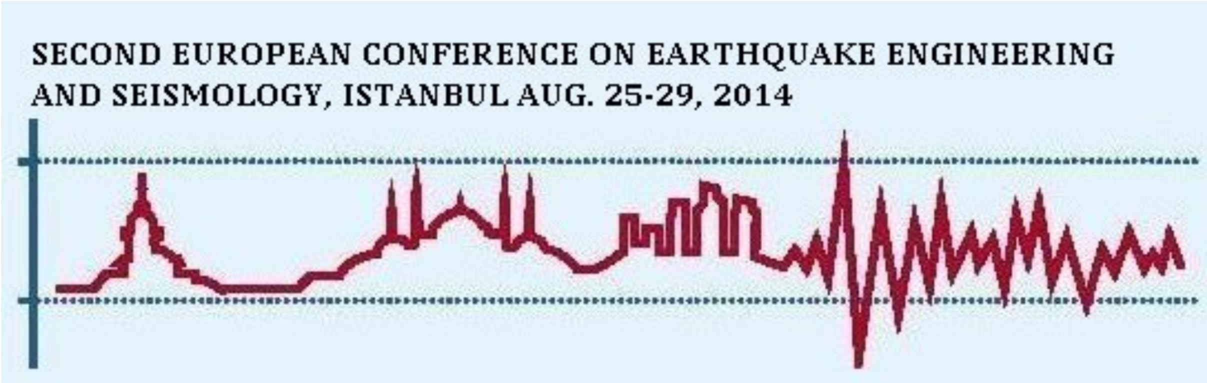

GROUND MOTION SELECTION AND MODIFICATION METHODS FOR SEISMIC RISK ASSESSMENTS

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ABSTRACT

One of the most demanding challenges in earthquake risk and loss assessment is the appropriate selection of ground motion records. Real ground motions can be selected and scaled according to a target earthquake scenario, that traditionally is defined by implicit causal parameters (magnitude, distance and epsilon). More recently different ground motion selection and modification (GMSM) methods appear with a common formulation that consists in guaranteeing a close match of the suite of records to the theoretical distribution of any set of ground-motion intensity measures conditioned on the occurrence of a specific ground motion intensity measure (usually obtained from probabilistic seismic hazard analysis). The scaled records should therefore be consistent with the target hazard scenario, in order to accurately estimating the nonlinear response of structures.

This paper examines the influence of several ground motion selection and modification (GMSM) procedures on the distribution of the structural response and, at the end, in the estimation of the seismic risk. The study compares the bias introduced in the structural response and its propagation to risk estimations, when following different scenario-based approaches and an increased number of records.

INTRODUCTION

The seismic design of structures based on their expected performance have been gaining importance in the recent years. To this end, the selection and scaling of the input ground motions is a frequently required issue that practicing engineers must face when assessing the structural performance for a given target hazard level. Many approaches have been presented for the selection of input ground motions differing from the objective point of view, with the aim to accurately estimate either the mean response and the probability distribution of the response (Ay and Akkar 2012). The selection and scaling of ground motions proposed in most utilized design and assessment engineering codes, which concern is mainly on the mean structural responses, is commonly performed on the basis of a close match to a target design response spectrum (Katsanos et al. 2010). Generally this target mean spectrum consists of a uniform hazard spectrum (UHS) representing at all the frequencies the same hazard probability at the site, however this practice is seen to lead to biased estimates of the structural response since UHS is not

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possible to represent at the same time the joint occurrence or exceedance of all of the spectral ordinates, in other words, the UHS is not able to represent the spectrum of a single event itself (Baker and Cornell 2006). This statement stems from the fact that a UHS represents an envelope over rupture magnitude (M), source-to-site distance (R) and epsilon (ε) contributors to hazard.

An alternative selection and scaling of records, to the one based on target response spectra, includes those methods which selection of input ground motions is solely dependent on guaranteeing similar magnitude and distance ranges of the hazard scenario, being therefore scaled to a target spectral level (Shome et al. 1998). Nonetheless, the significant dispersion associated to the estimation of the structural responses is an important limitation of this approach, in particular for increasing inelasticity levels (Ay and Akkar 2012).

Baker and Cornell (2006) shown the importance of the ground motion parameter epsilon (ε), as part of a vector valued intensity measure, in the context of a probabilistic assessment of structures. The spectral shape parameter was latter included in a newly derived group of target spectrum methods that conversely to the UHS are conditioned to a spectral ordinate at only a single period (CMS), at other periods the conditioned mean spectrum (CMS) has variance. An alternative approach might be to select ground motions in accordance with an earthquake scenario, not conditioned on any spectral values (CS) so that the response spectrum will have variance at all periods.

The ability to account for the mean and variance are also addressed in the studies of Ay and Akkar (2012) and Bradley (2010). The former procedure, selects and scales ground motions that are compatible with the M, R and ε implicit causal parameters, through a framework where each recording is scaled for a specific target intensity level that is established from the distance between the individual spectral ordinate and the corresponding spectral value computed from a consistent GMPE. An empirical correlation between the elastic and the inelastic behavior of an equivalent SDOF system is also used in the selection process. On the other hand, the generalized conditional intensity measure (GCIM) approach presented by Bradley is based on the use of random realizations from the conditional multivariate distribution of several explicit ground motion intensity measures, conditioned on the occurrence of a specific ground motion intensity measure. The suite of selected ground motions compatible to the theoretical multivariate distribution is then consistent and a natural extension of seismic hazard analysis.

This paper is intended to examine the influence of ground motion selection procedures on seismic risk assessment and loss estimations. The study begins by evaluating the performance of six different scenario-based GMSM approaches on the definition of the probabilistic distribution of the fragility of two non-seismically designed structures, one in RC and one in steel. The number of ground motions and corresponding scaling factors, as well as the significance to several intensity measure types (IMTs) are also analyzed herein. The paper closes with a discussion on the impact of the GMSM approaches on the seismic risk of the structures. To this end, the probabilistic SAC/FEMA closed-form probabilistic framework (Cornell et al. 2002), assuming a second-order hazard approximation (Vamvatsikos 2013), is adopted.

GROUND MOTION SELECTION AND MODIFICATION METHODS

As illustrated in the introduction, a wide variety of techniques have been developed for selecting input ground motions for the structural analysis. The selection and scaling process is a critical issue in performance-based earthquake engineering, and is probability the toughest task when dynamic analyses are required. Bradley (2012) has labelled the uncertainty introduced in the numerical computation of the seismic demand hazard due to the selection of ground motions as a methodology-type source error, which can be vanished with an appropriate selection technique.

In order to illustrate the effect on the multiple stages of a risk assessment, a total of six GMSM methods were examined based on the mean and variance of the conditioned scenario-based spectrum and implicit causal parameters, such as magnitude (M), distance to rupture (R) and epsilon (ε). A random (Rand) selection of ground motion records was also considered, representing the lower bound of accuracy of the methodologies under analysis. The various ground motion record selection methods adopted in this work are presented hereafter.

Conditional spectrum – CS

The conditional spectrum method may be shortly defined as a procedure that seeks to the target mean and variance computation of the scenario spectrum, Fig.1, whose spectral accelerations are conditioned at periods of interest (herein the fundamental period), Eq. 1 and 2.

$$\mu_{\ln Sa(T_i)|\varepsilon(T^*)} = \mu_{\ln Sa(T_i)} + \rho(T_i, T^*) \cdot \varepsilon(T^*) \cdot \sigma_{\ln Sa(T_i)} \quad (1)$$

$$\sigma_{\ln Sa(T)|\ln Sa(T^*)} = \sigma_{\ln Sa(T)} \cdot \sqrt{1-\rho(T,T^*)^2} \quad (2)$$

Where $\mu_{\ln Sa(T_i)|\varepsilon(T^*)}$ is the mean matrix of the values of ln Sa(T_i) conditioned on ε(T^*), and $\sigma_{\ln Sa(T)|\ln Sa(T^*)}$ represents the standard deviation of the values of ln Sa(T_i) conditioned on ln Sa(T^*). T^* is usually the fundamental period of the structure.

This methods sets the reference for matching of a set of real ground motion records using the disaggregation information, such as the causal earthquake M, R and ε, and the GMPM (Jayaram and Baker 2008). Jayaram's "greedy" optimization algorithm (Jayaram et al. 2011) was applied for the selection of ground motion records with no control of the scaling factors for the conditioned spectral acceleration.

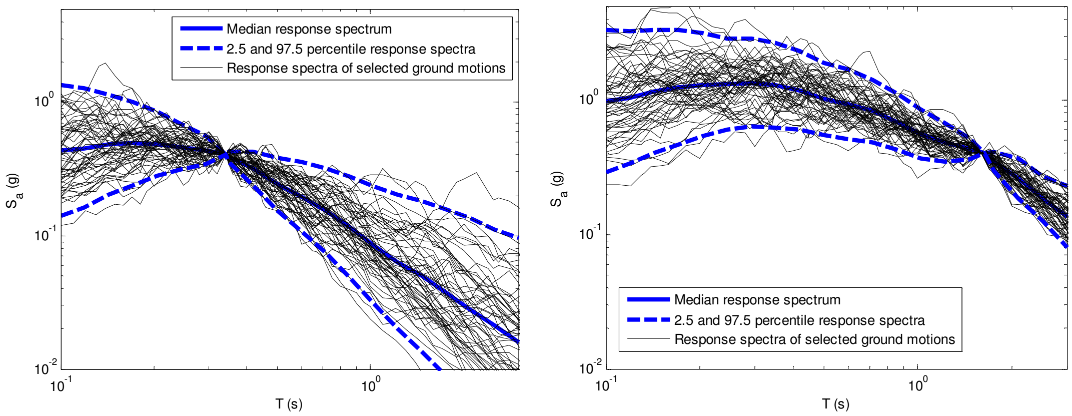

Figure 1. Response spectra of selected ground motion records for Sa(T_1=0.34 s), left, and Sa(T_1=1.63 s), right, having 1% in 50-years probability of exceedance.

Conditional mean spectrum – CMS

Baker and Cornell (2006) proposed an innovative method for the selection of ground motion records with the intention to overcome the limitations associated with the conservative adoption of UHS. The CMS method provides the mean response spectrum, conditioned on occurrence of a target spectral acceleration value at the fundamental period, requiring only existing GMPM and PSHA results. In the present study a narrow band of ± one standard deviation was also included, delimiting the lower and upper bounds for matching the target conditional mean spectrum of the scenario, Fig.2. No control of the scaling factor was considered. The fit of records compatible to the CMS was achieved by the Harmony Search (HS) algorithm and its several variants (Macedo et al. 2013). This algorithm has been implemented in SelEQ developed at the University of Porto (Dias et al. 2010).

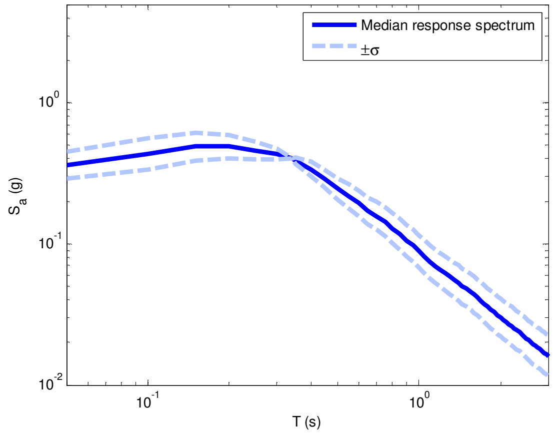

Figure 2. Mean conditioned spectra and one standard-deviation for a Sa(T1=0.34 s) having 1% in 50-years probability of exceedance.

Rupture magnitude and source-to-site distance – MR

Possibly one of the most common ground motion selection procedure, the herein termed MR approach aims to minimize the deviation between the disaggregated mean values of M and R, to the corresponding values of the selected ground motion records. In this study records are selected complying with the minimum deviations to the disaggregated mean M and R, taking into account that only a horizontal component of each record is selected and ensuring that spectral ordinates are not scaled over than 3 times at the fundamental period of the structure.

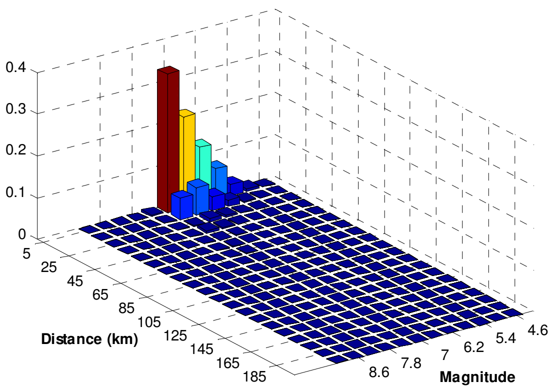

Figure 3. M and R disaggregation for Sa(T1=0.34 s) having 1% in 50-years probability of exceedance.

Epsilon – Eps

Similarly to what was performed in the aforementioned MR method, Eps records were selected so as to minimize the deviations between the ε_i values for each record and the ε mean value from the scenario, Eq. 3, limiting the maximum value of the scaling factor to 3.

$$\varepsilon_i(T) = \frac{\ln Sa_i(T) - \mu_{\ln Sa}(M,R,T)}{\sigma_{\ln Sa}(T)} \tag{3}$$

Where $\mu_{\ln Sa}(M,R,T)$ and $\sigma_{\ln Sa}(T)$ are the predicted mean and standard deviation, respectively, of *ln* Sa at a given period, and *ln* $Sa_i(T)$ is the log of the spectral acceleration of each selected ground motion record. The first two parameters are computed from attenuation models.

It is also ensured that only a horizontal component of each record is selected.

Rupture magnitude, source-to-site distance and epsilon – MRE

The MRE procedure minimizes the deviations of the M, R and ε values for each record and the M, R and ε mean values from the hazard scenario. The same control on the scaling factor and repetition of selected records defined above was considered.

Random – Rand

This selection procedure follows solely the preliminary compatibility with the local site conditions, such as the geological, tectonic and seismological characteristics. Therefore, records were selected from stable continent and active shallow crustal regions, as well as with similar hazard information (minimum M and R) provided by the studies of Vilanova and Fonseca (2007) and Sousa and Costa (2009). Although being recognized as the less accurate selection approach in this study, its consideration herein is deemed important since this still be the most applied selection criteria, not only when incremental dynamic analysis are needed but also in scientific research. For the sake of this comparison no control on the scaling factor was endorsed in this procedure.

CASE STUDY

The study presented herein was performed with the intention to assess the impact of a ground motion selection and scaling technique on the derivation of the distribution of the structural response and, therefore, on the risk assessment. Thus, two non-seismically designed frame buildings were considered, a 5-storey steel and a 3-storey reinforced concrete. In brief, the RC building consists of a moment frame with irregular bay spans and floor heights built in Europe during the 50's (pre-seismic code). This frame has a natural period of vibration of 0.37s and has been randomly generated assuming the geometric and material statistical distributions for this class of buildings, as proposed by Silva *et al.* (2014). In turn, the steel structure is a five-storey, three-bay regular frame with a fundamental period of vibration of 1.63s. More information on the characteristics of this structure may be found in Araújo (2013). Both buildings were modelled and analysed using the open source software OpenSEES (PEER, 2005). The simulation model captures both material nonlinearities in beams and columns, and large deformation (P – Δ) effects. Concentrated springs idealized by backbone response curves and the associated hysteretic rules developed by Lignos and Krawinkler (2010) were included in the steel structure model, whereas in the RC building a fibre based approach was followed.

The comparative analysis of the GMSM methods is developed assuming a site located in Lisbon, Portugal, including rock soil conditions ($vs,_{30}$=760 m/s). Probabilistic seismic hazard and disaggregation calculations were performed for this site location using the OpenQuake engine (Monelli et al. 2012). Although being necessary for the sake of the present study, one should note that the evaluation of the seismic hazard model for Portugal was not a priority of the work (additional information should be referred to the works of Sousa and Costa (2009) and Vilanova and Fonseca (2007). Nevertheless, following the work of Silva (2012), the Atkinson and Boore (2006) and the Akkar and Bommer (2010) ground motion prediction models (GMPM) were selected, demanding for multiple causal M, R and GMPM, addressed within a 3D disaggregation for the exceedance probabilities of the spectral acceleration (Sa) at the fundamental period (T1) corresponding to different intensity levels. A total of 911 non-pulse records, compatible with the seismological, geological and tectonic environment of the Portuguese mainland territory, were selected from the PEER and ESMD databases.

RESULTS

The influence of the considered GMSMs on the derivation of the fragility functions and risk assessment will be presented in this section, discussed the impact of the number of ground motion records, as well as the influence of considering different failure criteria.

The scenario-based sets of ground motion records were obtained considering 9 intensity levels ranging from 0.1g to 2.0g. A number of 60 records was assumed for each intensity level, that is believed to be an efficient number. In order to assess the efficiency of considering this amount of records in the derivation of the fragility functions 100 random generations of bins with 20 and 40 records were conducted.

The fragility functions have been derived by controlling different failure criteria, defined both by local and global engineering demand parameters. In the case of the RC structure the shear and the chord rotation demands were controlled based on the limits proposed in part 3 of Eurocode 8 (CEN 2005), the global and the inter-story drifts were checked assuming the limits established by HAZUS MR5 (2001) and ASCE 41-06 (ASCE 2007), respectively, and the level of strains developed in the concrete and the reinforcement steel verified by comparisons with the maximum strain values referred in Crowley et al. (Crowley et al. 2004). In turn, the local deformation demands developed in the steel building were controlled considering the plastic rotation limits proposed in part 3 of Eurocode 8 (EC8-3), while both global and inter-story drifts were controlled based on the limits defined by HAZUS MR5 and ASCE 41-06, respectively. An additional criterion, assuming the most critical demand parameter verified for each intensity level was also adopted for the derivation of the fragility functions for both structures, being designated by Envelope. Finally, three limit states consistent with the ones proposed in EC8-3, namely the damage limitation (DL) limit state, the significant damage (SD) limit state and the near collapse (NC) limit state, were considered.

Impact of the GMSM method in the estimation of the response

Figure 4 depicts the impact of the selected suite of ground motion records from the six GMSM methods on the derivation of the envelope fragility functions, each set containing 60 records and for the three considered limit states of damage. One should note that the random set of records (herein termed as Rand) was only applied in the assessment of the RC structure in such a way to serve as an extreme threshold in the accuracy of the structural response assessment. It may be observed that, on the one hand, the Rand selection method systematically leads to flatter fragility functions at every limit state, resulting in higher probabilities of failure for lower values of spectral acceleration, which is expected to have an important impact in the quantification of the risk, but also, on the other hand, although the MRE, MR and ε selection methods resulted in fragility functions relatively similar, these somehow differ from those obtained by using the reference CS and CMS selection methods. In fact, the two methods lead to similar fragility functions, which has been a common trend observed in both structures. It may be interesting to note that for the NC limit state, with the exception of the Rand selection method, all other GMSMs lead to fragility functions with almost the same median values, differing in the levels of dispersion.

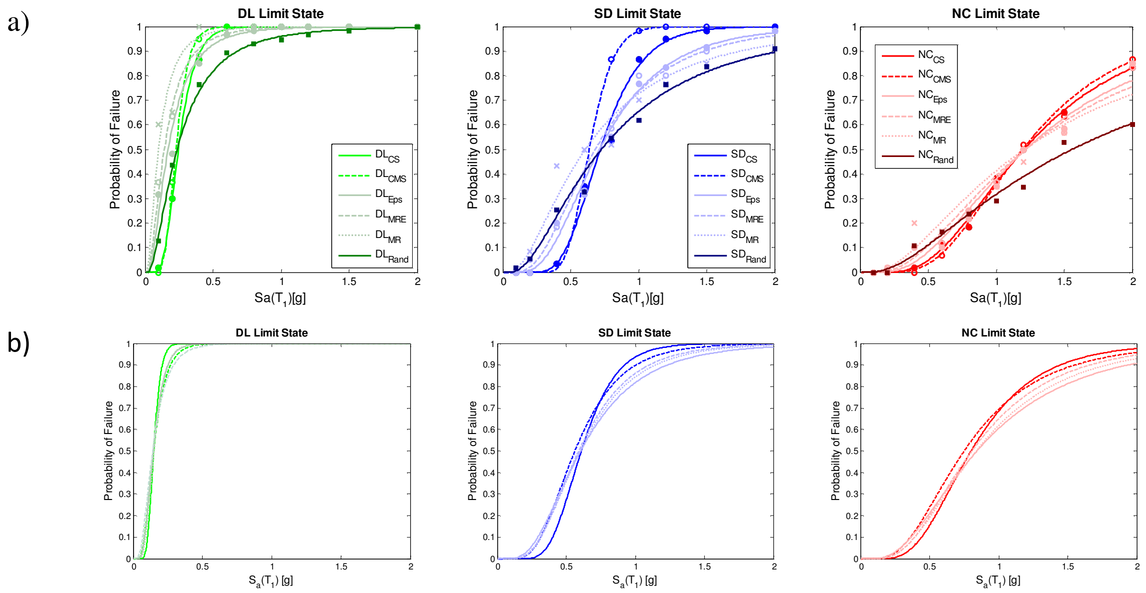

Figure 4. *Envelope* fragility functions derived from the various GMSM methods for the RC (a) and steel (b) buildings.

With the intention to evaluate the accuracy of each GMSM method, it is necessary to quantify the likelihood of the selected ground motion records and the target hazard scenario. This estimation is dependent on both the participation of higher modes in the structural response and the magnitude of the period elongation. The latter effect results from the progress into significant nonlinear demands to the structure, which is more likely to occur at higher levels of seismic intensity, on the other hand the former is typically controlled by the ground motion characteristics, the overstrength associated with each mode and the response quantity examined (Maniatakis et al. 2013).

The two analyzed frame structures are mainly dominated by a first-mode behavior, with more than 90% of the effective modal mass being mobilized at the fundamental period of vibration. Therefore the discrepancies among selection methods will arise from a misfit of the distribution of spectral accelerations of the selected suite of ground motion records, at the periods of vibration ranging from T1 to a value close to 1.5 or 2 times the fundamental period (CEN 2004, Katsanos et al. 2012). Aiming to provide a measure of the quality of a GMSM method it was proposed an index representing the goodness-of-fit of the distribution of the spectral accelerations for the suite of selected ground motions to the 'true' mean and standard deviation values of the intensity measure, representing the hazard scenario at each intensity level (obtained from disaggregation).

This index is calculated as the median along the records of the sum of the deviations between the spectral accelerations of the suite of selected records to the distribution of the values of $\mu_{\ln Sa(\mathrm{T}_i)|\varepsilon(\mathrm{T}^*)}$ (determined from attenuation relationships), at all periods between T1 and 2T1, Eq. 4.

$$I_{[T_1,2T_1]} = median\left(\sum_{i=1}^{n}\left[\mu_{\ln Sa(\mathrm{T}_i)|\varepsilon(\mathrm{T}_1)} - \ln Sa_{GM}\left(T_i\right)\right]^2\right) \tag{4}$$

Where *n* is the number of selected ground motion records in each set, $\mu_{\ln Sa(\mathrm{T}_i)|\varepsilon(\mathrm{T}_1)}$ is the mean matrix of the values of ln $Sa(T_i)$ conditioned on $\varepsilon(T_1)$, computed from Eq. 1, and ln $Sa_{GM}(T_i)$ is the logarithmic value of the spectral acceleration of the selected ground motions at the range of periods between T1 and 2T1.

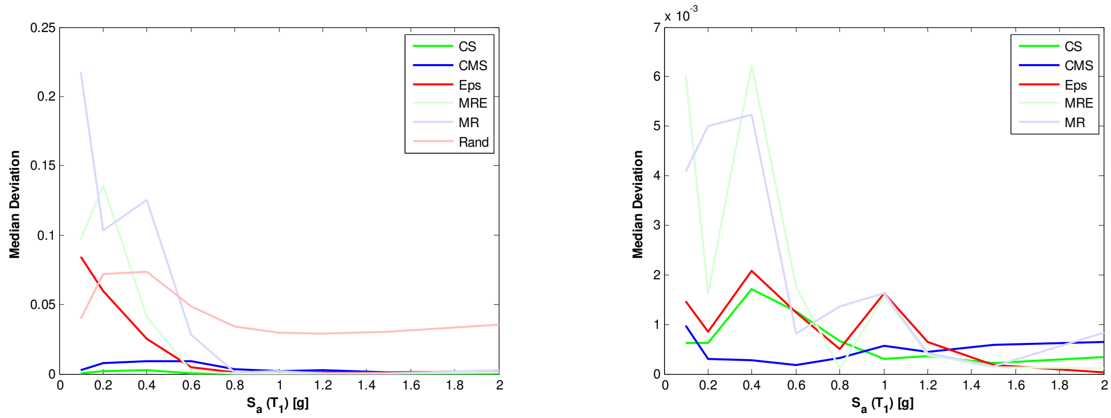

Figure 5. Values of $I_{[T1,2T1]}$ for the GMSM methods estimated for the RC (left) and steel (right) buildings.

Figure 5 depicts the evolution of index $I_{[T1,2T1]}$ with the increase of seismic intensity, computed for each GMSM method and for the RC and steel buildings. It can be clearly observed that CS and CMS are, among the studied record selection approaches, the ones with suite of ground motion records associated with lower deviations to the theoretical distribution of spectral accelerations. This fact although expected, is noticeably identified regardless of the seismic intensity level, leading to unbiased estimates of the seismic demands with respect to the considered intensity measure. In the case of the RC structure higher values of $I_{[T1,2T1]}$ are found, what is explained by the spectral shape at the vicinity of the fundamental period (T_1=0.34s), where the spectra are conditioned, thus contributing to this higher dispersion, Fig. 1. On the contrary, for the steel structure the conditioned period of vibration (T_1=1.63s) is found in the constant displacement range of the spectra, being associated with considerably lower scatter of the spectral ordinates and therefore justifying the similar trends on the fragility functions derived from any selection methodology. Therefore, the structural response is unequally affected with the applied records selection procedure in its mean and dispersion, being the magnitude of these differences dependent on the characteristics of the structure, namely the fundamental period, the mass modal participation and the period elongation. The aforementioned results suggest that when a scenario-based selection of records is needed the decision between GMSM methods should also take into consideration the structure-specific modal conditions. Notwithstanding these differences, for the NC limit state (Fig. 4), one may observe an identical distribution of the response among the records selection methods, clearly explained by the marginal differences observed in $I_{[T1,2T1]}$ at seismic intensity levels ranging from 0.6g. Moreover, limiting the selection of records only to magnitude and source-to-site distance causal parameters (MR) exhibited a significant bias in the estimation of the response of the RC building, again also captured in the estimation of index $I_{[T1,2T1]}$ mainly for lower intensity levels, while for the steel structure minor differences are evidenced in the comparison to the remaining methods. The same conclusions were highlighted in the study of Luco and Bazurro (2007), suggesting that special care must be taken depending on the fundamental period of vibration of the structure. A selection governed by the spectral shape (Eps) is followed by a good match to the 'true' distribution, consistent with the results of the CS and CMS methods for intensities higher than 0.6g, whilst the estimation of the response would not benefit much from adding to the selection filter the additional implicit causal parameters (M and R). Finally, the results for the Rand selection has revealed a clear biased estimation of the response either for the lower or for the higher intensity levels. This approach that considers a selection of records based on the type of rupture mechanism, range of admissible magnitudes and site conditions, despite being widely used in several loss assessment studies, is associated with a noticeable misfit to the hazard scenario, hence revealing the importance of an adequate ground motion selection and scaling method.

Impact of the selection and number of records on the risk assessment

The previous section has revealed the importance that a 'robust' selection of records can assume in the estimation of the response of structures, leading in certain cases to deviations between methods of about 30%, Fig. 4. Although the differences in the fragility functions derived from each suite of ground motion records, the impact of the selection and modification methods is yet unknown. Thus the present study aims to identify how and in which scale the selection of records influences the risk assessment, following the SAC/FEMA closed-form probabilistic framework (Cornell et al. 2002) assuming a second-order hazard approximation as proposed by Vamvatsikos (2013). Furthermore, the damage criteria and the number of records were also included in this comparison, for both structures and limit states of damage (Damage Limitation, Slight Damage and Near Collapse).

The set of damage criteria used in the derivation of the fragility functions try to cover the many engineering demand parameters that are better correlated to the structural state of damage, including the interstorey and global drifts, the local plastic rotations of the elements and the concrete and rebar strain values. Thresholds for these failure criteria are admitted in the most common and applied seismic assessment and design codes and, as referred, were included in this study. It can be observed in Fig. 6 the important role played by each damage criterion, despite being more clear in the case of the RC structure, where the section strains control the derivation of the fragility functions and thus the behavior of the building. On the contrary, the envelope fragility functions for the steel structure are not only defined by a single EDP along the seismic intensity levels and therefore this fact explains the similar trends found in the risk estimations within GMSM methods and failure criteria. Furthermore, one should also point out the fact that for the steel building the envelope fragility functions do not necessarily imply, as expected, a maxima in the risk estimation, what is related to the bias in the fit of the Lognormal distribution (fragility function) to the discrete response values. This uncertainty is deemed relevant, even when the parameters of the Lognormal distribution are estimated using the Maximum Likelihood Estimation method, what suggests that special care shall be devoted to this source of uncertainty in loss assessment studies, as also referred by Bradley (Bradley 2012).

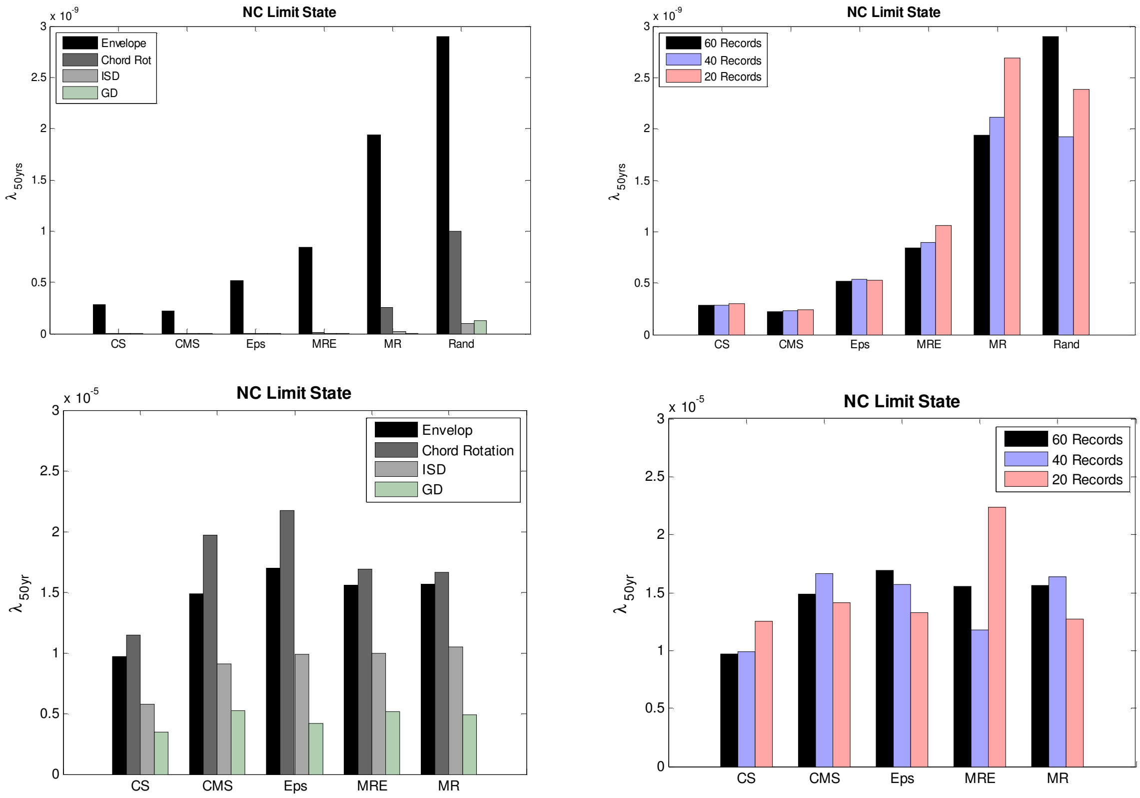

Figure 6. Risk assessment of the RC (top) and steel (bottom) buildings, considering several damage criteria (left) and 20, 40 and 60 records (right), for a 50 years time interval.

Analyzing the influence of the GMSM methods in the risk results, one observe that close probability values are ascertain when following the CS and CMS approaches, revealing always lower risk estimations of the structures, that in the case of the RC building can assume values approximately 10 times smaller than the ones obtained through a random selection of records. Once again, for the steel structure the trends in risk estimations, although in agreement to what has been said to the other analyzed building, showed a more stable scenario among methods, nevertheless on average the risk results are 50% lower when using the CS method. In what regards to the number of records it is also drawn from Fig. 6 that the estimations of the structural risk are affected in different ways depending on the selection method. The CS and CMS methods are not really sensitive to the number of records used in each dataset, particularly in the case of the RC building. Cimellaro et al. (2009) suggests a minimum of 20 records per set to have an accurate estimation on the fragility function, however this condition is not entirely satisfied in the present study, especially if the scenario-based ground motion selection criteria are exclusively the implicit causal parameters. Moreover, and regardless of the GMSM method, using at least 40 records seems reasonable to obtain an accurate estimation on the collapse fragility functions and risk values of both structures.

CONCLUSIONS

In this paper a comparison between various ground motion selection methods (GMSM) was presented in the context of seismic loss estimation. The influence of using different number of records and failure criteria was examined, as well as the statistical significance of the scaling factor and intensity measure types (IMT) in the derivation of the fragility functions.

It becomes clear from this study that special care should be taken when the selection of the ground motions is simply conducted by conditioning the characteristics of the earthquake defined in terms of magnitudes (M), distances (R) and epsilon (ε), while, in turn, the CS and the CMS methods were seen to systematically lead to similar results, without being significantly affected by the number of ground motion records. Still, further studies on these issues are deemed necessary. Additionally, it was shown that the selection of different failure criteria in the derivation of the fragility functions is an important source of bias in the quantification of seismic risk.

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