Bull Earthquake Eng (2010) 8:339–362
DOI 10.1007/s10518-009-9146-1

ORIGINAL RESEARCH PAPER

REXEL: computer aided record selection for code-based seismic structural analysis

Iunio Iervolino · Carmine Galasso · Edoardo Cosenza

Received: 9 March 2009 / Accepted: 17 July 2009 / Published online: 4 August 2009

Abstract In code-based seismic design and assessment it is often allowed the use of real records as an input for nonlinear dynamic analysis. On the other hand, international seismic guidelines, concerning this issue, have been found hardly applicable by practitioners. This is related to both the difficulty in rationally relating the ground motions to the hazard at the site and the required selection criteria, which do not favor the use of real records, but rather various types of spectrum matching signals. To overcome some of these obstacles a software tool for code-based real records selection was developed. REXEL, freely available at the website of the Italian network of earthquake engineering university labs (http://www.reluis.it/index_eng.html), allows to search for suites of waveforms, currently from the European Strong-motion Database, compatible to reference spectra being either user-defined or automatically generated according to Eurocode 8 and the recently released new Italian seismic code. The selection reflects the provisions of the considered codes and others found to be important by recent research on the topic. In the paper, record selection criteria are briefly reviewed first, and then the algorithms implemented in the software are discussed. Finally, via some examples, it is shown how REXEL can effectively be a contribution to code-based real records selection for seismic structural analysis.

Keywords Eurocode 8 · Hazard · Seismic design · Response spectrum

1 Introduction

One of the key issues in nonlinear dynamic analysis of structures is the selection of appropriate seismic input, which should allow for an accurate estimation of the seismic performance based on the seismic hazard at the site where the structures is located.

I. Iervolino (✉) · C. Galasso · E. Cosenza
Dipartimento di Ingegneria Strutturale, Università degli Studi di Napoli Federico II,
via Claudio 21, 80125 Naples, Italy
e-mail: iunio.iervolino@unina.it

If the probabilistic risk assessment of structures is concerned, procedures have been recently developed to properly select the seismic input. The basic steps are: (1) choosing a ground motion (GM) parameter which is considered to be representative of the earthquake potential with respect to the specific structure (i.e., a GM intensity measure, or IM[1]); (2) to obtain the probabilistic seismic hazard analysis (PSHA) at the site, and disaggregation, for the chosen IM; (3) to determine probability of collapse in terms of one or more engineering (structural) demand parameters, or EDPs, as a function of the IM (i.e., the fragility function); (4) to average the fragility over the hazard to obtain the overall failure probability; i.e., the seismic risk (Cornell 2004).

Consistently with the load-resistance factor design (LRFD), code-based procedures apparently approximate this procedure in a semi-deterministic fashion (Iervolino and Manfredi 2008). They often require to define a design (reference) spectrum whose ordinates have a small probability of exceedance.[2] Secondly, a scenario event or design earthquake has to be defined referring to the local seismicity (although the link of the design spectrum with the hazard at the site may be very weak). Then, in the case of nonlinear dynamic analysis, codes basically require a certain number of records to be chosen consistently with the design earthquake and the code spectrum in a broad range of periods. Finally, the performance of the structure is assessed verifying whether the maximum or average response of the structure to the records exceeds the seismic capacity.

Studies show how the most of practitioners may experience difficulties in handling code-based record selection, first of all because determining the design earthquakes may require hazard data often not readily available to engineers, or, when these are provided by authorities (e.g., in Italy), it may still require seismological skills beyond their education (see Sects. 2, 3). Furthermore, if real records are concerned, to find a suite matching a design spectrum in a broad sense, may be hard or practically unfeasible if appropriate tools are not available (Beyer and Bommer 2007; Iervolino et al. 2008, 2009). These issues traditionally favored the use of spectrum matching accelerograms, either artificial or obtained through manipulation of real records. On the other hand, real records are the best representation of seismic loading for structural assessment and design, motivating attempts to develop tools for computer aided code-based record selection, one of which being that of Naeim et al. (2004).

The recent years' work of the authors in this direction resulted in REXEL, a computer software freely distributed over the internet, which allows to build design spectra according to Eurocode 8 (EC8) (CEN 2003), the new Italian seismic code (NIBC) (CS.LL.PP. 2008), or completely user-defined, and to search for sets of 7, 14 or 21 groups[3] of records, from the European Strong-motion Database. These sets are compatible to the reference (i.e., target) spectra with respect to codes' provisions, but reflect also some research-based criteria considered relevant for seismic structural assessment.

REXEL searches for sets of records for a various range of structural applications (building-like and non-building-like structures, isolated buildings, bridges, tall structures, industrial facilities, etc.) and seems to actually make the selection fast and effective in the most of cases. In the following, the procedures concerning determination of seismic action and record

[1] For various reasons, one of the main being that hazard is easily computable, the IM is often related to the response spectrum of the record; e.g., the peak ground acceleration or PGA, and the spectral acceleration at the first mode, or some function of the spectral shape in a range of period of interest.

[2] This is, in principle, analogous to choosing a conservative value of the action in the LRFD in which actions are amplified and the capacity is reduced on a probabilistic basis.

[3] Each group may be made of 1, 2 or 3 component GMs. This means in the case of size 21, for example, the set features 63 GMs.

selection, according to EC8 and the NIBC, are briefly reviewed along with the findings of other studies on the topic. Then, the software's algorithms are described; the use of REXEL is illustrated via some examples which show how it can effectively aid code-based record selection for seismic structural analysis.

2 Record selection in EC8

2.1 EC8 Part 1—buildings

In EC8—Part 1 (CEN 2003) the seismic action on structures is defined after the elastic acceleration response spectrum. In Part 1, which applies to buildings, the spectral shapes are given for both horizontal and vertical components of motion. In *section*[4]*3.2.2* of the code two spectral shapes, Type 1 and Type 2, are defined, the latter applying if the earthquake contributing most to the seismic hazard has surface wave magnitude not >5.5, otherwise the former should be used. All shapes have a functional form which depends, apart from the soil class, on a single value, a_g, anchoring the spectrum to the seismicity of the site. a_g refers to the seismic classification of the territory in each country; it is basically related to the hazard in terms of peak ground acceleration (PGA) on rock for the site (see "EC8 reference spectra" in the "Appendix").

Once the reference spectrum has been defined, EC8—Part 1 allows the use of any form of accelerograms for structural assessment; i.e., real, artificial or obtained by simulation of seismic source, propagation and site effects. To comply with Part 1 the set of accelerograms, regardless its type, should basically match the following criteria:

(a) a minimum of 3 accelerograms should be used;
(b) the mean of the zero period spectral response acceleration values (calculated from the individual time histories) should not be smaller than the value of a_g S for the site in question (S is the soil factor);
(c) in the range of periods between 0.2 T_1 and 2 T_1, where T_1 is the fundamental period of the structure in the direction where the accelerogram will be applied, no value of the mean 5% damping elastic spectrum, calculated from all time histories, should be <90% of the corresponding value of the 5% damping elastic response spectrum.

According to the code, in the case of spatial structures, the seismic motion shall consist of three simultaneously acting accelerograms representing the three spatial components of the shaking, then three of condition (a) means 3 times the number of translational components of motion to be used (e.g., three groups of motion each of those includes the two horizontal and the vertical recordings).

In *section 4.3.3.4.3*, the code allows the consideration of the mean effects on the structure, rather than the maxima, if at least seven nonlinear time-history analyses are performed. Moreover, the vertical component of the seismic action should be taken into account only for base-isolated structures, and for some special cases in regular buildings, if the design vertical acceleration for the A-type site class (a_{vg}) is >0.25 g. Finally, some provisions regarding duration are given for artificial accelerograms, while real or simulated records should be *adequately qualified with regard to the seismogenetic features of the sources and to the soil conditions appropriate to the site*.

[4] References to sections and verbatim quotations of codes are given in Italic hereinafter.

2.2 EC8 Part 2—bridges

Eurocode 8—Part 2 (CEN 2005) refers to the same spectral shapes of Part 1 in order to define the seismic input for time-history analysis of bridges. The requirements for the horizontal components are somehow similar to those for buildings but not identical. The relevant points are:

(a) for each earthquake consisting of a pair of horizontal motions, the SRSS spectrum shall be established by taking the square root of the sum of squares of the 5%-damped spectra of each component;
(b) the spectrum of the ensemble of earthquakes shall be formed by taking the average value of the SRSS spectra of the individual earthquakes of the previous step;
(c) the ensemble spectrum shall be scaled so that it is not lower than 1.3 times the 5% damped elastic response spectrum of the design seismic action, in the period range between 0.2 T_1 and 1.5 T_1, where T_1 is the natural period of the fundamental mode of the structure in the case of a ductile bridge.

As Part 1, Part 2 also allows the consideration of the mean effects on the structure when non-linear dynamic analysis is performed for at least seven independent GMs and the vertical action has to be considered in special cases only. Part 2 has specific provisions for near-source conditions and cases in which the spatial variability of GM has to be considered.

2.3 Findings of previous investigations about record selection in EC8

In other studies the authors investigated the actual applicability of EC8 provisions about record selection. In particular, in Iervolino et al. (2008) it was investigated whether it is possible to find unscaled real record sets fulfilling, as much as possible, the requirements of EC8—Part 1. The investigations were based on the former Italian classification in seismic zones now superseded by the new seismic code (see following section), but still adopted in similar forms in many countries.

Combinations were found in the European Strong-motion Database, or ESD, for sites featuring moderate-to-low seismicity, while it was not possible to find suitable results for the more severe design spectra. Moreover, the condition of having unscaled record sets strictly matching EC8 spectra resulted in a large record-to-record variability in the spectral ordinates within the same set. Both shortage of compatible sets for the severe spectra and large individual spectra scatter, could be avoided searching for records with a spectral shape as similar as possible to that of the code (after rendering the spectra non-dimensional dividing their ordinates by the PGA). Nevertheless, this implies amplitude scaling in the time domain (amplitude scaling, or simply scaling, hereinafter) of the records, and may lead to large scaling factors.

As a general conclusion it was found that provisions do not easily allow to select suitable real record sets, factually favoring the use of records obtained either by computer techniques or manipulation of real records to have a spectral shape coincident to that of the reference in a broad range of periods. This is mainly because:

1. it is almost unfeasible for practitioners to search in large databases to find suites of seven real records (eventually multi-component) whose average matches closely the design spectral shape without a specific software tool;
2. the spectra based on seismic zonation may be too severe in a way that do not exist suites of unscaled records whose average has such spectral shape;

3. it is not easy to control the variability (very large) of individual spectra in a combination, and this, in the fortunate case when combinations are found, may impair the confidence in the estimation of the seismic performance using such a set;
4. the requirement of selecting records consistent with the earthquake events dominating the hazard at the site (i.e., the design earthquakes) requires PSHA/disaggregation data and skills seldom available to practitioners;

In Iervolino et al. (2009) a similar study concerning EC8—Part 2 was carried out. It was found that, although seemingly different, the requirements of the two part of the code are substantially equivalent and lead to similar results in terms of combinations found (i.e., combinations complying with Part 2 are likely to comply also with provisions of Part 1) and limitation of applicability to real records. As discussed in the following, more advanced codes (i.e., NIBC) and/or tools as REXEL may help to overcome, in the most of cases, the issues 1–4 above.

3 Seismic input according to NIBC

Eurocode 8 has design spectra related to the seismicity via only one parameter, this is also because of the unavailability of detailed country-wide hazard analysis results in most European countries. In other fortunate cases such as Italy, the building code (CS.LL.PP. 2008) links the seismic design actions on structures directly to the PSHA. In fact, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) evaluated probabilistic seismic hazard for each node of a regular grid having 5 km spacing and covering the whole Italian territory with over 10^3 nodes. This resulted in hazard curves in terms of PGA (also disaggregation is provided for PGA) and spectral acceleration, Sa(T), for ten different periods from 0.1 to 2 s. Hazard curves are lumped in nine probabilities of exceedance in 50 years (from 2 to 81%). All data can be accessed at http://esse1-gis.mi.ingv.it (see also Montaldo et al. 2007).

New Italian seismic code acknowledges these data defining completely site-dependent design spectra which, although given with standard (EC8-like) functional form, practically coincide with uniform hazard spectra (UHS) on rock for the site in question. The exceedance probability the UHS has to refer to depends on the limit state of interest, the type and the nominal life of the structure. In case the soil is not rock/stiff (the classification is the same as EC8) coefficients apply to amplify the spectrum accordingly; see "NIBC reference spectra" in the "Appendix".

As per EC8, the signals can be artificial, simulated and natural accelerograms. Three is still the minimum number of records to use, and seven allows the consideration of the mean effects on the structure as design values (rather than the maxima).

For the artificial records also the main condition the set of records should satisfy is the same as per EC8. The average elastic spectrum has not to underestimate the 5% damping elastic code spectrum, with a 10% tolerance, in the larger range of period between [0.15 s, 2 s] and [0.15 s, 2 T_1]. This condition applies to ultimate limit states, while for serviceability limit states the largest of the two ranges [0.15 s, 2 s] and [0.15 s, 1.5 T_1] has to be considered. For seismically isolated structures the code provides, reasonably, a narrower range for the average matching, i.e., [0.15 s, 1.2 T_{is}], where T_{is} is the equivalent period of the isolated structure.

Real records or accelerograms generated trough a physical simulation of earthquake process, may be used, provided that, again as in EC8, *the samples used are adequately qualified with regard to the seismogenetic features of the source and the soil conditions appropriate to*

the site. Selected real records have to be scaled to approximate somehow the elastic response spectrum in a range of periods of interest for the structure.

These statements allows for some arbitrariness in record selection, which may be considered positive as they enable, in principle, to determine the source parameters dominating the hazard at the site (i.e., the design earthquakes) by, for example, disaggregation of seismic hazard; then, the records may be scaled to match the reference spectrum at the period corresponding to the first mode of the structure, which is the current best practice in record selection and manipulation (Iervolino and Manfredi 2008). However, even in the fortunate Italian case, where the hazard data are available for any given site, the features of the source and GM at the site from disaggregation (e.g., magnitude, distance, and epsilon) are not always available to practitioners. In fact, INGV provides disaggregation values for peak acceleration only, while it is now acknowledged that the disaggregation should be performed for those ranges of the response spectrum more relevant for the behavior of the structure, for example, close to the fundamental period; see Convertito et al. (2009) for a discussion. On the other hand, some studies have shown that in most of the cases some of the variables dominating the hazard and recommended for consideration by codes (i.e., magnitude and distance) may be not particularly relevant for a correct estimation of the structural response if the spectral shape is the parameter driving record selection (Iervolino and Cornell 2005).

New Italian seismic code accounts for these considerations about record selection and required input information. In fact, the instructions for code application allow, as an alternative, in the case of real accelerograms, record selection procedures which apply to artificial record; i.e., average spectral compatibility in a period range. As an additional feature it is recommended to choose, if possible, records having spectral shape similar to that of the code. In this case one can avoid to reflect explicitly specific source parameters in selection (i.e., to not reflect specific design earthquakes). If this implies amplitude scaling of the records, it is also specified that the scale factor is to be limited in the case of signals from events of small magnitude (CS.LL.PP. 2009).

4 REXEL 2.31 beta

To enable record selection according to both approaches of EC8 and NIBC, a specific software tool was developed (Fig. 1). It features a MATHWORKS-MATLAB® graphic user interface (GUI) and a FORTRAN engine, based on the software developed for the studies of Iervolino et al. (2008, 2009). In particular, the computer program was developed to search for combinations of seven[5] accelerograms compatible in the average with the reference spectra according to code criteria discussed above. It is also possible to reflect in selection the characteristics of the source (if available) and site, in terms of magnitude (M), epicentral distance (R), and EC8 soil site classification. In fact, REXEL 2.31 beta, freely available on the internet at the website of the Italian consortium of earthquake engineering laboratories (*Rete dei Laboratori Universitari di Ingegneria Sismica – ReLUIS*; http://www.reluis.it/index_eng.html), currently contains the accelerograms belonging to the ESD (http://www.isesd.cv.ic.ac.uk/; last accessed July 2007) (Ambraseys et al. 2000, 2004).

The procedure implemented for record selection deploys in four basic steps:

1. definition of the design (reference) horizontal and/or vertical spectra the set of records has to match on average; the spectra can be built according to EC8, NIBC, or user-defined;

[5] Seven has to be intended as the size of the set which may include 1-component, 2-components, or 3-components records, which means 7, 14 or 21 waveforms, respectively.

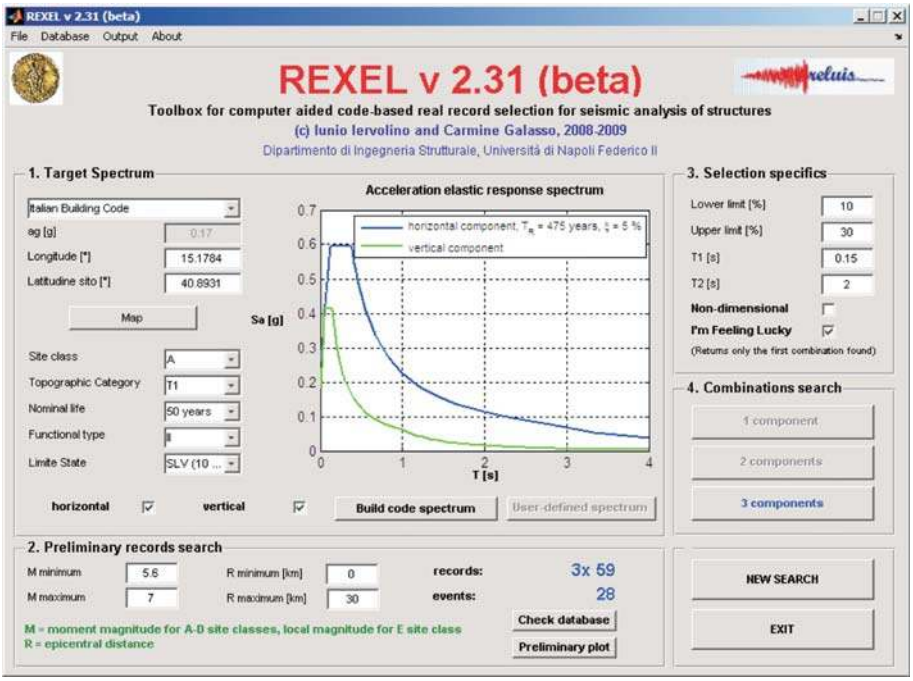

Fig. 1 Image of the software GUI

2. list and plot of the records contained in the ESD and embedded in REXEL which fall into the magnitude and distance bins specified by the user for a specific site class;
3. assigning the period range where the average spectrum of the set has to be compatible with the reference spectrum, and specification of tolerances in compatibility;
4. running the search for combinations of seven records which include one, two of all three components of motion and that, on average, match the design spectrum with parameters specified in step 3.

Other functions are related to visualization of results, return of selected waveforms to the user, and secondary options, such as search for combinations of size larger than 7. In the following descriptions of fundamental phases 1–4 are given, although for a more complete user guide one should refer to the REXEL tutorial (Iervolino and Galasso 2009).

4.1 Reference (design) spectrum

To build the elastic acceleration response spectrum for the site of interest three options are available in REXEL: (1) NIBC; (2) EC8 (Type 1 spectra); and (3) user-defined spectral shape.

In case (1) it is necessary to enter the geographical coordinates of the site (applicable to Italy only), *longitude* and *latitude* in decimal degrees, and to specify the *Site Class* (A, B, C, D or E of EC8), the *Topographic Category*, *Nominal Life* of the structure, *Functional Type* of the structure and the *Limit State* of interest (these are required by the code to define the return period of the seismic action, see "Appendix"). Then the software automatically generates the spectrum accordingly.

In case (2), it is necessary to specify only the anchoring value of the spectrum, a_g, and the site class. The value of a_g can be defined manually by the user or, in the case of sites on the Italian territory, can be obtained automatically from the geographical coordinates of the site.

In both cases (1) and (2), if the spectrum is to be obtained automatically after the geographical coordinates, the software has built-in the official hazard data of the NIBC (derived from the INGV study).

In case (3) the spectral acceleration ordinates corresponding to 123 periods between 0 and 4 s (i.e., the same format of ESD spectra) have to be entered by the user.

Finally, it is necessary to specify the component of the spectrum to consider; i.e., horizontal and/or vertical. The two orthogonal independent components that describe the horizontal motion (X and Y) are characterized by the same elastic response spectrum as per the considered codes, while the component that describes the vertical motion (Z) is characterized by a specific spectrum. It is possible to select X/Y and Z separately or contemporarily, depending on the number of components of GM (1, 2 or 3) desired to be included in the set.

4.2 Design earthquake (source) parameters

The software has built-in the records of the ESD database (in terms of three components corrected acceleration waveforms and 5% damping spectra) which are from free field instruments and from events of magnitude[6] larger than 4 (any faulting style). No restrictions were applied with respect to the processing of the records, the effect of which at least on spectral displacements, was investigated by Akkar and Bommer (2006). REXEL provides histograms of the embedded records (Fig. 2).

The soil type is decided in step 1 while defining the spectrum, and this choice automatically limits the search of the combinations to the records belonging to this specific site class. Moreover, the user can choose to search for combinations coming from specific M and R ranges.[7] This may prove useful if data about the events of interest are available, for example from disaggregation of seismic hazard, and it is consistent with code criteria which require to select records taking care of the seismogenetic features of the source of the design earthquake. Therefore, the user can specify the magnitude and distance intervals, $[M_{\min}, M_{\max}]$ and $[R_{\min}, R_{\max}]$, in which the records to be searched have to fall. After these bounds are defined, the software returns the number of records (and the corresponding number of originating events) available in the intervals. This list constitutes the inventory of records in which to search for suites of seven which are in the average compatible with the code spectra of step 1. These spectra may also be plotted along with the reference spectrum to have a picture of the spectra REXEL will search among.

4.3 Spectrum matching parameters and analysis options

In this step the parameters related to the spectral compatibility are defined. In which period range, $[T_1, T_2]$, the reference spectrum has to be matched has to be defined first. T_1 and T_2

[6] The EC8 Type 1 spectra apply if the event of interest has surface wave magnitude larger than 5.5 (see "Appendix"). Therefore in the case of selection according to EC8 the user can limit the magnitude to be above the threshold (see following section); alternatively he can include records from lower magnitude events.

[7] It is always moment magnitude (M_W), except for soil E where M is expressed in terms of local magnitude (M_L), as M_W was not available in ESD. R is always the distance from the epicenter of the event because fault distance (the only alternative measure of distance given in the database) was available for part of the records only. However, in those cases where the latter is also available it is provided by REXEL. Note that some records were recorded beyond 500 km although their fraction is negligible and therefore almost invisible in Fig. 2.

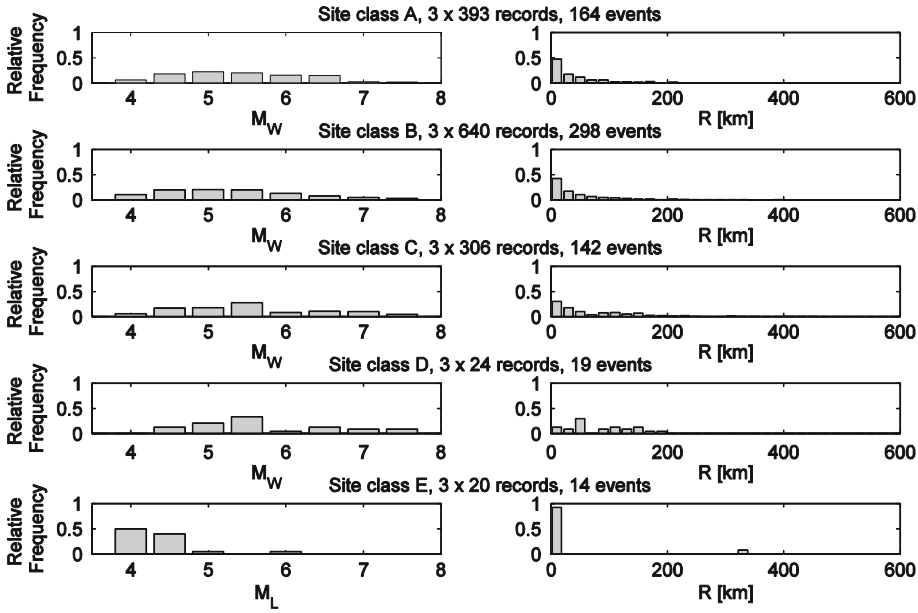

Fig. 2 Magnitude and distance distributions of ESD records featured in REXEL 2.31 beta. Relative frequency is computed with respect to the total number of recording stations available for the specific site class

can be any pair in the 0–4 s range. Secondly, the tolerances allowed in spectral matching are required. This means the user has to specify the tolerated deviations (*lower* and *upper* limits) in percentage terms, the average spectrum of the combination can have with respect to the reference in the specified period range. EC8, for example, explicitly states that the average elastic spectrum must not underestimate the code spectrum, with a 10% tolerance (lower limit) but does not provide any indication about the upper limit. It is economically viable to reduce as much as possible the overestimation of the spectrum, and this is why also an upper limit was introduced in REXEL.

In this phase it is also possible to select the *Non-dimensional* option, which corresponds to choose whether to search for *unscaled* or *scaled* record sets. In fact, REXEL 2.31 beta allows to obtain combinations of accelerograms whose average is, in the desired period range, above the reference spectrum times the lower bound tolerance and below the reference spectrum times the upper bound tolerance, being not manipulated (original records), but it also allows choosing sets of accelerograms compatible with the reference spectrum if linearly scaled in amplitude. If this second option is chosen, the user has to check the *Non-dimensional* box, which means the spectra of the list defined in step 2 are preliminarily normalized dividing the spectral ordinates by their PGA. Combinations of these spectra are compared to the non-dimensional reference spectrum.[8] If this option is selected, it is also possible to specify the maximum mean scale factor (SF) allowed; REXEL will discard combinations with an average SF larger than what desired by the user.

The user can also select the option *I'm feeling lucky* in order to stop the analysis after the first compatible combination is found. This option, in the most of cases, allows to immediately

[8] This, as already demonstrated in Iervolino et al. (2008, 2009) allows to have combinations whose spectra are similar to reference spectrum, then reducing the record-to-record spectral variability within a set, which is a desirable feature if one has to estimate the seismic demand on the basis of 7 analyses only.

get a single combination compatible with the reference spectrum, otherwise, the search may take a very long time (as warned by the software, which computes the number of combinations of 7 to be investigated if a certain number of records preliminarily is selected in the database).[9] Alternatively, the *maximum number of compatible combinations to find* after which the search has to stop, can be specified.

4.4 Combinations search

At this point the initial list of records and the analysis parameters are set and it is possible to decide which kind of search to perform. The software searches for combinations of:

(a) seven 1-component accelerograms whose average matches the reference spectrum in the specified range of periods and with the provided upper- and lower-bound tolerances. The found combinations can be applied in one direction for plane analysis of structures;[10]

(b) seven pairs of accelerograms. This option allows to search for 14 records which are seven 2-components recordings (both X and Y components of 7 recording stations only), which on average[11] are compatible with the reference spectrum; this kind of search is for cases in which horizontal motion has to be applied in both directions of a 3D structure;

(c) seven groups of accelerograms which include the two horizontal and the vertical component of seven recordings (i.e., 21 records which are the X, Y and Z components of seven recording stations only) for full 3D analysis. In this case, the selection proceeds in two sub-steps: first, the combinations compatible with the horizontal component of the code spectrum are found, exactly as in case (b); then, the software analyzes the vertical components of only those horizontal combinations which have been found to be compatible with the code spectrum, and verifies if the set of their seven vertical components is also compatible with the vertical code spectrum. The tolerances and period ranges for average vertical spectral matching may be different from those regarding horizontal components and may defined by the user after the horizontal analysis has finished.

An important feature of REXEL is that the list of records out of step 2, which is an input for this phase, are ordered, when the analysis is launched, in ascending order of the parameter defined in Eq. 1, which gives a measure of how much the spectrum of an individual record deviates from the reference spectrum. In Eq. 1, $\mathrm{Sa}_j(T_i)$ is the pseudo-acceleration ordinate of the real spectrum j corresponding to the period T_i, while $\mathrm{Sa}_{\mathrm{reference}}(T_i)$ is the value of the spectral ordinate of the target spectrum at the same period, and N is the number of spectral ordinates within the considered range of periods.

$$\delta_i = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\mathrm{Sa}_j\,(T_i) - \mathrm{Sa}_{\mathrm{reference}}\,(T_i)}{\mathrm{Sa}_{\mathrm{reference}}\,(T_i)}\right)^2} \tag{1}$$

Preliminary ordering allows to analyze first the records which have a similar spectral shape with respect to the reference. This ensures the first combinations (e.g., the one found with the

[9] This is given by the binomial coefficient; for example if 100 records are selected, the maximum number of combinations which have to be checked for spectral compatibility are about 16 billions.

[10] Note that this option applies alternatively to horizontal or vertical components of motion, although it is unlikely one is looking for a suites of seven vertical accelerograms only.

[11] The average is taken on the 14 records all together as found appropriate in Iervolino et al. (2008) for EC8—Part 1. This is not perfectly consistent with provisions of EC8—Part 2, which require the average to be taken to the seven SRSS spectra; nevertheless, the two procedures were found to be equivalent to some extent in Iervolino et al. (2009).

I'm feeling lucky option) to be those with the smallest individual scattering in respect to the reference spectrum, as shown in the following examples. This is an important point although codes, generally, do not ask to control this individual spectral variability, only requiring to control the average spectrum of the combination. On the other hand, large individual variability may affect the accuracy of the estimation of the structural performance if a limited number of records (e.g., 7) is employed (Cornell 2004). Moreover, this also enables to have individual records in the combination with a spectral shape as much as possible similar to that of the target spectrum. This is consistent with the current research on the topic, which considers the spectral shape as the most important proxy for earthquake damage potential on structures, more than event parameters as M and R.

4.5 Post-analysis

After the analysis has finished, REXEL returns a list of combinations whose average spectrum respects compatibility with the reference in the chosen range of periods and with the assigned tolerances. The results of the analysis are sorted so that the combinations with the smallest deviation from the spectrum of the code are at the beginning of the output list, due to the preliminary ordering of records according to δ_i. Combinations returned are uniquely identified by a serial number; this code can be used to display the spectra of a specific combination of interest and obtain the acceleration time-histories grouped in a compressed file. Each record is identified by the 8 characters filename whose initial six digits are the waveform ID associated to records in the ESD, while the last two may correspond to *xa*, *ya*, and *za* indicating the component of the recording: X, Y and Z, respectively.

If a specific combination is chosen REXEL also returns the mean value of M and R of the combination and the information about the individual records as retrieved by the ESD that is, recording station, event (time, date and country), M, R, fault mechanism, etc. In the case of non-dimensional sets, the scale factors of the individual records and the mean scale factor of the combination are given. For all the combinations found, it is possible to calculate the deviation of each accelerogram, and the deviation of the average spectrum from the reference elastic response spectrum. In this latter case Eq. 1 is still used, replacing $\mathrm{Sa}_j(T_i)$ with the average spectral acceleration of the combination.

4.6 Different 2 and different 3 options

Although both considered codes only require a minimum size for GM suites of 7 in order to consider the mean effects on the structure, it is known how this number may affect the confidence (i.e., the standard error) in the estimation of the structural response, which increases as the variability of individual records with respect to the reference increases. Therefore, in the case one wants to run the analyses with a larger number of records, REXEL has two options which both are applicable to the list of results of the analyses discussed in the previous section:

- *Different 2* allows to search within the list of output, pairs of combinations (i.e., 2 sets of 7 records of the type (a), (b), or (c) above) which have accelerograms from earthquake events which do not overlap. This allows to have a larger set of 14 one- or multi-component records, spectrum matching in the average, in which there are no dominating events. For each found pair of sets the software also computes the maximum deviation δ_i of the individual records in the two original combinations and this may be a parameter for choosing one pair with respect to another;
- *Different 3* allows to search within the list of output, triplets of combinations (3 of 7 one- or multi-component records) having no accelerograms in common although may

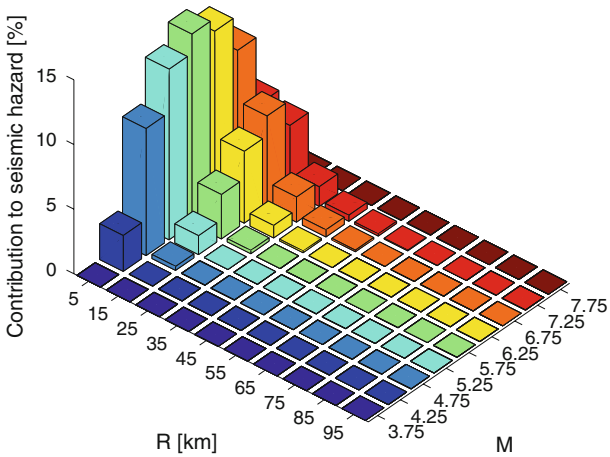

Fig. 3 Disaggregation of the PGA with 475 years return period on rock for Sant'Angelo dei Lombardi

have common events. This analysis provides sets of 21 records which, still, fulfill the code-required average spectral compatibility with the given tolerances.

The examples below illustrate the developed tool capabilities and how it, in many cases, allows for a rational and fast selection of seismic input for code-based nonlinear dynamic analysis of structures.

5 Illustrative applications

5.1 Selection according to NIBC

As an example let's consider selection of horizontal accelerograms according to NIBC for the life safety limit state of an ordinary structure (*Functional class II*, see "NIBC reference spectra" in the "Appendix") on soil type A with a nominal life of 50 years (which corresponds to design for a 475 years return period according to the code) and located in Sant'Angelo dei Lombardi (15.1784° longitude, 40.8931° latitude; close to Avellino in southern Italy). Setting the coordinates of the site and the other parameters to define the seismic action according to NIBC, the software automatically builds the elastic design spectrum. Consider also that selection should reflect disaggregation of PGA hazard[12] on rock with a 10% probability of exceedance in 50 years (Fig. 3) at the site, which may be easily obtained by the INGV website given above. Specifying the M and R intervals to [5.6, 7] and [0 km, 30 km], respectively, REXEL 2.31 beta founds 177 records (59 × 3 components of motion) from 28 earthquakes, whose horizontal spectra, unscaled and non-dimensional, are given in Fig. 4, which the software automatically returns. REXEL will search among these spectra.

Assigning, as tolerances for the average spectral matching, 10% lower and 20% upper in the period range 0.15–2 s and selecting the option to stop the search after the first combination is found (i.e., *I'm feeling lucky*), REXEL immediately returns the combination of accelero-

[12] Note that it is often recommended to consider as design earthquakes the results of hazard disaggregation for the spectral ordinates in the range of interest for the nonlinear structural behavior. This may differ from disaggregation of PGA hazard, especially when M and R joint distribution has multiple modal values (Convertito et al. 2009).

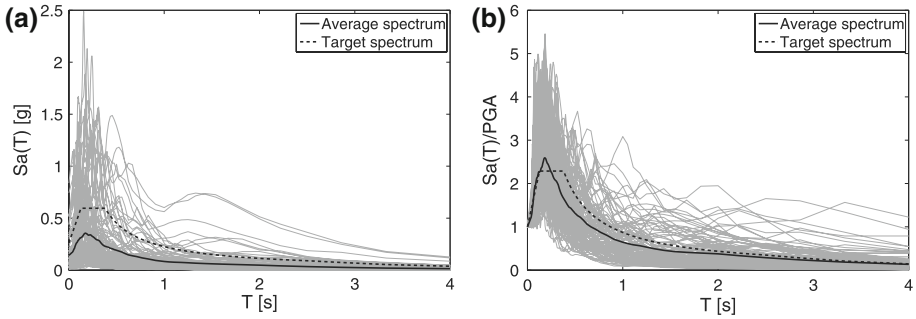

Fig. 4 Plot of the spectra found in the ESD for the selected *M* and *R* bins in the case of site class A

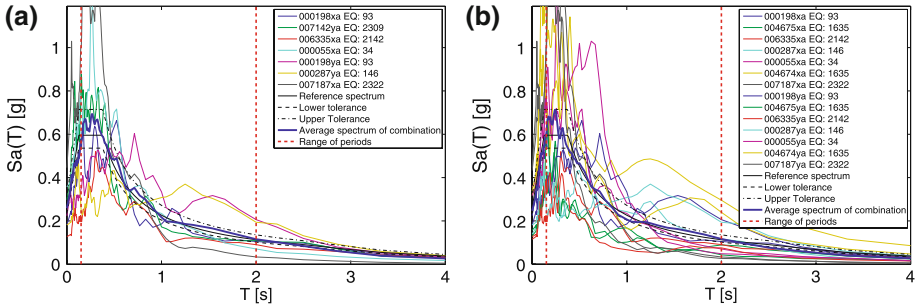

Fig. 5 Unscaled combinations found for the assigned example in Sant'Angelo dei Lombardi using the *I'm feeling lucky* option in the case of horizontal 1-component (**a**) and 2-components (**b**) GMs

grams in Fig. 5a if the 1-component search is performed. In the figure, which the software automatically plots, thick solid lines are the average of the set and the code spectrum, while the dashed are the tolerance and period range bounds where compatibility is ensured. Solid thin lines are the seven individual spectra of the combination. In the legend the ESD station and component IDs, along with the earthquake IDs, are given.

Selecting the search for set of seven pairs of horizontal components (e.g., for the analysis of spatial structures), instead, the software returns the 14 records of Fig. 5b. Note that in this case the records are seven pairs of *X* and *Y* components of seven stations only. In Tables 1 and 2 the data about the two combinations[13] are given as they are returned by REXEL.

It is was claimed in the description of the software that the first combination has a low scatter with respect to subsequent combinations eventually found. This may be shown, for example, not selecting the *I'm feeling lucky* option and limiting the maximum number of combinations to 1,000 and repeating the same two searches above. Then, REXEL returns, in about one minute with a standard personal computer, 1,000 1-component compatible combinations, and in a few minutes, 520 combinations featuring both the two horizontal components of motion. Figure 6a and b show the last combination (no. 1,000 and no. 520, respectively) of the output list in the two cases.

Although all average spectra of Figs. 5 and 6 match with similar good approximation the code spectrum, it is evident that the preliminary ordering of accelerograms according to δ_i enables the high ranking combinations to have individual spectra with a smaller dispersion with respect to the reference spectrum.

[13] Data about combinations are not given for the subsequent examples for the sake of brevity, nevertheless they can be easily obtained by the reader from the information in the legend of the figures.

Table 1 Essential record data returned by REXEL for the combination of Fig. 5a

ESD record ID	ESD event ID	Earthquake name	Date	M	Fault mechanism	*R* (km)
000198xa	93	Montenegro	15/04/1979	6.9	Thrust	21
007142ya	2309	Bingol	01/05/2003	6.3	Strike slip	14
006335xa	2142	South Iceland (aft.)	21/06/2000	6.4	Strike slip	15
000055xa	34	Friuli	06/05/1976	6.5	Thrust	23
000198ya	93	Montenegro	15/04/1979	6.9	Thrust	21
000287ya	146	Campano Lucano	23/11/1980	6.9	Normal	23
007187xa	2322	Avej	22/06/2002	6.5	Thrust	28

Table 2 Essential record data returned by REXEL for the combination of Fig. 5b

ESD station ID	ESD event ID	Earthquake name	Date	M	Fault mechanism	*R* (km)
000198	93	Montenegro	15/04/1979	6.9	Thrust	21
004675	1635	South Iceland	17/06/2000	6.5	Strike slip	13
006335	2142	South Iceland (aft.)	21/06/2000	6.4	Strike slip	15
000287	146	Campano Lucano	23/11/1980	6.9	Normal	23
000055	34	Friuli	06/05/1976	6.5	Thrust	23
004674	1635	South Iceland	17/06/2000	6.5	Strike slip	5
007187	2322	Avej	22/06/2002	6.5	Thrust	28

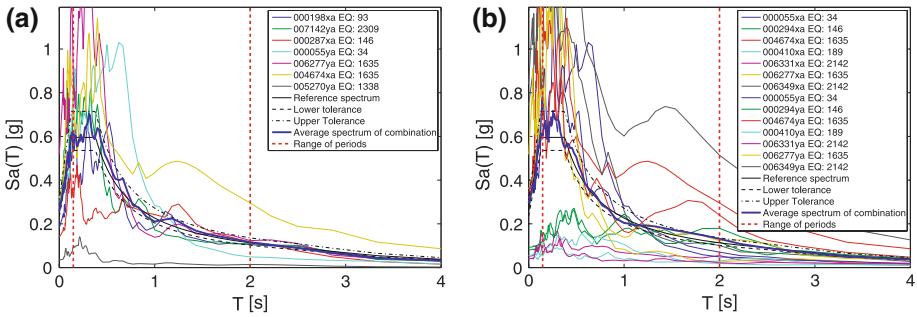

Fig. 6 Last of 1,000 and 520 unscaled combinations found for the assigned example in Sant'Angelo dei Lombardi in the case of horizontal 1-component (**a**) and 2-components (**b**) GMs

Nevertheless, the presented results show that the deviation of the individual spectra compared with the reference can still be large (e.g., Fig. 5b). To reduce the scatter of individual records further, the *Non-dimensional* option can be used, which means that records found have to be linearly scaled to be spectrum matching in the average. In this case, repeating the search for Sant'Angelo dei Lombardi simply considering accelerograms with $M \geq 6$ and R within 0–25 km, with the same compatibility criteria as per the previous case and using the option *I'm feeling lucky*, REXEL returns immediately combinations shown in Fig. 7a and b, which feature records less scattering with respect to those unscaled of Fig. 5. In this case, the individual scale factors are given in the legend. Note also that the code asks for the maximum value the average scale factor (SF_{mean}) can assume, which in this case was limited to 2.

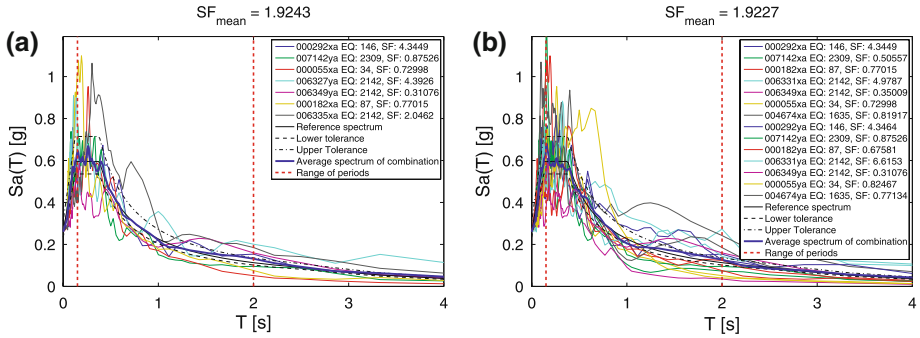

Fig. 7 Scaled combinations found for the assigned example in Sant'Angelo dei Lombardi using the *I'm feeling lucky* option in the case of horizontal 1-component (**a**) and 2-components (**b**) GMs

5.1.1 Search that includes the vertical component of seismic motion

REXEL 2.31 beta allows selecting combinations of accelerograms that include the vertical component of the records, although NIBC and EC8 require to account for it only in peculiar cases. Considering again the same example in Sant'Angelo Lombardi, and specifying as the M and R intervals as [6, 7.8] and [0 km, 50 km], respectively, REXEL founds 58 groups of accelerograms from 23 events.

Assigning a tolerance compatibility of the average of 10% lower and 30% upper for the horizontal component, and 10% lower and 50% upper for the vertical component, in the range of periods 0.15–2 s (for the horizontal components) and 0.15–1 s (for the vertical component), the software returns 100,000 scaled combinations compatible with the horizontal reference spectrum (the maximum number of combinations was limited to 100,000, for simplicity), 160 of which are also compatible with the vertical reference spectrum. The maximum value of the average scale factor was limited to 2.

Finally, note that when searching for combinations that include the vertical component, it may not be appropriate to use the *I'm feeling lucky* option. In fact, the first combination compatible with the horizontal code spectrum (returned by the software) may not necessarily satisfy the compatibility criteria with the vertical spectrum. For example, in the considered case of Fig. 8, the first combination, which has all the three components matching the

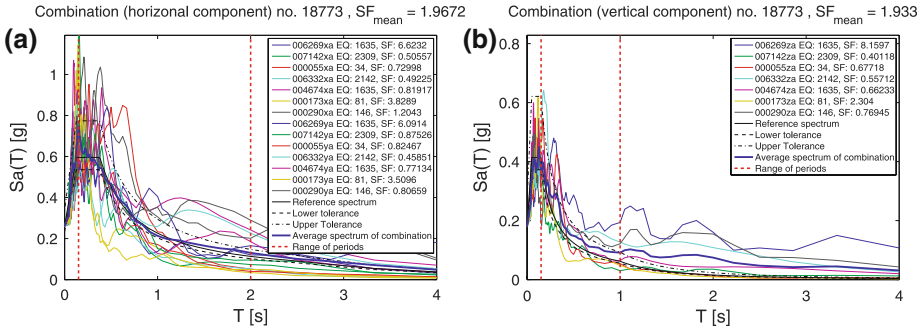

Fig. 8 First scaled combination found for the assigned example in Sant'Angelo dei Lombardi which includes the two horizontal (**a**) and the third vertical (**b**) components of GM matching the respective reference spectra

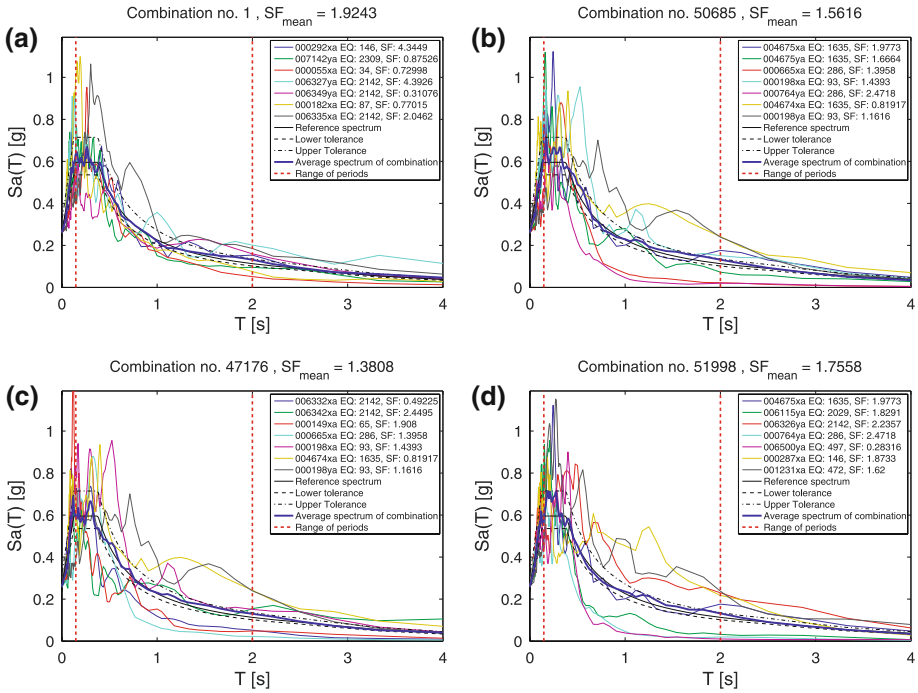

Fig. 9 Scaled pair of combinations without overlapping events, **a** and **b**, and triplet without overlapping records **a**, **c** and **d**, for the considered example

reference spectra, only comes after 18,772 combinations found which match the horizontal spectrum.

5.1.2 Different 2 and different 3

After having performed a search to find 100,000 1-component combinations for the site in question (with same constraints of the scaled search in Sect. 5.1) it is possible to use the option *Different 2* limiting, for the sake of simplicity, to 100 the maximum number of pairs of combinations to find. Then, REXEL returns 100 pairs of combinations comprised of accelerograms all coming from different events. An example of these pairs found is given by the two combinations of Fig. 9a and b (see legends to check that earthquake IDs are not overlapping between the figures). Using the option *Different 3*, and limiting for simplicity to 100 the maximum number of triplets of combinations to find, REXEL returns 100 triple combinations having no accelerograms in common. An example of the triplets found with *Different 3* is given by the combinations of Fig. 9a, c, and d (see legends to check that stations codes are not overlapping among the figures).

5.2 Selection according to EC8

Suppose now one needs to select horizontal accelerograms according to EC8 provisions with reference to the ultimate limit state for the same structure still located in Sant'Angelo dei Lombardi, but considering soil type B. In this case the software returns automatically the

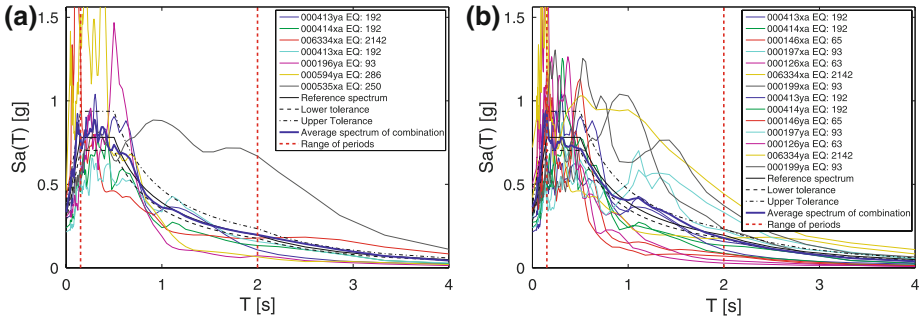

Fig. 10 Unscaled combinations found for the assigned example in case of EC8 selection using the *I'm feeling lucky* option in the case of horizontal 1- (**a**) and 2-components (**b**) GMs

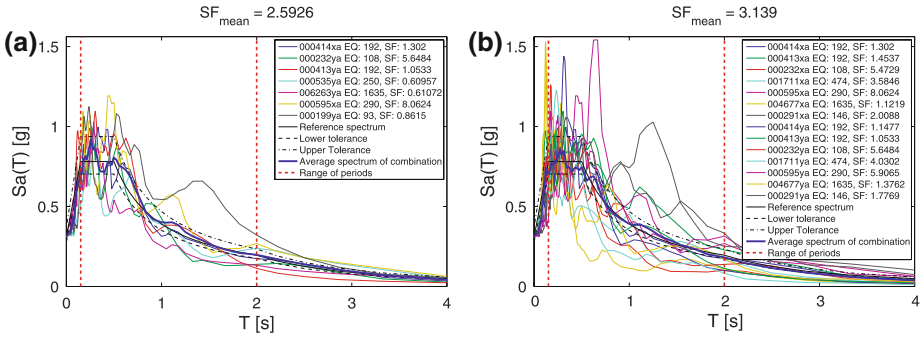

Fig. 11 Scaled combinations found for the assigned example in case of EC8 selection using the *I'm feeling lucky* option in the case of horizontal 1-component (**a**) and 2-components (**b**) GMs

code spectrum because it is able to determine the a_g value for the site (0.27 g). In the case the site is not Italian the user has to input the a_g value of interest.

Specifying the M and R intervals equal to [5.6, 7] and [0 km, 30 km], respectively, assigning a compatibility tolerance with respect to the average spectrum of 10% lower and 20% upper in the period range 0.15–2 s and selecting the quick search option, the software immediately returns the combinations shown in Fig. 10a and b, in the case of 1-component and 2-components search, respectively.

Selecting the *Non-dimensional* option, the software immediately returns the combinations of Fig. 11a and b. The mean scale factor was limited to 5 as it, although larger than 2 used in the previous example, allows to search among more combinations and may be still considered acceptable.

Note that in case of site class B the individual records of the scaled combination (e.g., Fig. 11b) have a scatter with respect to the reference spectrum which is comparable to that of the corresponding unscaled combination (i.e., Fig. 10b), unlike what happens for the case of soil A (see Fig. 5 and Fig. 7). The records among which REXEL searched in this case are given in Fig. 12.

5.3 Selection in case of user-defined spectrum

To explore the feature of REXEL allowing to search for sets of records compatible with an user-defined spectrum, lets' consider the UHS with a 63% probability of exceedance

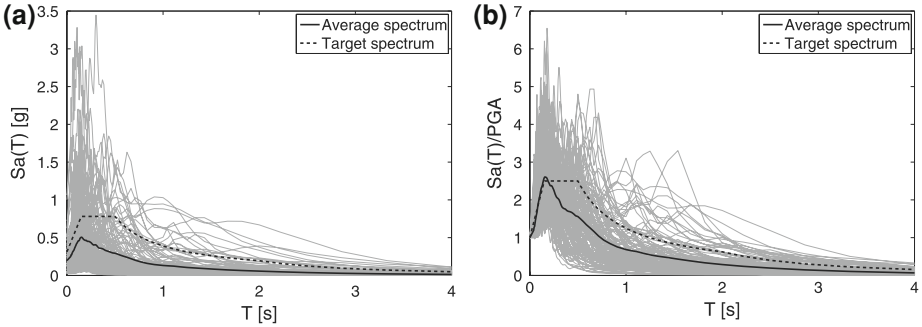

Fig. 12 Plot of the spectra found in the ESD for the selected *M* and *R* bins in the case of site class B

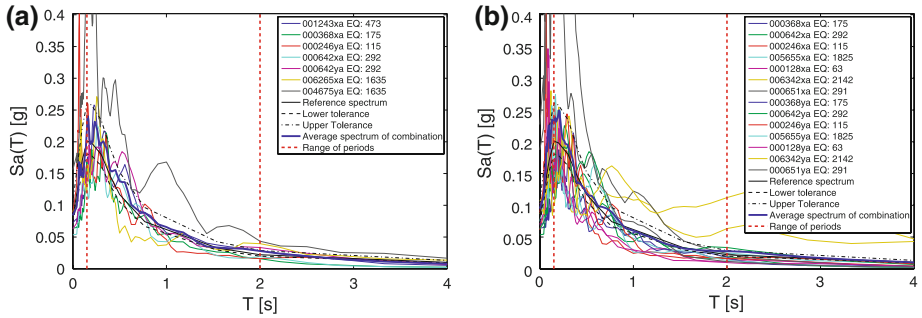

Fig. 13 Unscaled combinations found for the assigned example in case of user-defined spectrum selection using the *I'm feeling lucky* option in the case of horizontal 1-component (**a**) and 2-components (**b**) GMs

in 50 years for Sant'Angelo dei Lombardi (50 years return period). To this aim the spectral ordinates in the 0–4 s range have to be input by the user, those between 0 and 2 s were retrieved interpolating the online hazard data of INGV, those from 2 to 4 s were obtained by linear extrapolation (such arbitrary choice does not affect the described example).

Specifying the *M* and *R* intervals equal to [5.5, 6.5] and [0 km, 30 km], respectively, assigning a compatibility tolerance with respect to the average spectrum of 10% lower and 30% upper in the period range 0.15–2 s and selecting the fast search option, the software immediately returns the combinations of accelerograms shown in Fig. 13a and b.

Selecting the *Non-dimensional* option, the software immediately returns the combinations of Fig. 14a and b. Once again the mean scale factor was limited to 2.

6 Comparison with the classification in seismic zones

New Italian seismic code, to define the seismic actions on structures, goes beyond the concept of classification of national territory in seismic zones, which still applies in many countries. Previously, in fact, the seismic action was defined by standard spectral shapes depending on the soil type and anchored to the ground acceleration of reference. This reference value was identified based on the site of interest belonging to one of four possible seismic zones. A site belonged to Zone I, II, III or IV depending on the PGA on rock with a 10% probability of exceedance in 50 years falling in one of the intervals]0.25 g, 0.35 g],]0.15 g, 0.25 g],]0.05 g,

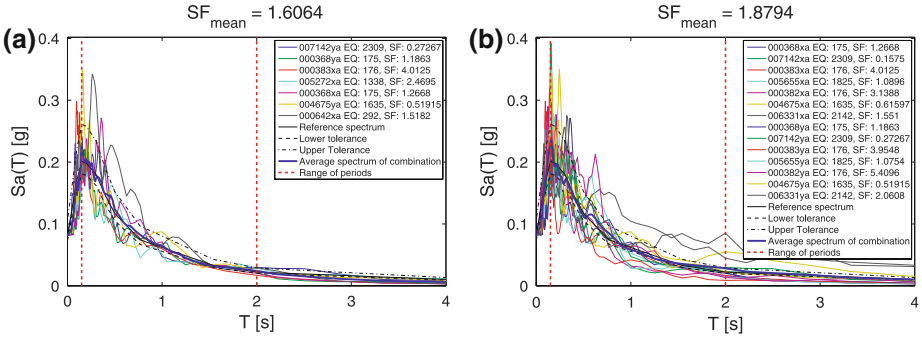

Fig. 14 Scaled combinations found for the assigned example in case of user-defined spectrum selection using the *I'm feeling lucky* option in the case of horizontal 1-component (**a**) and 2-components (**b**) GMs

Table 3 Results of comparison, in terms of search for unscaled combinations, for Sant'Angelo dei Lombardi according to the new and the former seismic classifications

Site class	$a_g = 0.27$ g	$a_g = 0.35$ g
A	12016	2
B	6174	0
C	3	0
D	0	0
E	0	0

0.15 g] and ≤0.05 g, respectively. To each of these areas an a_g value equal to the upper limit of the acceleration range defining the zone was conservatively assigned. This had several consequences, first of all the code spectra were only indirectly related to the seismic hazard. Moreover, these spectra were often significantly over-estimated if compared to the uniform hazard spectra with a 10% probability of exceedance in 50 years. This lead to the difficulty of finding unscaled real records for the spectra anchored to the most severe a_g values, as shown in previous studies recalled in Sect. 2.

REXEL and the new classification enable a more effective selection of seismic input. For example, if one needs to select 2-components sets of unscaled accelerograms according to EC8 requirements for Sant'Angelo dei Lombardi considering as anchoring values of the spectrum: (1) the real PGA on rock with a 10% probability of exceedance in 50 years (0.27 g, from INGV data); (2) the value 0.35 g (according to the old seismic classification), he gets the number of combinations found results in Table 3.[14] The tests were carried out assuming a [6, 7.8] M range and R varying from 0 to 40 km, assigning a tolerance compatibility of the average of 10% lower and 30% upper in the range of periods 0.2–2 s.

The comparison shows that, at least in the case of soil conditions where the number of records is larger, the new seismic classification not based on hazard zonation allows, or at least simplifies, seismic input selection. Note that search for softer soil classes did not return any result mainly because the shortage of records in the ESD (Fig. 2).

[14] In the investigation of Iervolino et al. (2008) no combinations were found also for A type site class, this result here are not perfectly the same because the initial database and search conditions do not coincide precisely.

7 Conclusions

In the paper, the main issues related to code-based record selection were briefly presented with reference to EC8 (Part 1 and Part 2) and the new Italian building code. Based on previous studies, it is shown how record selection provisions may be not easily applicable to real records. To overcome the most of the obstacles the practitioner may face when determining the seismic input for structural analysis a software tool for automatic selection of seven real recordings, including 1, 2 or 3 components of GM, was developed and presented. The main selection criterion, for unscaled or scaled sets, is the compatibility, in broad period ranges, of the average spectrum with respect to the reference spectra (which the program automatically builds) of the new Italian building code, of EC8, or user-defined. REXEL 2.31 beta, freely available on the internet on the RELUIS website also ensures that individual records in the combinations returned have a spectral shape like that of the target as much as possible, which is important as spectral shape is currently seen as the best proxy for earthquake damage potential on structures. The current version of the software relies on records from the European Strong-motion Database; nevertheless, in future developments data from other repositories could be implemented.

The capabilities of REXEL were tested via several illustrative applications regarding selection of multi-component GM suites according to code- and hazard-based spectra, for different site classes and limit states or return periods. In this way it was demonstrated how the finding of spectrum-compatible sets of records, whose average is compatible with the target, can be significantly improved and facilitated. In fact, REXEL allows to select records controlling the tolerance according to which the average matches the reference spectrum. It also allows to account, beside the site class, for earthquake source characteristics (i.e., magnitude and distance) which may be useful if information on the design earthquake, for example from disaggregation of seismic hazard, is available at the time of the structural analysis.

Finally it is to note that, in principle, the developed tool may be used for the assessment of not only ordinary building-like structures, but also isolated buildings, industrial components, and geotechnical systems. REXEL, therefore, may prove to be useful for practitioners to select the seismic input for code-based seismic assessment via dynamic analysis.

Acknowledgments The study presented in this paper was developed within the activities of "Rete dei Laboratori Universitari di Ingegneria Sismica—ReLUIS" for the research program funded by the "Dipartimento della Protezione Civile" (2005–2008).

Appendix

EC8 reference spectra

The spectral shapes for the two horizontal orthogonal components of the seismic action, if the earthquakes that contributes most to the seismic hazard defined for the site have a surface-wave magnitude >5.5, is given by Eq. 2:

$$\begin{cases} 0 \le T < T_{\mathrm{B}} : S_{\mathrm{a}}(T) = a_{\mathrm{g}} S \left[1 + \frac{T}{T_{\mathrm{B}}} (\eta 2.5 - 1) \right] \\ T_{\mathrm{B}} \le T < T_{\mathrm{C}} : S_{\mathrm{a}}(T) = a_{\mathrm{g}} S \eta 2.5 \\ T_{\mathrm{C}} \le T < T_{\mathrm{D}} : S_{\mathrm{a}}(T) = a_{\mathrm{g}} S \eta 2.5 \left(\frac{T_{\mathrm{C}}}{T} \right) \\ T_{\mathrm{D}} \le T < 4s : S_{\mathrm{a}}(T) = a_{\mathrm{g}} S \eta 2.5 \left(\frac{T_{\mathrm{C}} T_{\mathrm{D}}}{T^2} \right) \end{cases} \tag{2}$$

Table 4 Values of the parameters describing the recommended elastic type 1 EC8 response spectra

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1.00	0.15	0.40	2.00
B	1.20	0.15	0.50	2.00
C	1.15	0.20	0.60	2.00
D	1.35	0.20	0.80	2.00
E	1.40	0.15	0.50	2.00

Table 5 Recommended values of parameters describing the vertical elastic response spectra

Ground type	a_{vg}/a_g	T_B (s)	T_C (s)	T_D (s)
A, B, C, D, E	0.90	0.05	0.15	1.00

where T is the vibration period of a linear single-degree-of-freedom (SDOF) system; a_g is the design ground acceleration on type A site class; T_B and T_C are the lower and the upper limits of the constant spectral acceleration region, respectively; T_D is the value defining the beginning of the constant displacement range of the spectrum; S is the soil factor and η is the damping correction factor ($\eta = 1$ for 5% viscous damping). The a_g values have to be determined by the national authorities. The values of T_B, T_C and T_D and S depend upon the ground type; the recommended values of these parameters are given in Table 4.

The vertical component of the seismic action is represented by elastic response spectrum of Eq. 3. For the five ground types A, B, C, D and E, the recommended values of the parameters describing the vertical spectra are given in Table 5.

$$\begin{cases} 0 \le T < T_B : S_{va}(T) = a_{vg}\left[1 + \frac{T}{T_B}(\eta 3.0 - 1)\right] \\ T_B \le T < T_C : S_{va}(T) = a_{vg}\eta 3.0 \\ T_C \le T < T_D : S_{va}(T) = a_{vg}\eta 3.0\left(\frac{T_C}{T}\right) \\ T_D \le T < 4\,\text{s} : S_{va}(T) = a_{vg}\eta 3.0\left(\frac{T_C T_D}{T^2}\right) \end{cases} \tag{3}$$

NIBC reference spectra

The spectral shape for the two horizontal orthogonal components of the seismic action is given by Eq. 4, where T is the vibration period of a linear SDOF; a_g and η have the same meaning of EC8; S is the product of the stratigraphic factor, S_S, and the topographic amplification factor, S_T; T_B and T_C are the limiting periods of the spectrum's plateau; T_D is the lowest period of the constant displacement spectral portion; F_o is an amplification factor (equal to the ratio between the maximum spectral ordinate and the a_g value). The ordinates and shapes (i.e., T_B, T_C, T_D and S) depend both on the seismic hazard and site class. The same stratigraphic profiles of EC8 are considered.

$$\begin{cases} 0 \le T < T_B : S_a(T) = a_g S\eta F_o\left[\frac{T}{T_B} + \frac{1}{\eta F_o}\left(1 - \frac{T}{T_B}\right)\right] \\ T_B \le T < T_C : S_a(T) = a_g S\eta F_o \\ T_C \le T < T_D : S_a(T) = a_g S\eta F_o\left(\frac{T_C}{T}\right) \\ T_D \le T < 4\,\text{s} : S_a(T) = a_g S\eta F_o\left(\frac{T_C T_D}{T^2}\right) \end{cases} \tag{4}$$

Table 6 Recommended values of parameters describing the vertical elastic response spectra

Ground type	S_S	T_B (s)	T_C (s)	T_D (s)
A, B, C, D, E	1.0	0.05	0.15	1.00

Table 7 Possible values for P_{V_R}, C_U and V_N

P_{V_R} (Limit state)	C_U	V_N
81%—Operability	0.7—Provisional structures	≤10 years—Temporary structures
63%—Damage	1.0—Ordinary structures	≥50 years—Ordinary structures
10%—Life safety	1.5—Important structures	≥100 years—Important structures
5%—Collapse	2.0—Strategic structures	

The spectral shape for the vertical component of the seismic action is given by Eq. 5, where T is the vertical vibration period of a linear SDOF and F_v is the vertical amplification factor (related to F_o as $F_v = 1.35F_o\left(a_g/g\right)^{0.5}$). T_B, T_C and T_D values for the vertical response spectrum are given in Table 6.

$$\begin{cases} 0 \le T < T_B : S_{va}(T) = a_g S\eta F_v \left[\frac{T}{T_B} + \frac{1}{\eta F_o}\left(1 - \frac{T}{T_B}\right)\right] \\ T_B \le T < T_C : S_{va}(T) = a_g S\eta F_v \\ T_C \le T < T_D : S_{va}(T) = a_g S\eta F_v \left(\frac{T_C}{T}\right) \\ T_D \le T < 4\,\text{s} : S_{va}(T) = a_g S\eta F_v \left(\frac{T_C T_D}{T^2}\right) \end{cases} \tag{5}$$

The Annex B of NIBC provides a_g, F_o and T_C^* (i.e., the T_C value for type A site class) values for the nine return periods of seismic action (from 30 to 2,500 years) and for each node of a regular grid having an about 5 km spacing and covering the whole national territory. These values are derived from the mentioned INGV seismic hazard study. In particular, the F_o and T_C^* values are obtained minimizing, for a given site and for a given return period, the deviation between the code acceleration, velocity and displacement spectra and the corresponding UHS from the INGV study.

The return period to be considered depends on a (temporal) reference period (V_R, in years) and on the probability of exceedance of the a_g value in the reference period (P_{V_R}), Eq. 6. P_{V_R} depends on the limit state of interest (Table 7). V_R is equal to the nominal life of the structure (V_N, in years), times the importance coefficient for the construction (C_U).

$$T_R = -V_R/\log\left(1 - P_{V_R}\right) \tag{6}$$

For a generic return period T_R (that does not fall in the set of return periods for which the spectra parameters are available in the code), the value of the generic parameter may be computed by Eq. 7:

$$\log(p) = \log(p_1) + \log\left(\frac{p_2}{p_1}\right)\log\left(\frac{T_R}{T_{R_1}}\right)\left[\log\left(\frac{T_{R_2}}{T_{R_1}}\right)\right]^{-1} \tag{7}$$

where, p is the value of the parameter of interest (a_g, F_o or T_C^*) corresponding to the required return period T_R; T_{R_1} and T_{R_2} are the return periods closest to T_R and for which the p_1 and p_2 values of the p parameter are available in the code.

Table 8 Expressions defining S_S and C_C

Site class	S_S	C_C
A	1.00	1.00
B	$1.00 \le 1.40 - 0.40 F_o a_g/g \le 1.20$	$1.10\,(T_C{}^*)^{-0.20}$
C	$1.00 \le 1.70 - 0.60 F_o a_g/g \le 1.50$	$1.05\,(T_C{}^*)^{-0.33}$
D	$0.90 \le 2.40 - 1.50 F_o a_g/g \le 1.80$	$1.25\,(T_C{}^*)^{-0.50}$
E	$1.00 \le 2.00 - 1.10 F_o a_g/g \le 1.60$	$1.15\,(T_C{}^*)^{-0.40}$

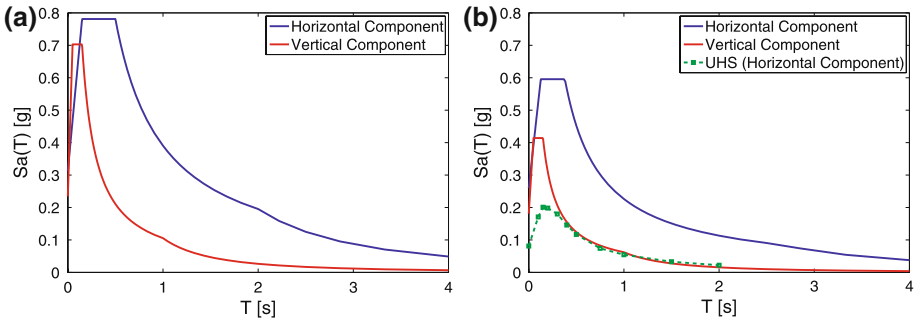

Fig. 15 EC8 spectra for Sant'Angelo dei Lombardi (site class B, $a_g = 0.27\,g$) (**a**), NIBC spectra for Sant'Angelo dei Lombardi (site class A) and UHS for a 50 years return period on rock (**b**)

For the sites that do not fall in the nodes of the reference grid for which hazard was computed by INGV, the values of the parameters needed for the definition of the elastic response spectrum may be computed as a weighted averages of the values assumed by the parameters in the four vertices of the elementary (rectangular) mesh containing the point of interest. In this case, the inverse of the distances between the points of interest and the four vertices may be used as weights, as in Eq. 8. In Eq. 8, p is the value of the parameter of interest (a_g, F_o or T_C^*) for the site under examination, p_i is the value of the parameter of interest for the ith vertex of the elementary mesh containing the site under examination, d_i is the distance between the site and the ith vertex of the mesh. The code also provides relationships between a_g, F_o and T_C^* and T_B, T_C and T_D, Eq. 9. The values S and C_C depend upon the site class (Table 8).

$$p = \sum_{i=1}^{4} \frac{p_i}{d_i} \Bigg/ \sum_{i=1}^{4} \frac{1}{d_i} \tag{8}$$

In Fig. 15 the horizontal and vertical spectra for the site of the examples discussed in Sect. 5 are given. In particular Fig. 15a gives the EC8 spectra, while Fig. 15b provides the NIBC spectra and the UHS corresponding to 63% in 50 years exceedance probability. The ordinates of the latter were retrieved from http://esse1-gis.mi.ingv.it/ using the geographical coordinates of Sant'Angelo dei Lombardi.

$$\begin{cases} T_C = C_C T_C^* \\ T_B = T_C/3 \\ T_D = 4.0 a_g/g + 1.6 \end{cases} \tag{9}$$

References

Akkar S, Bommer JJ (2006) Influence of long-period filter cut-off on elastic spectral displacements. Earthq Eng Struct Dyn 35:1145–1165

Ambraseys N, Smit P, Berardi R, Rinaldis D, Cotton F, Berge C (2000) Dissemination of European strong-motion data (Cd-Rom collection). European Commission, Dgxii, Science, Research and Development, Bruxelles

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, United Kingdom

Beyer K, Bommer JJ (2007) Selection and scaling of real accelerograms for bi-directional loading: a review of current practice and code provisions. J Earthq Eng 11(S1):13–45

CEN, European Committee for Standardisation (2003) Eurocode 8: design provisions for earthquake resistance of structures, Part 1.1: general rules, seismic actions and rules for buildings, prEN 1998-1

CEN, European Committee for Standardisation (2005) Eurocode 8: design of structures for earthquake resistance. Part 2: bridges, prEN 1998-2

Convertito V, Iervolino I, Herrero A (2009) The importance of mapping the design earthquake: insights for southern Italy. Bull Seismol Soc Am 99(5) (in press)

Cornell CA (2004) Hazard, ground-motions and probabilistic assessment for PBSD. In: Fajfar P, Krawinkler H (eds) Performance based seismic design concepts and implementation, PEER report 2004/05. Pacific Earthquake Engineering Research Center University of California, Berkeley, CA, USA

CS.LL.PP. (2008) DM 14 Gennaio, Norme tecniche per le costruzioni. Gazzetta Ufficiale della Repubblica Italiana 29 (in Italian)

CS.LL.PP. (2009) Istruzioni per l'applicazione delle norme tecniche delle costruzioni. Gazzetta Ufficiale della Repubblica Italiana 47 (in Italian)

Iervolino I, Cornell CA (2005) Record selection for nonlinear seismic analysis of structures. Earthq Spectra 21(3):685–713

Iervolino I, Manfredi G (2008) Review of ground motion record selection strategies for dynamic structural analysis. In: Bursi OS, Wagg DJ (eds) Modern testing techniques of mechanical and structural systems. CISM Courses and Lectures Number 502. Springer, Wien, New York

Iervolino I, Galasso C (2009) REXEL 2.31 beta—tutorial, available at: http://www.reluis.it/doc/software/REXEL_Tutorial_ENG.pdf

Iervolino I, Maddaloni G, Cosenza E (2008) Eurocode 8 compliant real record sets for seismic analysis of structures. J Earthq Eng 12(1):54–90

Iervolino I, Maddaloni G, Cosenza E (2009) A note on selection of time-histories for seismic analysis of bridges in Eurocode 8. J Earthq Eng 13 (in press)

Montaldo V, Meletti C, Martinelli F, Stucchi M, Locati M (2007) On-line seismic hazard data for the new italian building code. J Earthq Eng 11(S1):119–132

Naeim F, Alimoradi A, Pezeshk S (2004) Selection and scaling of ground-motion time histories for structural design using genetic algorithms. Earthq Spectra 20(2):413–426