16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1645

Registration Code: S-Z1463181582

A NEW ENERGETIC BASED GROUND MOTION SELECTION AND MODIFICATION ALGORITHM

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Abstract

This paper presents a new ground motion modification and selection procedure that will be used for performing the response history analysis of structures. Nowadays, the availability of large ground motion databases allows performing time history analysis using real ground motion records. Since the main goal of response history analyses is to predict the dynamic behavior of structures, the most critical issue is the selection of a set of ground motions that determines a low variability of structural response. The proposed selection and scaling procedure approach derives from an energetic comparison at different frequency ranges of the horizontal component of the ground motion. The Conditional Mean Spectrum is used as target spectrum and only the records providing a relevant and effective contribution to the hazard of the site are considered. A set of ground motion with the same hysteretic energy demand can be obtained by matching the acceleration of the target spectrum at the period of interest T_{ref} and selecting only the scaled spectra having an equal Housner intensity in the period range $0.2T_{ref}$-$2T_{ref}$. In detail, the selection procedure consists in searching the set of horizontal components for each frequency band using an index which depends on the shape of the energy-frequency trend and of its dispersion around the mean value. This procedure generates a set of records which are spectrum compatible, having a similar hysteretic energy demand and a very low dispersion around the mean value. Low variability of the damage index values can be observed. As a result, this new approach allows selecting a set of spectrum compatible ground motions according to the frequency content and the expected structural damage for a given hazard scenario.

Keywords: ground motion; selection, modification; spectrum-compatibility; frequency content

1. Introduction

Prediction of the seismic response of structural and geotechnical systems is the goal of performance-based earthquake engineering. Development of a large quantity of finite element software is leading towards dynamic Non-linear Response History Analyses (NRHA). Furthermore, the availability of large ground motion databases allows to perform time history analysis using real ground motion records. Since the artificial or synthetic accelerograms do not describe realistically the earthquake parameters, it is common to use real ground motions that present undistorted frequency and energy content. Seismic hazard at the reference site and the structure behavior (mark out by its first-period) have to be considered in order to obtain the target spectrum. It represents the base of the ground motion selection procedure and takes into account the probabilistic hazard of the site for a given exceedance probability. The selection of real ground motion records is carried out in order to have an adequate mean spectrum-compatibility, through modification of each time history using a Scale Factor (SF).

A large variety of Ground Motion Selection and Modification (GMSM) procedure are proposed. The Seismic Performance Assessment of Buildings [1] defines three selection methodologies based on intensity, scenario and time characteristics. The intensity-based GMSM methods are commonly performed through modification of real records in order to reach the same intensity measure (IM) obtained from Probabilistic Seismic Hazard Analysis (PSHA) [2]. Each motion is scaled for matching a target response spectrum [3]. The most used IM parameter is the spectral acceleration corresponding to the fundamental period (reference period) of the structure with a damping ratio of 5%. In these cases, the selection of real accelerograms is based on the mean compatibility between response spectra and a target spectrum. Several authors proposed some formulation to take into account the dispersion quantity between the generic elastic response spectrum and the target one. Ambraseys et al. (2004) [4] proposed to verify spectral compatibility of a given record according to the parameter reported in Eq. (1):

$$D_{ms} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\frac{Sa_0(T_i)}{PGA_0} - \frac{Sa_S(T_i)}{PGA_S}\right)^2} \tag{1}$$

where N is the number of periods within the reference interval and $Sa_0(T_i)$ is the spectral acceleration of the record at period T_i. $Sa_s(T_i)$ is the target spectral acceleration at the same period value, and PGA_0 and PGA_s are the peak ground acceleration of the record at the period equal to zero and at the reference period, respectively. Iervolino et al. (2009) [5] proposed an expression to calculate the average spectrum deviation of the records with respect to the target one in a given period range (Eq. (2)).

$$D_i = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Sa_j(T_i) - Sa_S(T_i)}{Sa_S(T_i)}\right)^2} \tag{2}$$

The value of PGA is not considered as normalization factor. The scenario-based assessment is carried out according to the earthquake magnitude (M), source-to-site distance (R), faulting system and soil category of the site. Shome et al. (1998) [6] selected sets of real accelerograms based on the basis of four different magnitude–distance pairs, permitting a limited variation in the target values. Recent studies have shown the inefficacy of selection procedure M-R-based for the structural dynamic response. Baker and Cornell (2006) [7] confirmed that the source-to-site distance R is statistically insignificant to the structural response, while the earthquake magnitude gives significant contribution. In order to perform a soil response analyses or liquefaction analyses, the characteristics of the soil profile should be considered into the selection process. Thus, site classification in terms of shear waves velocity at the uppermost 30 m ($V_{S,30}$) becomes an essential parameter. In this case the earthquake scenario will be defined by means of the parameters M-R-$V_{S,30}$.

The description of the new method will be discussed in detail in paragraph 2, while in paragraph 3 the advantages associated with the method will be presented. Finally, a case study will be presented in paragraph 4. The structural performance of regular steel building will be investigated. The ground motion selection and modification procedure will be carried out through the associated module of OPENSIGNAL 4.1 software [8].

2. Description of the method

New GMSM procedure is proposed to minimize the dispersion value of the EDP resulting from the non-linear dynamic analysis. Having a set of ground motions that determines a low variability of structural response allows to define fragility curves for structural components with good accuracy. In a context of seismic performance assessment of a structural system, increase the accuracy leads to more careful estimation of consequence functions and resilience indexes. Fig. 1 shows the generic flowchart for evaluating the structural performance of a building.

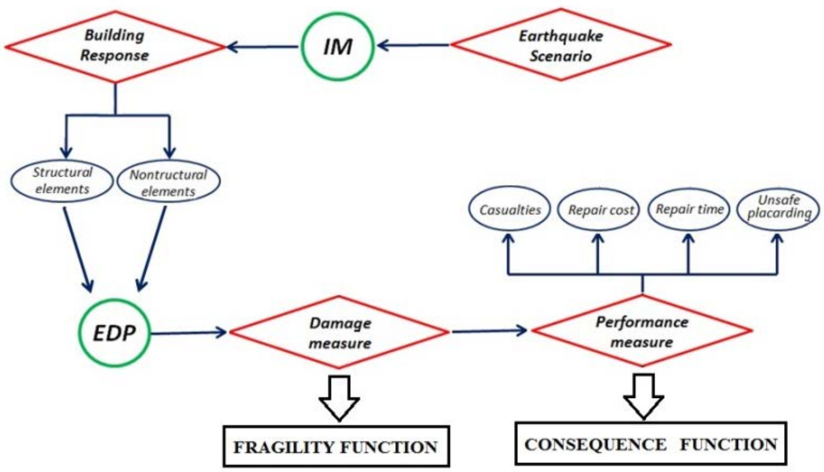

Fig. 1 - Seismic performance evaluation of a building

2.1. Target spectrum

The first assumption of the method regards the target spectrum used in the selection procedure. The Uniform Hazard Specrtum (UHS) is widely used as target spectrum in the dynamic analyses of buildings. It derives from PSHA [2] and defines the locus of spectral acceleration value at each period having given exceedance probability. Ground motions with different magnitude and epicentral distance values give contribution to the total hazard. It was observed that the high-frequency portion of the UHS is dominated by small nearby earthquakes, while the low-frequency portion is dominated by larger and distant earthquakes. The UHS is not representative as target spectrum for any individual seismic excitation because no single earthquake will produce a response in a wide range of frequency content. This limitation has led to focus on the Conditional Mean Spectrum (CMS-ε) which is obtained conditioning on a spectral acceleration at only one period according to commonly used de-aggregation parameters M, R and ε. The last parameter is a measure of the difference between the logarithmic spectral acceleration of a record and the mean or median logarithmic spectral predicted demand with a given attenuation model for the considered site. Baker and Cornell (2006) [7] investigated the dynamic response of a multi-degree of freedom system according to ground motions of a specified intensity (as measured of spectral acceleration at first period of the structure) and matching UHS and CMS-ε. It was observed that records selected based on CMS-ε produce smallest dispersions in structural dynamic response.

2.2. Modification procedure

Usually, the IM parameter used in the ground motion selection approaches is the spectral acceleration at reference period ($S_a(T_{ref})$). It gives information about the maximum seismic action bearing elastically by the structure. For regular MDOF systems, the period T_{ref} can be assumed equal to the first-mode (T_1) since the dynamic response of the structure is governed by the first mode. When the mass and the stiffness of the structure are not uniformly distributed in plan and elevation, its dynamic response is evaluated as linear combination of the modes. It is suggested to consider every mode such that the sum of the modal participation factor in the two horizontal directions is greater than 85%-90%. In these cases the reference period can be assumed as modal participation factor-weighted arithmetic mean of the periods associated with the *N* investigated modes (Eq. (3)).

$$T_{ref,h} = \frac{\sum_{i=1}^{N} T_{i,h} \cdot \left|g_{i,h}\right|}{\sum_{i=1}^{N} \left|g_{i,h}\right|} \tag{3}$$

where T_i and g_i identify the i^{th} mode period and modal participation factor, respectively; while h index is associated with the horizontal component of the motion. The number of real ground motions available in the free database is not adequate to have a large number of motions with the same spectral acceleration at reference period. Modification of the records is a necessary step to collect a numerous set of compatible ground motions. Most of the modification procedures are based on the scaling the spectral acceleration at reference period of the record ($S_{a,i}(T_{ref})$) to the target spectral acceleration ($S_{a,TS}(T_{ref})$) (Eq. (4)).This approach leads to consider records causing the same maximum elastic seismic action on the structure.

$$SF_{I,i} = \frac{S_{a,TS}(T_{ref})}{S_{a,i}(T_{ref})} \tag{4}$$

The new proposed method provides to modify each record in two parallel ways. First modification procedure is carried out according to Eq. 4 and the second one is based on the value of Housner intensity at reference period range. For each record, the Housner intensity is calculated in the range $\Delta T = 0.2 \cdot T_{ref} - 2 \cdot T_{ref}$ ($I_{H,i}(\Delta T)$) that corresponds to the period interval in which the mean spectrum-compatibility has to be verified. The target Housner intensity ($I_{H,TS}(\Delta T)$) is evaluated from the Pseudo Velocity Spectrum (PVS). Eq. (5) illustrates the Housner intensity-based scale factor of i^{th} record.

$$SF_{II,i} = \frac{I_{H,TS}(\Delta T)}{I_{H,i}(\Delta T)} \tag{5}$$

2.3. Selection procedure

Selection procedure is based on the energy content of the ground motion in the different representative frequency bands. As known, the energy of a periodic signal is directly proportional to its square amplitude. According to Fourier series, an earthquake can be decomposed in infinite harmonic periodic functions having given amplitude (A_i) and frequency (ω_i). Fourier transform gives information about the amplitude contribution for each frequency of the ground motion. Thus, Fourier transform is used to evaluate the trend of the square amplitude (A_i^2) in the frequency domain (energy-frequency relationship). In order to simplify the results, the frequency domain is sampled in different bands (Δf) of 0.5 Hz. For each Δf, the cumulative energy proportional coefficient is evaluated as sum of each single contribution in the given band.

The target energy content is calculated with a simple approach based on the amplification function (|A|). After sampling the period domain of the target spectrum for each discrete period, the amplification function is evaluated as ratio between the spectral acceleration at considered period and the spectral acceleration at $T=0$ (Peak Ground Acceleration, PGA). Eq. (6) shows the amplification function for the i^{th} period value.

$$|A_i| = \frac{S_{a,TS}(T_i)}{S_{a,TS}(T=0)} = \frac{S_{a,TS}(T_i)}{PGA_{,TS}} \tag{6}$$

According to the definition of amplification function and setting a damping ratio ξ equal to 5%, the predominant frequency of the target ($\omega_{f,i}$) is calculated (Eq. (7)).

$$|A_i| = \frac{1}{\sqrt{\left(1-\left(\frac{\omega_{f,i}}{\omega}\right)^2\right)^2 + \left(2\cdot\xi\cdot\frac{\omega_{f,i}}{\omega}\right)^2}} \tag{7}$$

Appling same procedure to every sampled period, a distribution of couple $(|A_i|)^2$- $\omega_{f,i}$ is evaluated. Dividing the frequency domain in bands of 0.5Hz and summing every contribution inside them, the target percentage energy band content is obtained. Fig. 2 summarizes the procedure just discussed.

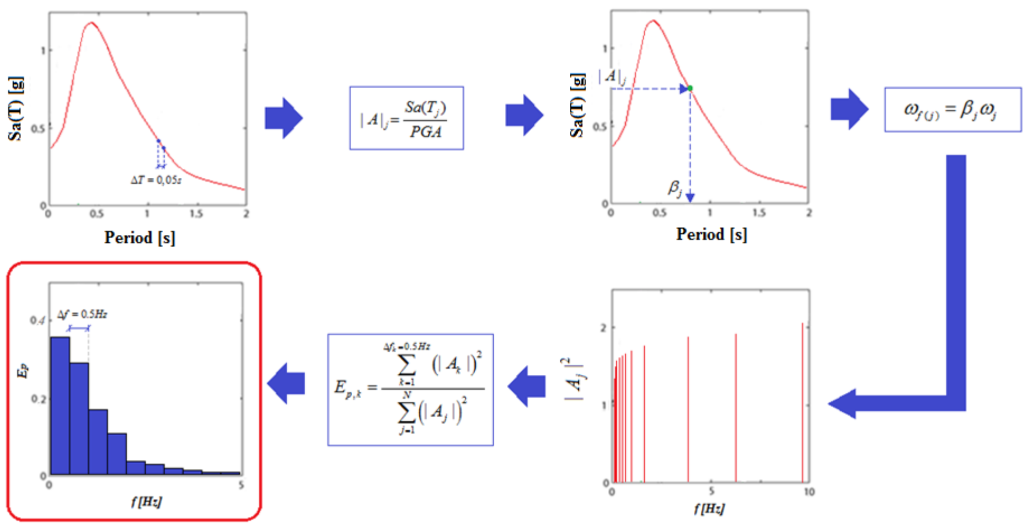

Fig. 2 - Scheme of the procedure used to obtain the energy content in the discretized frequency domain

Selection procedure is implemented according to the following ordered five steps:

1) Set maximum and minimum value of SF_I and select all the records within the interval $SF_{I(min)}$-$SF_{I(max)}$.
2) Set maximum absolute percentage dispersion of *PGA* (σ_{PGA}).
3) Set maximum and minimum values of moment magnitude and epicentral distance according to the de-aggregation study of the site.
4) Select only the record verifying the condition reported in Eq. (8).

$$(1-\sigma_{SF}) \leq \frac{SF_{I,i}}{SF_{II,i}} \leq (1+\sigma_{SF}) \tag{8}$$

where σ_{SF} represents the dispersion coefficient associated with the scale factors. It is suggested to use a dispersion value less than 15 %.

5) Among the records coming from 1) and 2), a set of seven records (in both horizontal directions for structural analyses and in a given horizontal direction for performing soil response analyses) is selected by comparing energy content of each record with the target one.

This step is the real innovation of the method since the spectrum-compatibility is achieved through the energy content of ground motions. For a generic compatible record, the energy trend coefficient (C_E) reported in Eq. (9) is evaluated.

$$C_E = \frac{1}{\left[|E_{p,j(i)} - E_{p,j(TS)}| \cdot \lambda_i\right]} \tag{9}$$

where $E_{p,j(i)}$ and $E_{p,j(TS)}$ represent the energy percentage content for j^{th} frequency band of the i^{th} record and for the target, respectively. The coefficient λ_i indicates the cumulative shape dispersion of the energy content of the i^{th} record with respect to the target one (Eq. (10)).

$$\lambda_i = \sum_{j=1}^{20} | E_{p,j(i)} - E_{p,j(TS)} | \tag{10}$$

For each frequency band, all the records will be descending ordered of C_E values. According to the percentage contributions of energy band content, a number n_j of records is selected for each band in order to have the greater values of C_E coefficient. This procedure starts from Δf: *0-0.5Hz* and is stopped when the progressive number $\sum_{j=1} n_j$ achieve value of 7.

3. Advantages of procedure

3.1. Consistency with hazard scenario

Selection procedure is implemented according to the de-aggregation of the site. This allows to select only the records having M-R that gives substantial contribution to the hazard.

3.2. Consistency with target PGA

Selection procedure based only on the spectral acceleration at reference period may lead to have PGA not close to the value derived from the hazard analysis. This has implications in terms of inadequate spectrum-compatibility in the range of low periods. In addition, wide variability of PGA for a set of records can produce big scattering of the maximum dynamic responses of a structure. Thus, setting a maximum absolute dispersion of PGA with respect to the target one tends to limit variation of dynamic response of a system.

3.3. Equal elastic seismic action

The first proposed modification approach is usually used in other GMSM procedures. It has the advantage to scale each record in order to cause the same maximum elastic action on the structure. Scaling procedure must not cause a distortion in frequency and energy content of signal. For this purpose, it is suggested to set maximum and minimum limits for the scale factor ($SF_{I(min)}$ and $SF_{I(max)}$).

3.4. Hysteretic energy demand control

The ratio between the scale factor based on the reference spectral acceleration and on the Housner intensity has not to exceed the value of $1 \pm \sigma_{SF}$; where the dispersion parameter is set to be less than 15 %. This is equivalent to consider records having approximately the same value of Housner intensity as well as to cause elastic seismic action on structure. Since the Housner intensity is a measure of the hysteretic demand, every modified record causes in the structure a roughly equal hysteretic energy dissipation (E_H). Further advantage of this modification procedure is reflected in the mean spectrum-compatibility. Having an approximately equal Housner intensity means to control the average trend of the PSV and then the acceleration response spectrum for each record.

3.5. Input energy control

The selected records have the maximum energy content representativeness with the target energy distribution. In addition, the maximum amplitudes of the records are similar since the PGAs are consistent with relative hazard value. Thus, the energy based selection procedure is capable to control input energy on the structure, providing a set of motions with low variability of energy parameters (e.g. Arias intensity).

3.6. AV ratio control

According to Tso et al. (1991) [9], the energy and frequency content of a ground motion are related to the ratio between its peak ground acceleration and velocity (AV ratio). Analyses of 45 records led to identify three groups of AV ratio values (low, intermediate and high). Records of a given group showed a similar trend in terms of energetic content in frequency domain. Since the records selected have a moderate variability of energetic contributions in frequency domain, each of them assume a small variability of AV ratio.

3.7. Damage control

The damage of a structural system induced by a seismic excitation is directly proportional to the number (n) and amplitude (m) of plastic load-unload cycles. Manfredi and Cosenza (2001) [10] proposed a damage index (I_D) that describes the damage level of a structure through the Arias intensity, PGA and AV ratio (Eq. (11)).

$$I_D = \frac{2 \cdot g}{\pi} \cdot \frac{I_A}{PGA^2} AV \tag{11}$$

According to the this formulation, the ground motion hysteretic energy demand (E_H) is reported in Eq. (12).

$$E_{h,d} = F_y \cdot \left(\Delta u_{\max} - \Delta u_y \right) \cdot \left[1 + m \cdot (n-1) \right] \tag{12}$$

where m and n coefficient have been previously defined and they are directly proportional to I_D. The yielding action and displacement have been expressed by F_y and Δu_y, respectively. These two values are intrinsic parameters of the structure, while Δu_{max} represents the maximum dynamic response in terms of displacements. Having a low variability of hysteretic energy (E_H), PGA, AV ratio, and Arias intensity (I_A) lead to obtain a controlled dynamic response of the structure (Δu_{max}). Considering a multi-story building, its dynamic response may be alternatively expressed as sum of drift contribution at each story ($\sum_i \Delta u_{\max,i}$). According to Eq. (12), the new GMSM procedure guarantee the control of the maximum story drift obtaining a low dispersion among the seven selected records.

4. Case study

A five-story steel building has been considered to perform non-linear dynamic analyses. The lateral resisting frame is a dual system composed of moment resisting and brace frame in both directions. The H sections (wide channel, W) have been used for beams and columns while hollow structural sections (HSS) have been designed for brace system. The F.E.M. model of building has been created with Sap2000 [11]. The nonlinearity of the structural elements have been taken into account according to concentrated plasticity model. FEMA 356 Flexural Hinge (type *Moment M2-M3*) have been used for beam elements, FEMA 356 (type *P-M2-M3*) have been modeled for columns, and Steel-braces Axial Hinges have been used for brace system. Damping ratio of 3% has been assigned to the frames using Rayleigh damping formulation. The nonlinear dynamic analyses have been performed using non-linear direct integration method, taking into account P-Δ effects and applying the horizontal acceleration time histories in the two principal plan directions of the building model.

The case study building is an hospital located in Oakland, California, US (Lat: 37.7792, Long: -122.1620). The analyses have been performed for the five different Hazard Levels (HL): 50%, 20%, 10%, 5% and 2% of exceedance probability in 100 years. The mean value of moment magnitude ($M_{W,mean}$) and epicentral distance (R_{mean}) with the logarithmic spectral offset at reference period ($\varepsilon(T_{ref})$) have been evaluated according to Boore-Atkinson attenuation law [12]. All the data can be found through the interactive de-aggregation of USGS (http://geohazards.usgs.gov/deaggint/2008/) [13]. The shear wave velocity at the uppermost 30 m has been assumed equal to 736 m/s according to Global Vs30 Map Server (http://earthquake.usgs.gov/hazards/apps/vs30/) [13].The Conditional Mean Spectrum obtained from de-aggregation study (CMS-ε) has been considered as target spectrum [14] [15] and Baker and Jayaram [16] model has been considered as correlation law. Table 1 resumes the values of the IM parameters and PGA for each HL.

Table 1-Spectral acceleration at first-mode period and PGA for each IM

HL	50%	20%	10%	5%	2%
$Sa(T_{ref})$ [g]	0.2	0.41	0.58	0.76	0.98
PGA [g]	0.24	0.38	0.47	0.54	0.62

The building has an elastic first-mode period of 1 s and the associated spectral target acceleration is used as the IM parameter. Since the building is regular, the first period has been selected as conditioning period (T_{ref}). Seven groups of acceleration histories (for both horizontal directions) have been selected for each HL according to the new proposed GMSM procedure. The selection procedure has been carried out by using the "*GroundMotionSelectionAndModification*" tool of the software OPENSIGNAL 4.1 [8] (Fig. 3).

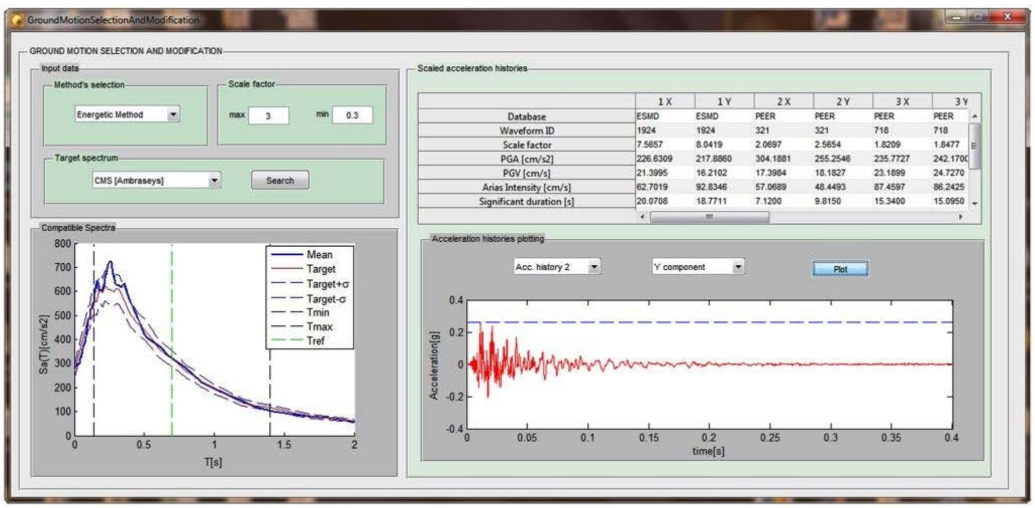

Fig. 3 – "*GroundMotionSelectionAndModification*" component of OPENSIGNAL 4.1 software

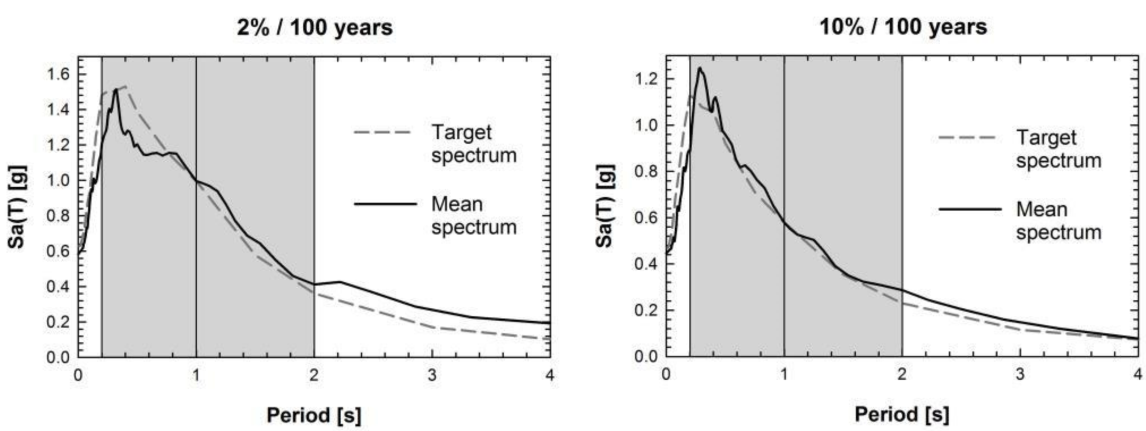

Fig. 4 - Spectrum-compatibility for 2% and 10% of exceedance probability as HL

Fig. 4 illustrates part of results of the GMSM procedures in terms of mean spectrum-compatibility. As shown in Fig. 4, the spectrum-compatibility criterion is excellenty respected especially for periods close to the conditioning one. The mean spectrum does not exceed the 10 % of the target spectrum in almost every periods within the range of interest. Table 2 provides an overview of mean (μ) and standard deviation (σ) of AV ratio and damage index I_D calculated according to Manfredi and Cosenza (2001) [10].

Table 2 – Mean and standard deviation for AV ratio and damage index I_D of the selected records

HL		50%	20%	10%	5%	2%
AV [g·s⁻¹]	**μ**	0.67	0.75	0.84	0.94	1.33
	σ	0.12	0.17	0.19	0.19	0.36
$I_D \cdot 10$ [-]	**μ**	0.55	0.52	0.57	0.80	0.85
	σ	0.24	0.27	0.35	0.34	0.30

Standard deviation values are limited especially for low HL. This affects the structural response providing low dispersion of EDP parameters for a given hazard scenario. The selected records have been used as input for non-linear dynamic analyses of structure in order to investigate the main characteristics in resulting structural responses. The geometric mean of maximum transient interstory drift has been used as EDP. Fig. 5 depicts the structural responses in terms of EDP values as function of spectral acceleration at first-mode period of the structure (IM).

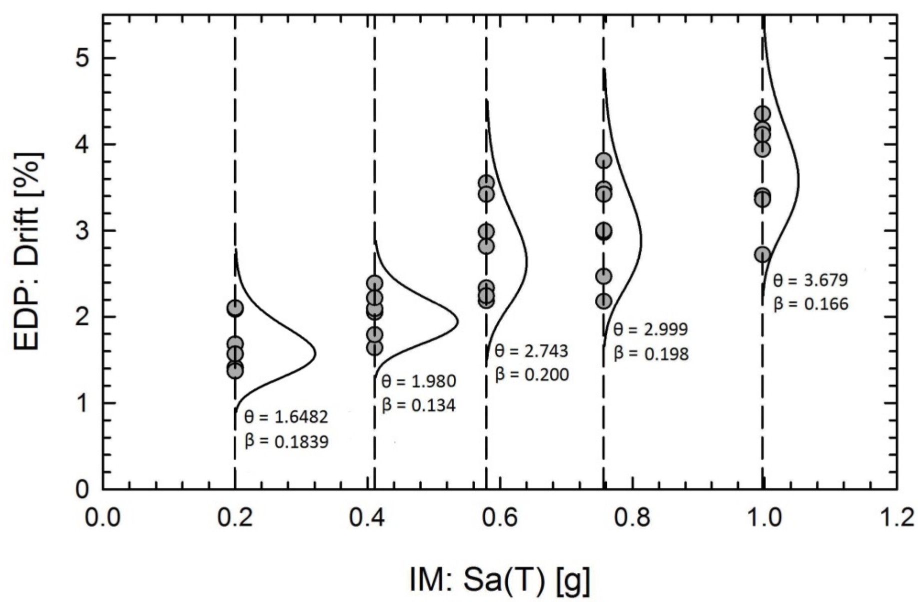

Fig. 5 - Maximum inter-story drift for each IM and statistical analysis of the results

Simple statistical analyses have been used to define the lognormal density distribution of structural responses for each IM, comparing the statistical results in terms of mean (θ) and disperson (β). Fig. 5 clearly shows that the new GMSM procedure is capable to obtain low dispersion values at each intensity level. This comparison is particulary relevant to current practice since dispersion of structural response affects the estimation of the fragility functions that provide information about the damage state of the elements.

5. Conclusion

Nowadays, the availability of large ground motion databases allows performing time history analysis using real ground motion records. The main goal of response history analyses is to predict the dynamic behavior of structures. Thus, the selection of a set of ground motions that determines a low variability in the structural response represents a critical issue. The new proposed GMSM procedure based on the energy content of the records leads to control the main parameters that affect the dynamic response of a structure. Furthermore, the selected records are consistent with the seismic hazard at the site, in terms of M-R parameters and spectral acceleration at the reference period. The ground motion set causes the same elastic response and produce approximately the same plastic dissipation on the structure. The selection of ground motions for structural dynamic analysis has been investigated aiming to measure the structural response associated to a given intensity level. The results of the analyses have shown that the selection method has a significant effect on the resulting estimates of structural response and on the prediction of the damage level in the structure. The proposed procedure is capable to minimize the dispersion of the structural dynamic response parameters with respect to the mean value. Low variability of EDP allows to increase the accuracy on the consequence functions estimation (casualties, repair time, repair costs, etc.). Therefore, the new GMSM procedure can be used to define the earthquake scenario for resilience analyses of a single building or for a group of buildings.

6. Acknowledgements

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC_IDEAL RESCUE_637842 of the project IDEAL RESCUE—Integrated Design and Control of Sustainable Communities during Emergencies.

7. References

[1] Applied Technology Council. (2011): Draft Guidelines for Seismic Performance Assessment of Buildings. Volume 1- Methodology ATC-58-1.

[2] Cornell, C. A. (1968): Engineering Seismic. Risk Analysis. *Bulletin of the Seismological Society of America, 58(5):1583-1606.*

[3] Katsanos, E. I .Sextos, A.G. & Manolis, G.D. (2009): Selection of earthquake ground motion records: A state-of-the-art review from a structural engineering perspective . *Soil Dynamics and Earthquake Engineering 30 (2010) 157–169.*

[4] Ambraseys , NN. Douglas, J. Rinaldis, D. Berge-Thierry, C. Suhadolc, P. Costa, G. Sigbjornsson, R. & Smit, P. (2004): Dissemination of European strong-motion data, vol. 2, CD-ROM collection. *Engineering and Physical Sciences Research Council, UK.*

[5] Iervolino, I. Galasso, C & Cosenza, E. (2009): REXEL: computer aided record selection for code-based seismic structural analysis, *Bull Earthquake Eng (2010) 8:339-362.*

[6] Shome, N. Cornell, C.A. Bazzurro, P. & Carballo, J.E. (1998): Earthquakes, records and nonlinear responses. *Earthquake Spectra 1998;14(3):469-500.*

[7] Baker, J. & Cornell, C. A. (2006): Spectral shape, epsilon and record selection. *Earthquake Engineering & Structural Dynamics,* 35**,** 1077-1095.

[8] Cimellaro, G.P. & Marasco, S. (2015): A computer-based environment for processing and selection of seismic ground motion records OPENSIGNAL. Front. Built Environ. 1:17. DOI: 10.3389/fbuil.2015.00017.

[9] Tso, W.K. Zhu, T.J. & Heidebrecht, A.C. (1991): Engineering implication of ground motion A/V ratio. *Soil Dynamics and Earthquake Engineering 11 (1992) 133-144.*

[10] Manfredi, G. (2001): Evaluation of seismic energy demand. *Earthquake Engineering & Structural Dynamics, DOI: 10.1002/eqe.17.*

[11] Computer and Infrastructure Inc. Sap2000, Version 17.3, Berkeley, CA.

[12] Boore, D. M., and Atkinson, G. M. (2008): 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,* 24(1), 99-138.

[13] USGS (2013). "Seismic Hazard Analysis tools. U.S. Geological Survey." < http://earthquake.usgs.gov/hazards/designmaps/grdmotion.php>.

[14] Baker, J. W. 2011. Conditional Mean Spectrum: Tool for Ground-Motion Selection. *Journal of Structural Engineering-Asce,* 137**,** 322-331.

[15] Lin, B. Haselton, C.B. & Baker, J. W. 2013. Conditional spectrum-based ground motion selection. *Earthquake Engineering & Structural Dynamics, DOI: 10.1002/eqe.2301.*

[16] Baker, J. W., and Jayaram, N. (2008). "Correlation of spectral acceleration values from NGA ground motion models." *Earthquake Spectra*, 24(1), 299-317.