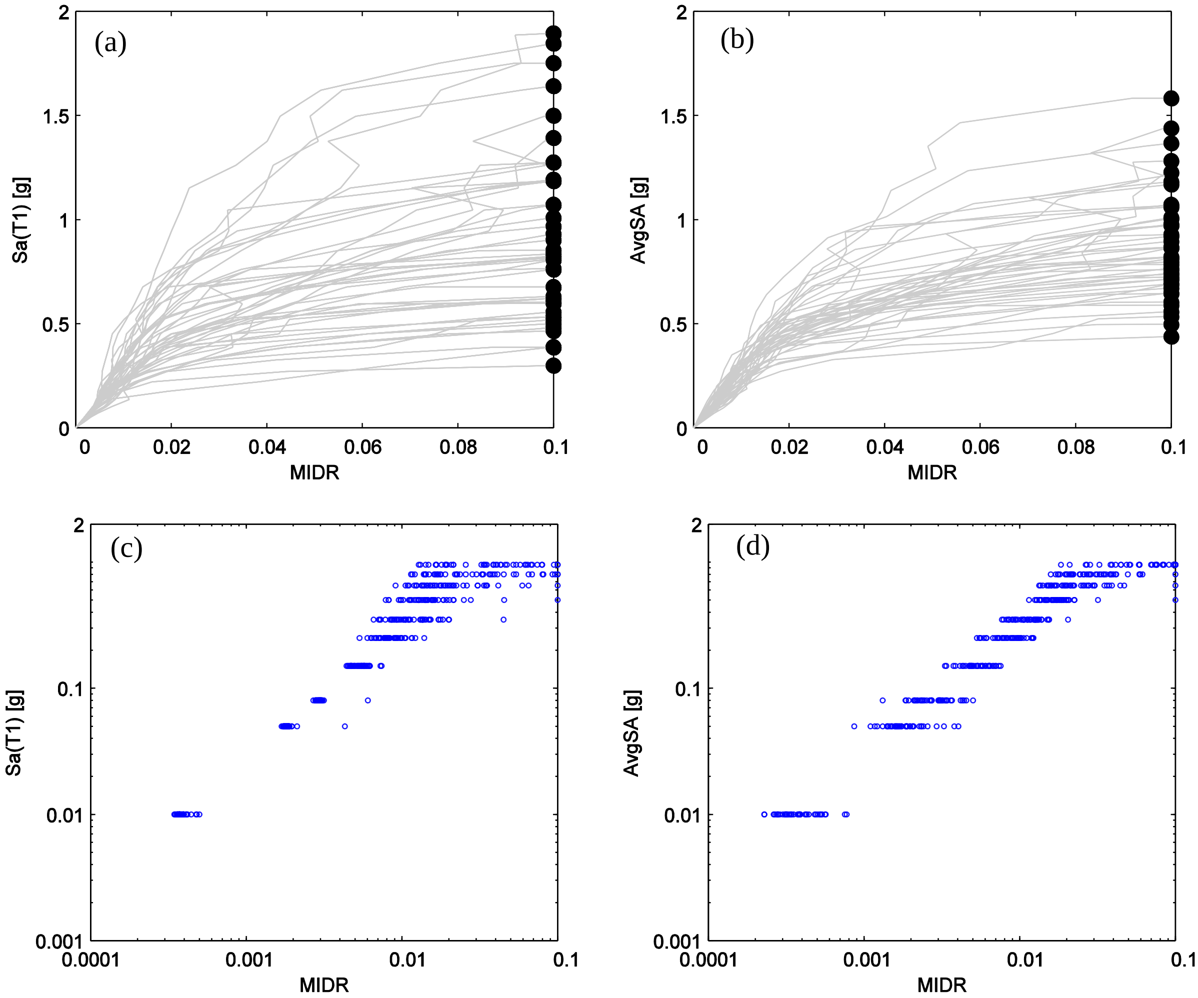

Fig. 3 – Nonlinear dynamic analysis results based on: IDA with (a) IM= SAT_1 and (b) IM=*AvgSA*, versus MSA with records selected for Ankara via (c) CS(SAT_1) and (d) CS(*AvgSA*).

4.2 Analytical fragility functions

Several damage criteria have been proposed in the literature (see Akkar et al. [38], for instance), to assign buildings to a damage state and generate the corresponding fragility functions. These may be based on the maximum roof displacement, inter story drift ratio, steel or concrete strain level, maximum base shear, and so on. For illustrative purposes only and for the sake of simplicity, we have limited our consideration to only the maximum inter story drift ratio along the building height, MIDR, as the damage measure gauging the overall structural performance up to global collapse.

For generating fragility curves based on MIDR we selected four different Limit States, LS1 through LS4, ranging from low to extensive damage for each EDP type. For MIDR, the probability of exceeding drifts of 0.75, 1.2, 2.0 and 4.0% were assumed. The resulting fragility curves obtained for MIDR are shown in Fig. 4, respectively. Therein, the site-specific fragility curves for Ankara, Istanbul and Erzincan as well as the ones obtained from site-indifferent IDA are depicted. In addition, the fragility curves obtained using the proposed single-run and multi-site methodology are compared against the arguably most accurate (and expensive) multi-run approach, from the weighted combination of multiple fragility curves. For the example at hand, equal weighting of the sites has been adopted throughout. By inspecting these two figures we observe the following:

1. First and foremost, the building fragility functions are site-dependent, as was expected based on the results presented in the building analysis section. The difference in the fragility curves for different sites suggests that the common approach of applying a *single* fragility function can bring large uncertainty and bias into loss estimation unless the accelerograms used for its development are carefully selected to be consistent with the seismic hazard of the region.

2. The site-insensitive fixed record set used for IDA, in almost all cases, underestimates the building capacity. This might not be a general conclusion for every record set, since a main observation already is that different sets do produce different fragility curves. For instance, it seems that the FEMA P695 record set employed for IDA actually represents well the seismicity of the site of Erzincan for assessing MIDR, whereas it is far from representing well the seismicity of Ankara. However, in line with what was stated above, one could conclude that using randomly selected record sets to perform dynamic analysis without at least some consideration to spectral shape and hazard consistency, can generate potentially biased risk estimates. One might argue that the methodology introduced by Haselton et al. [18] may help to adjust the IDA results to achieve site-dependence. In that approach (adopted also in FEMA P695 by definition of spectral shape factor), the median parameter only (and not dispersion) of the fragility function obtained from IDA is adjusted based on the ratio between the mean of the epsilons of the records in the adopted set versus the expected mean epsilon of the records appropriate for the site (from hazard disaggregation) corresponding to a relevant hazard return period. Still, this method has been calibrated only for collapse assessment based on MIDR. It is not obvious whether such an approach could be applied successfully for predicting other limit-states based on either local or global EDPs.

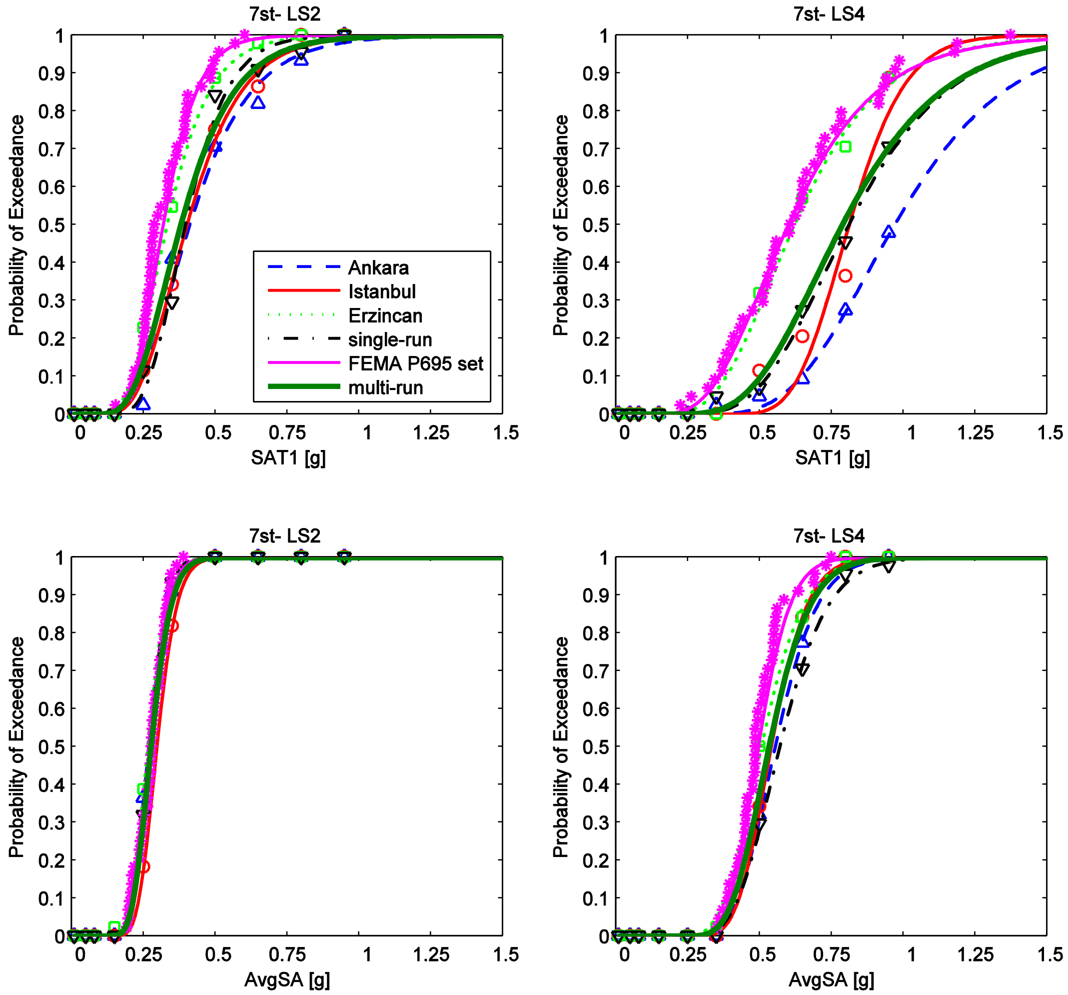

Fig. 4 – MIDR fragility curves obtained analytically for the 7-story building based on the two different IMs of SAT_1 and *AvgSA* and on record sets selected for different sites. (LS2 and LS4 are defined for MIDR values exceeding the limit states whose onset corresponds to 1.2 and 4.0%, respectively)

3. The use of *AvgSA*, at least in the cases analyzed here, bring the fragility curves of buildings at different sites closer together compared to those obtained using SAT_1. This suggests that, even if the user decides to use a single fragility function for multiple-sites without performing careful record selection, developing it via IDA based on *AvgSA* could be an acceptable approach. This feature of *AvgSA* could be explained with reference to its higher efficiency and sufficiency in building response prediction compared to SAT_1. Kohrangi et al. [30] and Kazantzi and Vamvatsikos [25] showed that *AvgSA* can

provide an efficient response estimation of local EDPs for buildings. This efficiency was observed to be uniform at different IM levels, whereas SAT_1 showed comparable efficiency and a reasonable sufficiency only when predicting MIDR at lower IM levels.

4. The proposed single-run multi-site methodology provides results that are very close to the comprehensive multi-run multi-site approach used as a benchmark. Whenever one fragility is sought to represent multiple sites, both methods offer a result that incorporates the input of all sites according to the assigned weights and sits in between their individually estimated fragility functions. Yet, the single-run approach does so at a vastly reduced cost, requiring exactly 1/N of the dynamic analyses per archetype building when N is the number of sites involved. Of course, the question still remains whether one fragility (per limit-state) or vulnerability, no matter how carefully crafted, can be used to accurately estimate the regional loss for a class of buildings. Yet, for purely practical reasons, this is the approach that is universally adopted. Only future research can provide a definitive answer.

5. Conclusions

The main focus of this study was to investigate whether or not building global fragility functions used in loss estimation procedures are independent of the site where the building is located. The current state of practice is application of identical fragility functions for similar building archetypes located in multiple-sites assuming that there is no effect of the site seismicity in building response. With this goal in mind, the building fragility functions for a reinforced concrete building example were derived using nonlinear dynamic analysis for three different sites with different seismicity. Careful hazard consistent record selection scheme based on conditional spectrum method as well as incremental dynamic analysis for comparison reasons were adopted. The results in this study, in contrary with the assumption described above, show that the building fragility functions at multiple sites are not identical. Such difference in the fragilities among sites, if not taken care of in practice, might cause significant errors in regional building loss assessments. This observation suggested further investigations for finding eventual solutions for this complexity.

In order to address this problem, two methodologies are proposed here. The first approach incorporates multiple fragilities obtained for each site into one fragility to be used for all the sites. The second approach incorporates multiple-sites using conditional spectrum based record selection considering the variability in the target spectrum of each site. The results here show that these two methods provide fragility curves which can be used to represent all the sites. In addition, the fragilities obtained from both methods are quite similar. This similarity offers considerable evidence in support of the proposed record selection scheme incorporating multiple sites.

Finally, two different IMs of spectral acceleration at the first building mode of vibration, $SA(T_1)$, and averaged in a period range, *AvgSA*, were examined here. The results show that when *AvgSA* is used, the scatter in the response among different sites is diminished compared with $Sa(T1)$. In addition, conditional spectrum based record selection conditioned on *AvgSA*, CS(*AvgSA*), seems to be a better solution for portfolio seismic risk assessment, since, firstly, *AvgSA* is an efficient building response predictor. Secondly, given its definition being valid in a period range it can be used for a class of buildings with different periods within the defined period range.

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7. References

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