JOURNAL OF EARTHQUAKE ENGINEERING
2022, VOL. 26, NO. 13, 6918–6942
https://doi.org/10.1080/13632469.2021.1961941

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Reconciling Eurocode 8 Part 1 and Part 2 Two-component Record Selection

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ABSTRACT

Eurocode 8 (EC8) allows the use of dynamic analysis for the design and assessment of structures and provides some constraints for the selection of acceleration time-histories as seismic input. However, when it comes to the selection of two-horizontal-component natural ground motion records, parts 1 and 2 of EC8, stipulate apparently different criteria. The first aim of this paper is to build up on previous studies and investigate whether this difference in provisions translates into the selection of systematically different sets of records. A series of record selection case-studies presented in this study, corroborate the preliminary findings of previous work, and show that this is not the case, that is, record sets chosen according to one group of criteria tend to satisfy the other by default. A second aim is to investigate the different options for selecting multi-component ground motion records in part 1, which turn out to be equivalent. Finally, a third issue tackled is the effect that different definitions of spectral acceleration, that the design spectrum refers to, can have on spectrum-compatible record selection, when two horizontal components are involved. The results indicate that, for some of these alternative definitions, such as maximum or random component spectral acceleration, sets obtained via direct spectrum compatibility may not always agree with a simple application of Eurocode 8 provisions. On the other hand, when spectral acceleration is defined as the geometric mean of the two components, consolidated record selection algorithms appear to guarantee spectrum compatibility.

ARTICLE HISTORY
Received 11 January 2021
Accepted 9 May 2021

KEYWORDS
Seismic input; bi-directional dynamic analysis; spectrum; design; assessment

1. Introduction

Modern seismic codes allow for design or assessment of structures to be based on dynamic analysis and prescribe several criteria for the selection of a number of acceleration time-series to serve as the seismic input. The use of naturally recorded earthquake-induced ground acceleration is nowadays basically the norm in this regard (Bommer and Acevedo 2004), in part due to the availability of easily accessible strong-motion databases (e.g., Bozorgnia et al. 2014; D'Amico, Felicetta, and Russo et al. 2020). This selection is based on code-prescribed compatibility of the set of accelerograms with the elastic design spectrum, which is typically interpreted to imply a fit of the selection's average to the target design spectrum, within a period-range that depends on the structure to be analysed.

When structures possess two main (e.g., orthogonal) directions of uncoupled dynamic response, it is commonplace to set-up two-dimensional numerical models for running the analyses, one per direction. In these simplest of cases, where the use of a plane structural model is acceptable, the definition of seismic input boils down to records of single-component horizontal ground motion.

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However, in the more general case, three-dimensional models are needed for dynamic analysis and the corresponding seismic input should therefore involve both horizontal components acting simultaneously on the structure.[1]

Eurocode 8 Part 1 (EC8-1, CEN 2004), that mainly concerns itself with the seismic design of buildings,[2] sets forth prescriptions for the definition of seismic input via spectrum compatible acceleration records without any particular distinction between one- or two-component horizontal motion. In fact, the EC8-1 elastic design spectrum, that is the target spectrum for the selection, is applicable in both directions regardless of orientation. The reasoning behind this could be that ground motion does not exhibit directionality beyond the immediate vicinity of the fault rupture (Pacor et al. 2018).

On the other hand, Eurocode 8 Part 2 (EC8-2, CEN 2005), which deals with the seismic design of bridges, prescribes record selection criteria specifically directed at the case of two-component horizontal ground motion. These selection criteria, are apparently different from those of EC8-1, and this raises the question: does the selection of spectrum-compatible double horizontal component record sets according to the prescriptions of EC8-1 and EC8-2 lead to differences in the representation of bidirectional seismic input?

The first objective of this study is to answer this question from a practical standpoint, by building on previous works that investigated various aspects related to the selection of recorded ground motions in accordance with the parts of Eurocode 8 (Iervolino, Maddaloni, and Cosenza 2008, 2009). These earlier works, which were primarily focused on the methodology for obtaining EC8-compliant record sets and the feasibility thereof, provided hints that differences in EC8-1 and EC8-2 criteria do not translate into differences in selected sets; however, they were based on a relatively small number of cases.

The second question that arises in this context, is if selection procedures for record sets compatible with the design spectrum should differ in the case of single- and two-component ground motion. This leads to the second objective of this study, which is to investigate whether the different options for multi-component record selection in EC8-1 lead to systematically different record selections: for example, the selection could proceed by seeking spectrum-compatibility of each horizontal component in separate manner or by pooling both of each record's components into a single compatibility verification. While these alternatives appear to be a matter of interpretation, both approaches are explored and discussed in this study.

By current standards of practice, record selection according to Eurocode 8 criteria is typically performed by engineers with the aid of dedicated software tools that implement consolidated algorithms (e.g., Iervolino, Galasso, and Cosenza 2010) to efficiently query available ground motion repositories. These digital repositories have sufficiently grown in size to overcome some of the limitations imposed on the earlier studies, pertaining to the number of EC8 compliant record combinations that could be extracted for certain cases. Therefore, it is useful to perform a dedicated and more extensive investigation into this question, namely if the perceived differences between the requirements of EC8-1 and EC8-2, or the alternative interpretations of EC8-1 requirements, warrant different treatment from such commonly used approaches, or if some of the time-tested algorithms can produce results that are satisfactory in all cases. This analysis is also partly motivated by the fact that, in a recent update of the Italian code and its applicative circular documents (CS.LL.PP 2018, 2019), which borrow heavily from the Eurocodes, selection criteria originating from both EC8-1 and EC8-2 were adopted.

A third issue that is examined by the present study is related to the possible definitions of the ground motion intensity measure (IM), that is the spectral acceleration, stemming from bidirectional ground motion. In fact, because elastic design spectra can often be considered as approximations of so-called uniform hazard spectra from probabilistic seismic hazard analysis (PSHA), these spectra are implicitly defined in terms of the spectral acceleration considered by the ground motion prediction equations (GMPEs) employed in the PSHA from which the spectra are defined (e.g., geometric mean, rotated median or the largest as-recorded component per spectral ordinate, to name but a few – see for example (Baker and Cornell 2006a)). Also in this case, a number of case-study selections are performed under various hypotheses for the underlying definition of spectral acceleration characterizing the target spectrum, which are then compared with the selection requirements of EC8-1.

The remainder of this article is organized in the following manner: first, the record selection criteria set forth in EC8-1 and EC8-2 are recalled. Then, the case-study record selections are presented, based on EC8-1 prescriptions, which are then checked a-posteriori for compliance with the criteria given in EC8-2. These EC8-1 compliant record selections are then revisited from the point of view of an alternative interpretation of the EC8-1 acceptance criteria, which involves separate spectrum-compatibility requirements to be met per direction, in the spirit of single-component record selection. Subsequently, the case-study selections are repeated considering various alternative definitions for the spectral ordinates of the code spectrum and whether the resulting record sets still meet EC8-1 criteria or not, is investigated. Finally, some concluding remarks are provided.

2. Record Selection Criteria according to Eurocode 8

The parts of EC8 that deal with building design (EC8-1) and bridge design (EC8-2), both contain provisions pertaining to the selection of acceleration records for dynamic analysis. Some of these provisions are mostly qualitative in nature and reiterate similar concepts; for instance, EC8-1 requires that the samples of recorded accelerograms used *"are adequately qualified with regard to the seismogenetic features of the sources and to the soil conditions appropriate to the site"*, while EC8-2 stipulates that the accelerograms *"should be selected from recorded events with magnitudes, source distances, and mechanisms consistent with those that define the design seismic action"*. Both of those stipulations call for record selection that is consistent with site-specific seismic hazard and it is known that this can be achieved, for example, with the aid of hazard *disaggregation* that can point to the most relevant earthquake scenarios behind potential occurrence or exceedance of the design spectral ordinates (Iervolino, Chioccarelli, and Convertito 2011). On the other hand, the quantitative acceptance criteria for the selected record samples are apparently different between EC8-1 and EC8-2, as briefly recalled in this section.

2.1. EC8-1 Provisions

According to paragraph 3.2.3, EC8-1 allows for the description of the seismic action on a structure by means of recorded *"ground acceleration time-history and related quantities"*, the latter referring to ground velocity or displacement. Under this premise, the set of accelerograms to be used as seismic input must respect a series of criteria. Regarding the record sample size, it is stipulated that *"a minimum number of 3 accelerograms should be used"*, but in that case the most unfavourable of the corresponding structural responses should be used for design verifications. On the other hand, if the number of records is increased to at least seven, the seismic design verifications may be performed using the average of the structural responses produced. Another requisite for the use of recorded ground motion, is that the acceleration records should be scaled in amplitude to match the design peak ground acceleration (PGA) at the site. This design PGA is given by the product of the PGA on rock, a_g, multiplied by the soil factor, S, corresponding to the site-specific subsoil conditions. Furthermore, it is prescribed that, within a range of periods between $0.2 \cdot T_1$ and $2 \cdot T_1$, no value of the mean 5% damping elastic spectrum, $\overline{Sa(T)}$, should be less than 90% of the corresponding value of the 5% damping elastic response spectrum, or target spectrum $Sa_{TARGET}(T)$. In this context, T_1 is the fundamental period of the structure under examination in the direction where the accelerogram will be applied.

From these record selection prescriptions set forth in EC8-1, it becomes apparent that a set of records could be considered code-compatible as long as the average of certain spectral ordinates does not recede below a prescribed lower-bound tolerance, regardless of the spectral variability of individual records within the set and without some corresponding upper bound for the average spectrum. In this light, algorithms proposed in the literature, dedicated to the extraction of code-compliant record sets from larger ground motion databases, typically introduce additional *spectrum compatibility* criteria, such as making sure that the distance of the selection's average spectrum from the target design spectrum is limited as much as possible (e.g., Iervolino, Galasso, and Cosenza 2010). Spectrum-compatible record selection, in the sense described above and with details that will be provided further ahead, is also adopted in the present study.

Another issue that emerges from the above description of EC8-1 provisions is that, although said provisions clearly contemplate the single-horizontal-component selection case, there is no specific disclaimer that the same criteria should not also apply to two-component record selection. In fact, past literature suggests that the same rules can also be applied for the definition of two-component seismic input for building structures (Iervolino, Maddaloni, and Cosenza 2008). One of the consequences of the direct application of these criteria to bi-directional pairs of horizontal ground motion records, is the fact that each component of the same pair should be scaled by a different scale factor (SF), in order for both of them to match the target design PGA. By arbitrarily labelling the orientations of the two as-recorded horizontal components, indicated as x and y, the corresponding scaling factors $\mathrm{SF}_{i,x}$ and $\mathrm{SF}_{i,y}$ for the i-th ground motion within a set, are given by Eq. (1):

$$\left\{\mathrm{SF}_{i,x} = \frac{a_g \cdot S}{PGA_{i,x}}, \mathrm{SF}_{i,y} = \frac{a_g \cdot S}{PGA_{i,y}}\right\}, \quad (1)$$

where $PGA_{i,x}$ and $PGA_{i,y}$ are the recorded peak ground acceleration values of the i-th ground motion record along x and y. Under the additional premise that all the applications included in the present study were developed considering the minimum number of records that allows the use of average response quantities in design verification, that is seven records, the code-compatibility condition can be written as per Eq. (2):

$$\overline{Sa}(\mathrm{T}) = \frac{1}{14} \cdot \sum_{i=1}^{7} \left[Sa_{i,x}(\mathrm{T}) \cdot \mathrm{SF}_{i,x} + Sa_{i,y}(\mathrm{T}) \cdot \mathrm{SF}_{i,y}\right] \geq 0.9 \cdot Sa_{TARGET}(\mathrm{T}), \quad \mathrm{T} \in [0.2 \cdot T_1, 2 \cdot T_1], \quad (2)$$

where $Sa_{i,x}(\mathrm{T})$ and $Sa_{i,y}(\mathrm{T})$ are the spectral acceleration evaluated processing the as-recorded horizontal components of the i-th ground motion.

An example of this acceptance criterion is provided by Fig. 1a, where the 14 scaled individual components of a certain set are shown, separated per direction, along with their mean. It can be seen that within a predefined period interval, whose lower and upper bound is indicated by T_{low} and T_{upp} respectively, the mean oscillates around the target spectrum without ever going lower than the limit of

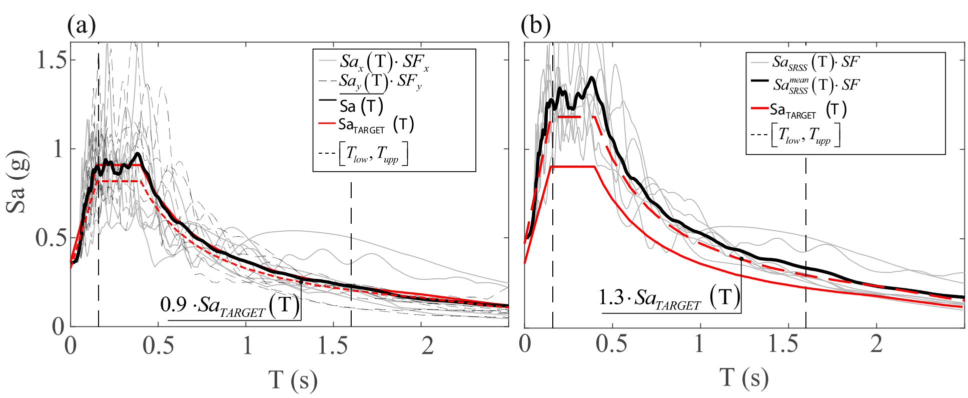

Figure 1. (a) Record selection of seven pairs of accelerograms whose response spectra satisfy EC8-1 criteria; (b) SRSS spectra, of the same seven pairs of accelerograms as in the previous panel, that satisfy EC8-2 criteria.

$0.9 \cdot Sa_{TARGET}(\mathrm{T})$, imposed in Eq. (2). Although the spectrum compatibility criterion expressed by this equation is held as a benchmark in this study, it is not unique, in the sense that EC8-1 criteria can also be subjected to alternative interpretations. As will be seen in the following paragraphs, alternatives involving the application of a single SF to both horizontal components of each bi-directional motion record or separately checking the spectrum compatibility of each single component are also considered and compared to this benchmark.

2.2. EC8-2 Provisions

According to EC8-2, whose design spectrum that forms the basis for determining the seismic input is the same as the one defined in EC8-1, said input may only be represented by two-horizontal-component ground motion records (if the vertical component can be neglected). This might be attributed to the fact that engineers are less likely to analyse bridge structures using two uncoupled plane numerical models, as they might do for building structures. EC8-2 compliance criteria for a selected record set involve the square root of the sum of squares (SRSS) of each record's two horizontal components, which is denoted as $Sa_{i,SRSS}(\mathrm{T})$:

$$Sa_{i,SRSS}(\mathrm{T}) = \sqrt{Sa_{i,x}(\mathrm{T})^2 + Sa_{i,y}(\mathrm{T})^2}, \tag{3}$$

where the subscript $i = 1, 2, .., 7$ identifies the generic ground motion out of the set of seven. The code-compliance criterion itself stipulates that the mean SRSS spectrum of the record set, $Sa_{SRSS}^{mean}(T)$, given by Eq. (4):

$$Sa_{SRSS}^{mean}(\mathrm{T}) = \frac{1}{7} \cdot \sum_{i=1}^{7} Sa_{i,SRSS}(\mathrm{T}), \tag{4}$$

has to be scaled by a factor SF so that it will remain above 1.3 times the target design spectrum within the period range from $0.2 \cdot T_1$ to $1.5 \cdot T_1$, that is:

$$Sa_{SRSS}^{mean}(\mathrm{T}) \cdot \mathrm{SF} \geq 1.3 \cdot Sa_{TARGET}(\mathrm{T}), \quad \mathrm{T} \in [0.2 \cdot T_1, 1.5 \cdot T_1], \tag{5}$$

This is illustrated in Fig. 1b, which shows the SRSS spectra of the same seven two-component records shown in panel 1a, all scaled by the same SF in order for their mean SRSS spectrum to exceed the limit of $1.3 \cdot Sa_{TARGET}(\mathrm{T})$ over all periods within the $[T_{low}, T_{upp}]$ range. It should be underlined that, according to this clause, a single scaling factor has to be determined and applied to the entire suite of records. This appears to be in contrast with the adopted interpretation of EC8-1 provisions for the selection of two-component ground motion sets given above. A possible motivation behind the EC8-2 scaling strategy may lie in the fact that, with a single SF per set, the two components of each individual record maintain their as-recorded amplitude ratio between them.

3. Comparison of Selection Criteria in Eurocode 8 Parts 1 and 2

As mentioned above, both EC8-1 and EC8-2 allow scaling recorded ground motion in amplitude. While EC8-2 explicitly calls for a single SF to be applied to both components of all the records within a set, EC8-1 makes no such explicit mention. In fact, one possible interpretation of EC8-1 provisions, is to scale each of the horizontal components of the same ground motion record by a potentially different SF. This interpretation may appear to introduce some distortion to the as-recorded ground motion, which the EC8-2 procedure avoids by design. However, said interpretation of EC8-1 stipulations should not worry too much, because the SFs that typically result for each record's horizontal components are similar to each other, as will be seen later on. Consequently, the following comparisons between the two procedures are feasible despite this difference in scaling philosophy. As a side-note, it should also be mentioned that, throughout this study, the maximum SFs were kept within limits that, as past studies indicate, avoid the introduction of scaling bias in the nonlinear dynamic responses (e.g. Iervolino and Cornell 2005). Setting this issue aside for the time being, this section attempts to compare the two sets of apparently different record selection criteria described above, directly in terms of their results, that is, code-compliant, spectrum-compatible sets, each comprising seven two-horizontal-component records.

3.1. Target Design Spectra and Case Studies Considered

In order to investigate the aforementioned apparent differences in seismic input selection philosophy between EC8-1 and EC8-2, a series of record selections are performed, considering a hypothetical reference fundamental period $T_1 = 0.8s$ for both orthogonal directions. This investigation comprises seven record selection scenarios, which are used as case-studies. Even though the selection scenarios also considered two more reference fundamental periods as part of this investigation ($T_1 = 0.3s$ and $T_1 = 1.5s$), their results were too similar to the seven presented below and therefore the choice was made to omit them as they added little more to the discussion and conclusions. Each scenario uses a target design spectrum corresponding to one of two sites, at the Italian cities of Cosenza and Milan (their locations are shown in Fig. 2a), with the former characterized by a (relatively) high seismic hazard while the latter by relatively lower hazard. In both cases, a flat topography is assumed, and for each site two alternative ground types are considered, namely A and C, according to EC8 classification.

According to EC8-1, structures in seismic regions have to be designed to fulfil the dual requirements of no-collapse under *rare* seismic actions and damage limitation under *frequent* seismic actions. To satisfy these, the verification of two limit states is required: an ultimate limit state (ULS) and a damage limitation state (DLS). The design actions associated to these limit states are expressed in terms of reference return period (T_r) of the seismic action (or, equivalently, with a reference probability of exceedance P_r within a given time interval). While the definition of T_r or P_r is left for each country's national annex, EC8-1 recommends the values $T_r = 475 years\ (y)$ or $P_r = 10\%$ in $50y$ for ULS, while for DLS it recommends $T_r = 95y$ or $P_r = 10\%$ in $10y$.

Although not explicitly stated in EC8, another objective is to prevent global collapse of the structure during an earthquake (Fardis 2008). While in EC8 it is implied that this performance objective is to be met through control of the inelastic response mechanism via detailing and application of capacity design principles, the Italian Code (CS.LL.PP 2018) actually adopts a collapse limit state (CLS). In this light, the CLS is also considered in the present study, characterized by $T_r = 975y$ (or $P_r = 5\%$ in $50y$), while for the ULS and SLS the values of $T_r = 475y$ ($P_r = 10\%$ in $50y$) and $T_r = 50y$ ($P_r = 63\%$ in $50y$) have been used, respectively. The return periods of the seismic action considered are those mandated by the Italian Code; a recap of these cases is provided in Table 1.[3]

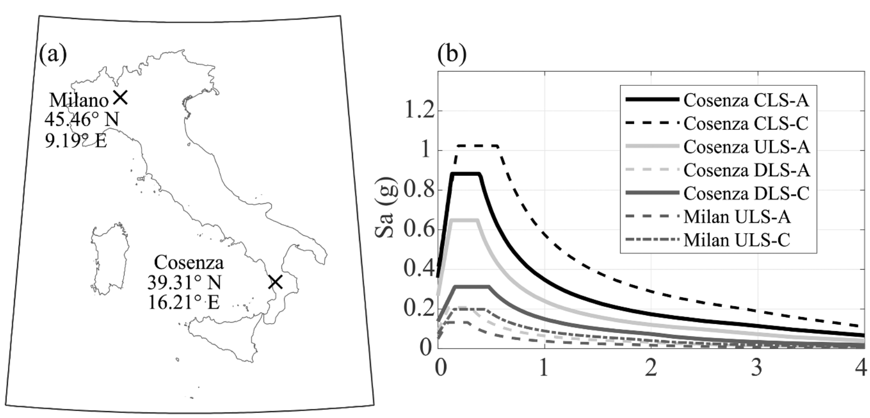

Figure 2. (a) Locations of the Italian sites used for the case-study and (b) corresponding target elastic design spectra, labelled according to limit state and soil category.

Table 1. Fifty years exceedance probability and return period for the three limit states considered.

Limit State	Exceedance probability in fifty years	Return period T_r (years)
CLS	5%	975
ULS	10%	475
DLS	63%	50

Table 2. Values of the parameters that define the shape of the target spectrum for each case-study.

Site	Limit State	Ground type	S	$a_g \cdot S\ (g)$	$T_B(s)$	$T_C(s)$	$T_D(s)$
Cosenza	CLS	A	1	0.357	0.15	0.40	2
	CLS	C	1.15	0.411	0.20	0.60	2
	ULS	A	1	0.266	0.15	0.40	2
	DLS	A	1	0.0915	0.15	0.40	2
	DLS	C	1.15	0.105	0.20	0.60	2
Milan	ULS	A	1	0.0497	0.15	0.40	2
	ULS	C	1.15	0.0572	0.20	0.60	2

In the present investigation, seven record selection scenarios are used as case-studies. For the target design spectrum, that was used in each case-study, the EC8 type 1 spectral shape was considered across the board. Type 1 spectra in EC8 are stated to correspond to prevalent causal events with surface-wave magnitude larger than 5.5.[4] The shape of the type 1 elastic design spectrum is:

$$\begin{cases} 0 \leq \mathrm{T} \leq T_B : Sa_{TARGET}(\mathrm{T}) = a_g \cdot S \cdot \left[\frac{\mathrm{T}}{T_B} \cdot (\eta \cdot 2.5 - 1)\right] \\ T_B \leq \mathrm{T} \leq T_C : Sa_{TARGET}(T) = a_g \cdot S \cdot \eta \cdot 2.5 \\ T_C \leq \mathrm{T} \leq T_D : Sa_{TARGET}(\mathrm{T}) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C}{\mathrm{T}}\right] \\ T_D \leq \mathrm{T} \leq 4s : Sa_{TARGET}(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C \cdot T_D}{T^2}\right] \end{cases} \tag{6}$$

where T_B, T_C and T_D are periods defining the transitions of spectral shape definition; η is the damping correction factor equal to 1 for 5% viscous damping (as is the case here). For the Milan site the ultimate limit state design spectra for soil type A (ULS-A) and soil type C (ULS-C) were considered while for the Cosenza site the considered scenarios were collapse limit state at soil type A and C (CLS-A, CLS-C), damage limit state at soil type A and C (DLS-A, DLS-C) and ULS-A. The EC8 elastic design spectra for all these cases are shown in Fig. 2(b); the corresponding parameters a_g, S, T_B, T_C, T_D are reported in Table 2.

At this point, it is worth highlighting that in EC8, the dependence of the elastic design spectrum on the site-specific seismic hazard is expressed through the single parameter a_g, i.e., the PGA on soil type A. In other words, the spectrum is completely defined once the anchoring value a_g is known, which is often provided by national codes or annexes to the Eurocode. The a_g values adopted in this paper for the limit states considered (shown in Table 2) are taken from the Italian code. The case studies cover a wide range of a_g values.

3.2. Ground Motion Database

The acceleration records used in this study were selected from within the NESS database (Pacor et al. 2018) which contains about 800 three-component ground-motion records from worldwide seismic events characterized by moment magnitude between 5.5 and 8.1 and Joyner-Boore distance, defined as the shortest distance from any site to the surface projection of the seismic event's rupture surface (Joyner and Boore 1981), ranging from zero to 140 km. As mentioned before, both EC8-1 and EC8-2 contain somewhat vague directives advocating record selection that is consistent with the seismological parameters of the causal event (e.g., magnitude and source-to-site distance from hazard disaggregation). However, recent research has shown that considerations of parameters such as magnitude and distance can be relaxed, when spectral shape is explicitly accounted for in the selection and the response quantity of interest is the maximum inelastic displacement of a structure (Baker and Cornell 2006b; Bojórquez and Iervolino 2011). In this light, the present study assumes that the spectrum compatibility criteria introduced in the record selection provide grounds for waiving fragmentation of the available record pool into bins of distance or magnitude.

For the purposes of the present study, the horizontal acceleration components of all records in the database were rotated to north-south and east-west orientations. As a consequence, the so-rotated horizontal ground motion components are not expected to possess any preferential orientation with respect to the finite-fault geometry of each record's causal seismic event. This means that the orientations which are arbitrarily labelled as x and y, in the context of record selection according to the aforementioned EC8-1 provisions where each record's components are pooled together, can be considered random directions.

3.3. Record Selection according to the EC8-1 Provisions

It is typical for ground motion selection algorithms to impose some spectrum-compatibility criterion when picking out records from within a large database. In this case, the square root of the mean squared deviation of the selection mean from the target, denoted δ_m, was used as a measure of the goodness-of-fit of the record set to the target spectrum:

$$\delta_m = \sqrt{\frac{1}{N} \cdot \sum_{j=1}^{N} \left(\frac{\overline{Sa(\mathrm{T}_j)} - Sa_{TARGET}(\mathrm{T}_j)}{Sa_{TARGET}(\mathrm{T}_j)} \right)^2} \tag{7}$$

In the definition of δ_m, N is the number of periods within the $[0.2 \cdot T_1, 2 \cdot T_1]$ period range where spectrum compatibility is checked, while $\overline{Sa(\mathrm{T}_j)}$ and $Sa_{TARGET}(\mathrm{T}_j)$ are calculated according to Eqs. (2) and (6) at periods T_j with $j = 1, 2, .., N$, respectively.

For each case-study target spectrum in Fig. 2b, the record selection proceeds as follows: first, all horizontal components available within the database are scaled according to Eq. (1); in this case, the directions x and y appearing in the equation are designations randomly assigned to each record's two horizontal components. At this point, records exhibiting scale factors SF_x or SF_y larger than 10 (an arbitrary value) are excluded from the subsequent elaborations. In the next stage, combinations of seven two-component records (14 accelerograms in total) are sought that minimize the goodness-of-fit parameter δ_m. It should be noted that, as clearly emerges from Eq. (7), the mean-from-target distance metric δ_m does not explicitly address the spectral shape variability of each individual record around the mean. However, this is in line with EC8 provisions that do not, in fact, include considerations on the spectral shape of individual records, with all acceptance criteria being relative to the mean spectrum of each record set. The iterative optimization technique adopted for minimizing δ_m was the same as that used in other works for performing record selections in a different context (Jayaram, Lin, and Baker 2011). Upon convergence of the iterative selection algorithm, verification of the code-compatibility inequality expressed by Eq. (2) is checked a-posteriori. At this stage, the confirmed code-compliant spectrum-compatible record set is put aside, and the selected records are temporarily removed from the available pool of the database. The selection procedure then loops anew to find the next combination. The iterative re-selection algorithm stops when the latest extracted combination exhibits a goodness-of-fit value of $\delta_m > 0.06$, which is a threshold that was calibrated through trial and error to keep the selections' means close to the target spectra, within the period range considered.

After a certain number of EC8-1 compatible sets have been obtained according to this procedure, the next step is to verify how many of those selected also satisfy EC8-2 prescriptions at the same periods $T_j, j = 1, 2, .., N$. In order to perform such a verification, one should first reconcile the fact that Eq. (2) defines the EC8-1 spectrum compatibility criterion using a different SF per horizontal component, while Eq. (5) adopts a single SF for the entire set for the definition of the EC8-2 rule.

In this direction, two possible solutions are considered; the first is to take the SRSS of the scaled components, where each single component has been assigned a different SF, and obtain their average, $\overline{Sa_{SRSS}(\mathrm{T})}$:

$$\overline{Sa_{SRSS}(T)} = \frac{1}{7} \cdot \sum_{i=1}^{7} \sqrt{\left(Sa_{i,x}(T) \cdot \mathrm{SF}_{i,x}\right)^2 + \left(Sa_{i,y}(T) \cdot \mathrm{SF}_{i,y}\right)^2} = \frac{1}{7} \cdot \sum_{i=1}^{7} Sa^{sc}_{SRSS,i}(T), \tag{8}$$

where $Sa^{sc}_{SRSS,i}(T)$is the SRSS of the i-th already scaled two-component record in the set and $\mathrm{SF}_{i,x}$, $\mathrm{SF}_{i,y}$ are obtained in accordance with Eq. (1). The second approach is to apply a single scale factor SF_{xy} to the SRSS of the unscaled components, $Sa^{unsc}_{SRSS}(\mathrm{T})$, and obtain a set average, which is denoted as $\overline{Sa^*_{SRSS}(T)}$:

$$\begin{cases} Sa^*_{SRSS}(T) = \frac{1}{7} \cdot \sum\limits_{i=1}^{7} \mathrm{SF}_{i,xy} \cdot \sqrt{Sa_{i,x}(T)^2 + Sa_{i,y}(T)^2} = \frac{1}{7} \cdot \sum\limits_{i=1}^{7} \mathrm{SF}_{i,xy} \cdot Sa^{unsc}_{SRSS,i}(T) \\ \mathrm{SF}_{i,xy} = \frac{1}{2} \cdot \left(\mathrm{SF}_{i,x} + \mathrm{SF}_{i,y}\right). \end{cases} \tag{9}$$

It is evident that the single SF adopted for the i-th two-component record, $\mathrm{SF}_{i,xy}$, is taken as the average of the two factors resulting from Eq. (1). According to those two alternative definitions of mean SRSS spectra for the scaled record sets selected in compliance with EC8-1 provisions, the ex-post verification of further compliance with EC8-2 provisions is summarized by the two simultaneous conditions given by Eq.(10):

$$\begin{cases} \overline{Sa_{SRSS}(\mathrm{T}_j)} \geq 1.3 \cdot Sa_{TARGET}(\mathrm{T}_j) \\ \overline{Sa^*_{SRSS}(\mathrm{T}_j)} \geq 1.3 \cdot Sa_{TARGET}(\mathrm{T}_j) \end{cases}, \quad \mathrm{T}_J, j = \{1, 2, \ldots, N\}, \tag{10}$$

where T_j, $j = 1, 2, .., N$ are the same periods considered in Eq. (7).This approach can be justified for two reasons, the first being that the possible alternative of evaluating a new SF to satisfy Eq. (5) would trivialize this compatibility verification, since there will always be a scale factor that will place the scaled average SRSS spectrum above the 30% amplified target. The second reason has to do with potential concerns that, by adopting different scale factors for a record's two horizontal components, one tends to distort the as-recorded seismic input and by extension the structural responses. However, this is not so much of a concern, due to the fact that the SFs, to be applied to the two components of the same record, are usually quite similar. In fact, it is easy to deduce that, when scaling both components to the target PGA, the ratio of two components' SFs is the reciprocal of their as-recorded PGAs:

$$\frac{\mathrm{SF}_x}{\mathrm{SF}_y} = \frac{PGA_y}{PGA_x}, \tag{11}$$

and for most of the ground-motions contained in the spectrum-compatible record sets the latter ratio is often close to unity. Evidence of this is provided in Fig. 3, where the frequency of encountering various PGA_y/PGA_x ratios within the selected record sets is shown in histogram format, one per case-study considered.

The figure clearly shows that most cases exhibit ratios that fall within the 0.5 to 1.5 range, with the most frequently encountered values being around 1, which is to be generally expected for ground motions (Beyer and Bommer 2006). In fact, because the different scale factors per component are controlled by their PGA ratio, the mean SF_y/SF_x ratio of every single selection considered in this part of the study is approximately 1. It was therefore deemed acceptable to also consider this different scaling philosophy in this investigation, alongside the alternative single-SF-per-record approach.

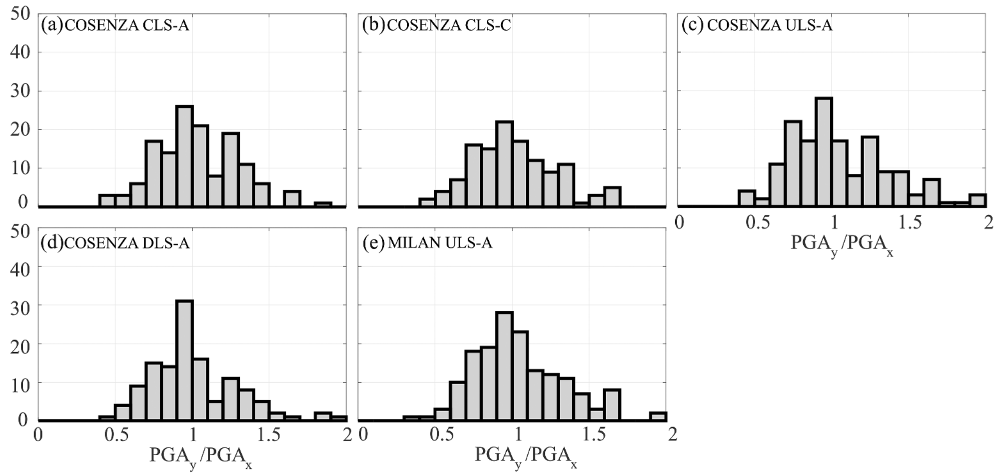

Figure 3. Ratio of as-recorded peak ground accelerations between each record's two horizontal components for all the ground motions within the selected sets. Each histogram corresponds to one of the case-study record selection scenarios presented: (a) Cosenza CLS-A, (b) Cosenza CLS-C, (c) Cosenza ULS-A, (d) Cosenza DLS-A, (e) Milan ULS-A.

Another issue that should be highlighted, is the fact that the compatibility check against EC8-2 provisions is performed within the period range dictated by EC8-1. Although EC8-2 actually prescribes an upper bound of $1.5 \cdot T_1$ instead of EC8-1's $2 \cdot T_1$, this not a cause of concern, since if a record set is code-compatible in the wider range of periods, it will remain so in the narrower range prescribed by EC8-2.

Finally, it should be noted that a similar approach has already been used in previous studies (Iervolino, Maddaloni, and Cosenza 2008, 2009), none of which, however, was specifically aimed at a reconciliation of EC8-1 and EC8-2, if at all. The main difference with the selections presented in the present study, lies in the fact that, due to the larger pool of available records, none of the selected sets contains records that are repeated in the others. In this case, records have been selected so that spectrum compatibility and code compliance are verified at $N = 145$ periods T_j that discretize the range from $T_{low} = 0.16s$ to $T_{upp} = 1.6s$ with a constant step of $0.01s$.

A summary of these results, in terms of number of alternative EC8-1 compatible selections found within the database and the percentage of those that also meets the requirements set forth in Eq. (10), is provided in Table 3.

For two of the case-study target spectra, namely Cosenza CLS-A and ULS-A, Fig. 4 provides graphical examples of record sets that are selected for compliance with Eq. (2), yet actually satisfy the condition of Eq. (10) as well. In the figure, it can be seen that $\overline{Sa_{SRSS}(T)}$ and $\overline{Sa^*_{SRSS}(\mathrm{T})}$, that is, the mean SRSS spectra obtained using, respectively, different SFs or the same SF for each record's two

Table 3. Number of selections satisfying EC8-1 prescriptions and number of the same selections that satisfy EC8-2 prescriptions as well (in the last column their ratio is expressed as a percentage).

Site	Limit State	Ground types	Number of selections EC8-1 compatible	Number of selections EC8-2 compatible	Simultaneous compliance to EC8-1 and EC8-2 (%)
Cosenza	CLS	A	20	18	90
	CLS	C	18	14	78
	ULS	A	23	19	83
	DLS	A	18	14	78
	DLC	C	48	47	98
Milan	ULS	A	23	19	83
	ULS	C	43	41	95

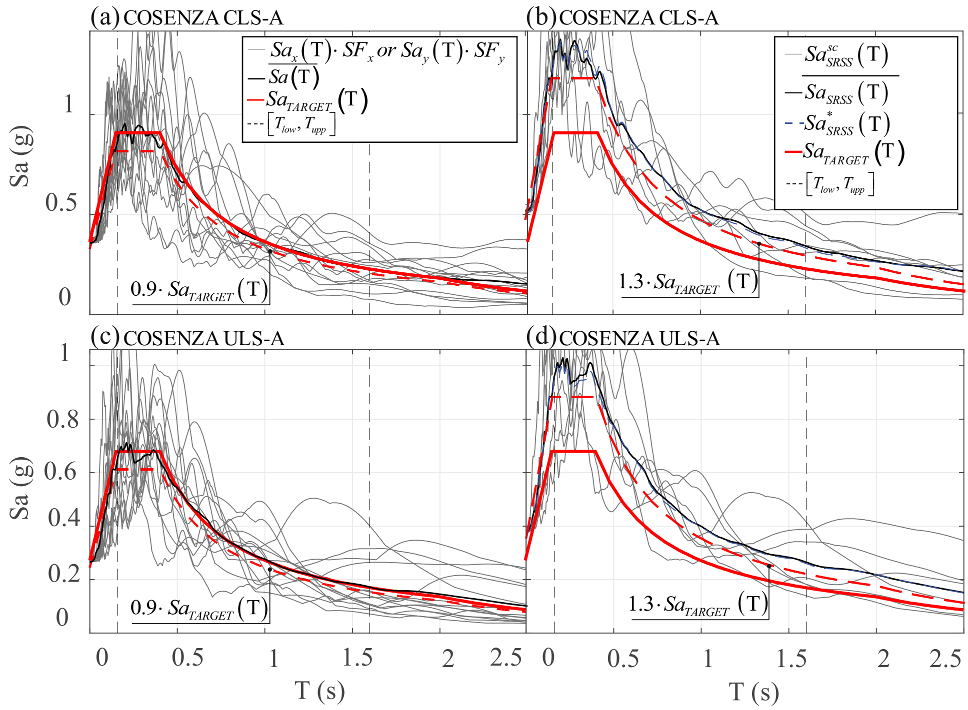

Figure 4. Examples of record sets that are selected for EC8-1 compatibility but turn out to satisfy EC8-2 criteria as well: (a) individual component and mean spectra for one of the sets obtained for the Cosenza CLS-A selection case-study, (b) individual record SRSS and mean SRSS spectra for the same selection shown to also verify EC8-2 criterion; (c) similar to the first panel for the Cosenza ULS-A scenario and (d) ex-post verification for the SRSS spectra of the previous set.

components, are similar to the point of being hard to distinguish. Information on the selected records and applied SFs corresponding to the two examples presented in Fig. 4 are provided in Tables 4 and 5. This is a trend that persists for the majority of selected sets. A more comprehensive overview of the results is provided by Fig. 5, where only the means of all selected record sets are shown, for the same case-studies.

According to the percentages provided in the table, in the worst of cases, there is compatibility between the two procedures for more than 75% of the record set selections. Equally importantly, in the cases where an EC8-1 compliant set does not satisfy EC8-2 prescriptions, this only occurs for narrow ranges of a few periods, within the broader range considered, as the figure shows. These results indicate that the apparent differences in record selection criteria between EC8-1 and EC8-2 do not seem to warrant an overhaul of consolidated record selection strategies for the case of bi-directional analysis.

Table 4. Scale factors per record and component, for the Cosenza CLS-A selection case-study shown in Fig. 4(a,b). Event name, date, magnitude and station code are also provided for each record.

Event name, Country	Date (year/month/day)	Station code	M[5]	SF_x	SF_y	SF_{xy}
Christchurch (first shock), New Zealand	2011/02/21	RHSC	6.2	1.26	1.54	1.40
Cavezzo (Emilia sequence), Italy	2012/05/29	MIR08	5.5	3.91	4.32	4.12
Darfield, New Zealand	2010/09/03	RHSC	7.1	1.53	1.77	1.65
Emilia (second shock), Italy	2012/05/29	SMS0	6.0	1.87	1.79	1.83
Zarand, Iran	2005/02/22	ZRN	6.5	1.10	1.51	1.31
Northridge, California, U.S.A.	1994/01/17	24396	6.7	3.67	2.85	3.26
Loma Prieta, California, U.S.A.	1989/10/18	58065	6.9	1.12	0.70	0.91

Table 5. Scale factors per record and component, for the Cosenza ULS-A selection case-study shown in Fig. 4(c,d). Event name, date, magnitude and station code are also provided for each record.

Event name, Country	Date (year/month/day)	Station code	M	SF_x	SF_y	SF_{xy}
Emilia second shock, Italy	2012/05/29	MIR02	6.0	1.25	0.99	1.12
Cape Mendocino, California, U.S.A.	1992/04/26	1585	6.7	1.08	0.96	1.02
Loma Prieta, California, U.S.A.	1989/10/18	47380	6.9	0.72	0.74	0.73
Parkfield, California, U.S.A.	2004/09/28	36510	5.9	2.58	3.62	3.10
Coyote Lake, California, U.S.A.	1979/08/06	G040	5.8	0.95	1.17	1.06
Cape Mendocino, California, U.S.A.	1992/04/25	1583	7	0.89	0.69	0.79
Coyote Lake, California, U.S.A.	1979/08/06	G030	5.8	0.99	1.14	1.07

3.4. Single- versus Two-component Record Selection for EC8-1

As mentioned in the preceding section, the EC8-1 record selection compliance criteria are more readily associated with single-component ground motion and the extension to bidirectional motion requires a degree of interpretation. Having hitherto laboured under the assumption that, for two-component record selection, spectrum-compatibility and compliance can be the checked by pooling all fourteen components to obtain a single mean, $\overline{Sa(\mathrm{T})}$, this paragraph will explore an alternative interpretation of EC8-1 criteria. In fact, it is conceivable to consider the compliance criteria satisfied for the bidirectional ground motion case, only if both means of the two separate orthogonal acceleration components remain above ninety percent of the target spectrum within the designated period interval. This alternative interpretation can be expressed by means of the twin conditions of Eq. (12):

$$\begin{cases} \overline{Sa_x(\mathrm{T}_j)} = \frac{1}{7}\cdot\sum_{i=1}^{7}\left[Sa_{i,x}(\mathrm{T}_j)\cdot \mathrm{SF}_{i,x}\right] \geq 0.9\cdot Sa_{TARGET}(\mathrm{T}_j) \\ \overline{Sa_y(\mathrm{T}_j)} = \frac{1}{7}\cdot\sum_{i=1}^{7}\left[Sa_{i,y}(\mathrm{T}_j)\cdot \mathrm{SF}_{i,y}\right] \geq 0.9\cdot Sa_{TARGET}(\mathrm{T}_j) \end{cases}, \quad \mathrm{T}_j, j=\{1,2,\ldots,N\}, \tag{12}$$

where $\overline{Sa_x(\mathrm{T})}$ and $\overline{Sa_y(\mathrm{T})}$ are respectively the average spectra of accelerograms grouped into two bins, arbitrarily labelled x and y, each collecting only one orthogonal component from each bidirectional ground motion record. Periods T_j are the same considered previously. In other words, the compliance of a set comprising seven bidirectional records is ostensibly split into simultaneous compliance of two single-component subsets, with no subset containing accelerograms belonging to the same record.

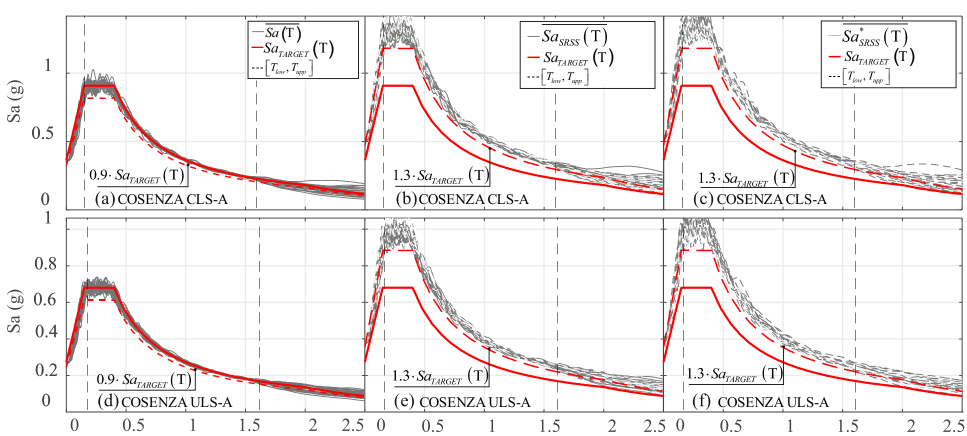

Figure 5. (a) Scaled component means for all EC8-1 compatible sets selected for the Cosenza CLS-A scenario and ex-post verification of EC8-2 criteria using the mean SRSS spectra (b) considering different scale factors for each record's components and (c) the same scale factor; (d) through (f) the same for the Cosenza ULS-A record selection scenario.

In this study, an effort is made to ascertain if this single-component-based alternative interpretation of the EC8-1 compliance criteria leads to systematic differences in the selected record sets. This premise is investigated by taking all of the spectrum-compatible record sets obtained for the seven case-study target spectra of the previous paragraph and rearranging the 14 total components of each set into all possible permutations of two groups of seven, with the limitation that the two horizontal components belonging to the same record will be never be found in the same group. Subsequently, all possible groupings are checked in order to ascertain if there exists at least one permutation that satisfies both conditions of Eq. (12).[6] An example of such a situation is provided by Fig. 6(a–c), where one of the EC8-1 compliant record sets for the Cosenza CLS-A target spectrum is shown; in the first panel it can be seen that the mean spectrum of all 14 components satisfies the compliance criterion of Eq. (2), while panels (b) and (c) show two arrangements of the same records, with one component per group, in a manner that each single-component subset also satisfies the alternative compliance criterion of Eq. (12). Naturally, the latter case implies that the records will be applied along two orthogonal directions of a structure according to the permutation that leads to this compliance-per-component. Tables 6 and 7 provide the SFs for each record's two components, as well as information needed to identify each record.

The result of this operation was that there was always at least one permutation of bidirectional record sets' horizontal components to be found, that satisfied the first of the two conditions in Eq. (12). In this light, it can be said that single-component EC8-1 compliant record selection seems to be guaranteed when the two-component pooling approach is adopted, at least for the case-study examples. However,

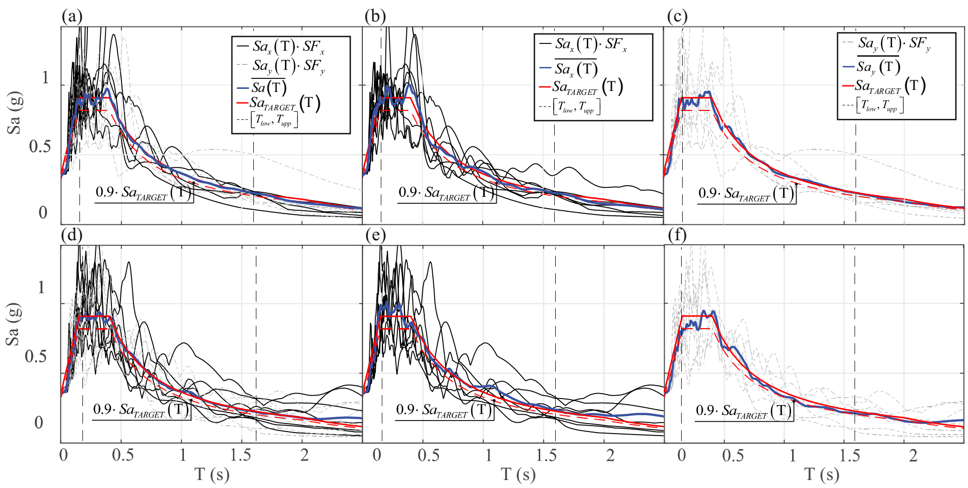

Figure 6. Selected record sets for the Cosenza CLS-A target spectrum: (a) EC8-1 compliance of the fourteen-component mean spectrum; (b) subsequent verification of the compliance of one permutation of seven components labelled *x* and (c) verification of compliance of the indicated as *y*; (d) another set selected for the same cases-study; (e) verification of compliance along *x*; (f) approximate compliance along *y*.

Table 6. Scale factors per record and component, for the first permutation shown in Fig. 6(a–c). Event name, date, magnitude and station code are also provided for each record.

Event name, Country	Date (year/month/day)	Station code	M	SF_x	SF_y	SF_{xy}
Parkfield, California, U.S.A.	2004/09/28	36455	5.9	1.32	1.27	1.30
Parkfield, California, U.S.A.	2004/09/28	36431	5.9	1.55	1.47	1.51
Imperial Valley, Mexico	1979/10/15	E130	6.5	3.37	2.71	3.04
Northridge, California, U.S.A.	1994/01/17	24047	6.7	2.38	2.15	2.26
South Napa, California, U.S.A.	2014/08/24	N016	6.0	1.06	0.68	0.87
Cavezzo (Emilia sequence), Italy	2012/05/29	T0819	5.5	1.09	1.37	1.23
Santa Barbara, California, U.S.A.	1978/08/13	NOH0	5.8	1.32	0.93	1.12

Table 7. Scale factors, for each record, for the second permutation of seven components shown in Fig. 6(d–f). Event name, date, magnitude and station code are also provided for each record.

Event name, Country	Date (year/month/day)	Station code	M	SF_x	SF_y	SF_{xy}
San Fernando, California, U.S.A.	1971/02/09	BHO0	6.7	5.99	3.68	4.83
Düzce, Turkey	1999/12/11	487	7.3	1.47	1.09	1.28
Imperial Valley, Mexico	1979/10/15	EDA0	6.5	0.96	0.73	0.85
Niigata, Japan	2004/10/23	NIG27	6.6	0.61	0.80	0.70
Loma Prieta, California, U.S.A.	1989/10/18	47179	6.9	3.92	3.09	3.51
Darfield, New Zealand	2010/09/03	DSLC	7.1	1.19	1.55	1.37
Niigata, Japan	2004/10/23	NIG1D	6.6	0.51	0.47	0.49

strict EC8-1 compliance for both distinct subsets of orthogonal components was not guaranteed 100% of the time. In fact, it was observed that in many cases, the simultaneous verification of code-compatibility in both orthogonal directions did not occur, strictly speaking. Nevertheless, the cases where $\overline{Sa_y(\mathrm{T}_j)} < 0.9 \cdot Sa_{TARGET}(\mathrm{T}_j)$ were consistently limited to only a couple of periods, out of 145 individual periods T_j checked within the [0.16s, 1.6s] interval, and the lower bound of the acceptance criterion was never undercut by more than 2%. An example of this situation is provided in Fig. 6(d–f), which shows another record set selected for the Cosenza CLS-A case-study. In this case, the permutation satisfies the criterion in the x direction, while the y direction mean spectrum only falls below the lower bound at around a period of 0.35 s and then only for about 1% of the corresponding spectral ordinate.

This example being representative of all cases considered, it can be said that it was always possible to find record sets that satisfy both alternative interpretations of EC8-1 requirements and that when the record's two horizontal orthogonal components are pooled together for the spectrum-compatibility based selection, the resulting record sets always approximately satisfy the single-component-based alternative criterion.

4. Record Selection considering Various Definitions of Spectral Acceleration

4.1. Definitions of Spectral Ordinates for Bidirectional Motion

Strong-motion databases usually provide the horizontal components of ground motion along the orientations that each recording instrument's sensors have been installed; this orientation is typically arbitrary with respect to the geometry of the fault on which the seismic event occurs. For this reason, ground shaking IMs, such as PGA or spectral ordinates, could differ for the same ground motion just by changing the way that these scalars are defined in terms of any two orthogonal ground motion components. GMPEs commonly used in PSHA adopt various definitions of the spectral ordinates characterizing both horizontal components, such as their geometric mean (e.g. Akkar and Bommer 2010), the arithmetic mean (e.g. Danciu and Tselentis 2007), the square root of the sum of squares (e.g. Kanno, Narita, and Morikawa et al. 2006), the maximum component (e.g. Bindi et al. 2010) or random component (e.g. Atkinson and Boore 2003). Lately, some definitions have also been proposed that no longer depend on the sensor orientations, such as the (non-geometric mean) median of the rotated horizontal components RotD50 (Boore 2010). More details on some of these definitions are provided in the following paragraphs.

4.1.1. Arithmetic Mean

The arithmetic mean between the two as-recorded horizontal components, $Sa_{AM}(\mathrm{T})$, is simply:

$$Sa_{AM}(\mathrm{T}) = 1/2 \cdot \left[Sa_x(\mathrm{T}) + Sa_y(\mathrm{T})\right]. \tag{13}$$

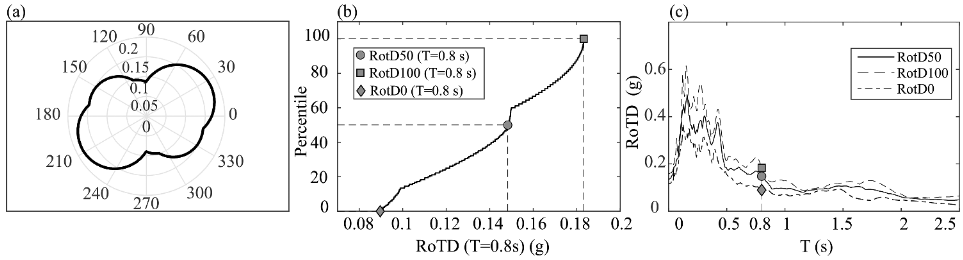

Figure 7. For a single ground-motion record (recorded by the station NIG during the event occurred in the northwest Niigata region of Japan on July 16, 2007): (a) plot in polar coordinates for the intensity measure at T = 0.8s; (b) empirical distribution function of the intensity measure evaluated for all the 180 possible angles at the same period and (c) the RotD0, RotD50 and RotD100 spectra.

Given the interpretation adopted in this paper for the implementation of EC8-1 record selection stipulations for two-component ground motion, it is possible to state that this is the intensity measure implicitly adopted during the record selections presented in the previous section. In fact, $\overline{Sa}(\mathrm{T})$ from Eq. (2) could be re-written as $\overline{Sa}(\mathrm{T}) = 1/7 \cdot \sum_{i=1}^{7} Sa_{i,AM}(\mathrm{T})$.

4.1.2. Geometric Mean, SRSS, Maximum and Random Component

The geometric mean of the two as-recorded components, $Sa_{GM}(\mathrm{T})$, is currently one of the most widely used spectral ordinate IMs, appearing in a multitude of recent GMPEs (e.g. Zhao, Zhang, and Asano et al. 2006; Cauzzi and Faccioli 2008 among the others). It is defined as:

$$Sa_{GM}(\mathrm{T}) = \sqrt{Sa_x(\mathrm{T}) \cdot Sa_y(\mathrm{T})}. \tag{14}$$

The square root of the sum of squares of spectral acceleration, $Sa_{SRSS}(\mathrm{T})$ has been already defined earlier in Eq. (3), during the discussion of EC8-2 record selection prescriptions. The maximum component, on the other hand, is defined as the larger of the two horizontal as-recorded components at each period. In other words, this can be regarded as an envelope of the two as-recorded spectra, which can be expressed as:

$$Sa_{max}(\mathrm{T}) = max\left[Sa_x(\mathrm{T}), Sa_y(\mathrm{T})\right]. \tag{15}$$

Finally, the random component IM definition, $Sa_{rnd}(\mathrm{T})$, simply constitutes a random choice of the spectral ordinate of one or the other as-recorded horizontal components of ground acceleration.

4.1.3. Orientation-independent Median Spectral Acceleration (Rotd50)

RotD50 is an IM recently introduced by Boore (2010) and is intended to be independent of the sensors' orientation, while avoiding use of the geometric mean of the two horizontal components of motion. This is evaluated by rotating the as-recorded components of ground motion over angles (θ) spanning 180°, using the rules of vector composition, and evaluating the spectral ordinates $Sa(T)$ for each orientation, as illustrated in Fig. 7. Generally speaking, the *pp* percentile of the spectral ordinate obtained over all orientations at each period, is represented by the notation RotD*pp*. Thus, RotD50 would be the median, RotD00 the minimum and RotD100 the maximum set of spectral ordinates obtained, respectively, as shown in the figure. This IM is also termed as period-dependent, in the sense that the same percentile at each period does not necessarily occur for the same rotation angle.

4.2. Methodology for Spectrum-compatible Record Selection considering Different IMs

This third part of the present investigation operates under the working assumption that the EC8 elastic design spectrum's ordinate could be considered as deriving from PSHA that uses any of the IM definitions described above. In fact, EC8 does not provide a specific IM definition for the design spectral ordinates in this regard, since the PSHA calculations for the definition of the anchoring value a_g at each return period fall within the jurisdiction of the editors of the various national annexes (Solomos, Pinto, and Dimova 2008). In this light, the actual definition of design spectral acceleration will depend on the IM adopted by the GMPE used in that PSHA. With this premise in mind, in this section the design elastic spectra considered are exactly the same as in the previous (whose parameters were reported in Table 2), but the underlying assumption for the IM defining the spectral ordinates changes each time.

In this context, for all the cases considered in this part of the investigation, there is a single scalar IM representative of both horizontal components of motion. Therefore, it is straightforward to deduce that, in order to impose a spectrum compatibility condition for the record selection while remaining consistent with each specific IM definition, one has to calculate a single spectrum per bidirectional ground motion record and match the target to the mean of these spectra. Thus, in order to apply the same record selection methodology adapted to this additional assumption, an adjusted definition of the goodness-of-fit parameter, δ_m^*, has to be introduced as:

$$\begin{cases} \delta_m^* = \sqrt{\frac{1}{N} \cdot \sum_{j=1}^{N} \left(\frac{\overline{Sa_{XY}(\mathrm{T}_j)} - Sa_{TARGET}(\mathrm{T}_j)}{Sa_{TARGET}(\mathrm{T}_j)} \right)^2} \\ \overline{Sa_{XY}(\mathrm{T})} = \frac{1}{7} \cdot \sum_{i=1}^{7} \left[Sa_{XY,i}(\mathrm{T}) \cdot SF_i \right] \end{cases}, \quad (16)$$

where $Sa_{XY}(\mathrm{T})$ is a placeholder for any of the alternative definitions of spectral acceleration given at the beginning of this section and accounting for both components of motion, SF_i is the scale factor required to bring the *i-th* record's spectrum on par with the target PGA, with $i = 1, 2, .., 7$. Apart from this adjustment, the record selection algorithm is applied in nearly verbatim fashion as in the previous section (more details to follow). Besides obtaining sets of seven double-component records, which are ostensibly spectrum-compatible and consistent with each definition of the spectrum, the objective of this record selection exercise is to retroactively check these selections for compliance with EC8-1 provisions.

Under the premises described in the previous paragraph, spectrum-compatible record sets are sought after, considering a variety of possible definitions for the target spectral ordinates. These selections are performed for all of the design scenarios (in terms of site, ground type and limit state) considered in the previous section and all of the alternative IMs introduced in the current section (geometric mean, maximum component, random component and RotD50). The selection methodology per IM considered runs as follows: first the $Sa_{XY}(T)$ ordinates, for all ground-motions contained in the available database, are evaluated in accordance with the current assumed IM definition and then all records are scaled a-priori, so that the *i-th* generic record satisfies the condition $\mathrm{SF}_i \cdot Sa_{XY,i}(T = 0) = Sa_{TARGET}(T = 0)$, with the zero-period spectral ordinate indicating PGA. Subsequently, the same optimization algorithm as before is applied for selecting records that tend to minimize δ_m^*, with each spectrum-compatible selection being gradually eliminated from the available record pool; in this case, a selected set is deemed spectrum compatible if it satisfies Eq. (17):

$$\overline{Sa_{XY}(\mathrm{T}_j)} \geq 0.9 \cdot Sa_{TARGET}(\mathrm{T}_j), \quad \mathrm{T}_j, j = 1, 2, \ldots, N, \quad (17)$$

where the number of discrete periods T_j, where these conditions are checked, remains the same as before. Finally, a verification of whether the selected sets satisfy EC8-1 requirements is performed, according to the interpretation embodied by Eq. (2). This implies that, for this verification, the as-recorded individual component accelerograms of the selected records are scaled anew according to Eq. (1). This investigation was conducted for five out of the seven selection scenarios introduced previously.

Table 8. Number of selections in which the mean $Sa_{GM}(T)$ spectra satisfy Eq. (17) and number of the same selections that satisfy EC8-1 prescriptions as well.

Site	Limit State	Ground types	Compatible selections	Number of selections EC8-1 compatible	EC8-1 compliance (%)
Cosenza	CLS	A	20	18	90
	CLS	C	18	14	77.78
	ULS	A	23	19	82.61
	DLS	A	18	14	77.78
Milan	ULS	A	23	19	82.61

4.2.1. Geometric Mean

Record selection using $Sa_{GM}(T)$ as the assumed *IM* of choice produced a number of compatible sets, almost all of which were found to satisfy the EC8-1 compliance criteria, as attested to by Table 8, which summarizes the results for all case-studies considered. A graphical representation of the procedure is given in Fig. 8 for two out of the five case-study record selection scenarios. The figure provides an example of a seven-record set selected so that $\overline{Sa_{GM}(T)}$ is compliant with the target spectrum of the

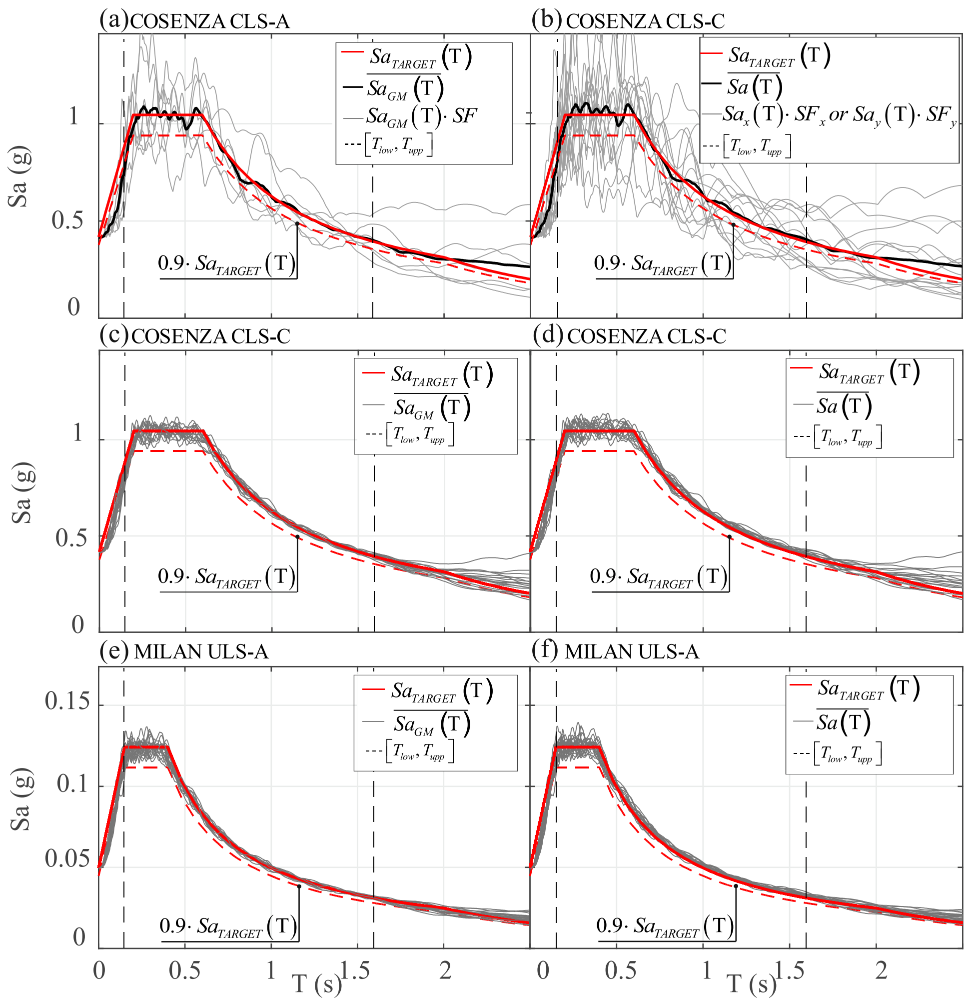

Figure 8. Results from cases where spectral acceleration ordinates are defined as Sa_{GM}. (a) Spectrum compatible record set according to Eq. (17) for the Cosenza CLS-C design scenario; (b) compatibility of the previous set with EC8-1 prescriptions; (c) mean spectra of all record sets satisfying Eq. (17) for the Cosenza CLS-C case; (d) verification of EC8-1 compatibility of the Cosenza CLS-C record sets; (e) mean spectra of all record sets satisfying Eq. (17) for the Milan ULS-A case; (f) verification of EC8-1 compatibility of the Milan ULS-A record sets.

Table 9. Number of selections in which the mean $Sa_{max}(T)$ spectra satisfy Eq. (17) and number of the same selections that satisfy EC8-1 prescriptions as well.

Site	Limit State	Ground types	Compatible selections	Number of selections EC8-1 compatible	EC8-1 compliance (%)
Cosenza	CLS	A	27	2	7
	CLS	C	25	1	4
	ULS	A	21	3	14
	DLS	A	21	0	0
Milan	ULS	A	32	8	25

Cosenza CLS-C scenario and the subsequent verification that $\overline{Sa(T)}$ calculated according to Eq. (2) continues to exceed 90% of the target within the predefined period range. Additionally, the means for all of the selected sets are shown plotted together against the target for the Cosenza CLS-C and Milan ULS-A scenarios, showing that the verification of EC8-1 criteria is universal in this case.

This total compliance seems to suggest that, if $Sa_{GM}(T)$ were adopted in the PSHA behind the EC8 design spectrum, selection algorithms that espouse this interpretation of EC8-1 stipulations (e.g. Iervolino, Galasso, and Cosenza 2010) could continue to be used regardless.

4.2.2. Maximum Component

Record selection performed using $Sa_{max}(T)$ as IM leads to the results that have been summarized in Table 9. The maximum number of compatible selections for any case study is 32 (Milan site, ULS, ground type A). Quite unlike what was observed for $Sa_{GM}(T)$, the spectra of the selected records only fulfil EC8-1 criteria in very few cases with the highest compatibility percentage being 25% (Milan site, ULS, ground type A) and going as low as zero in one case (Cosenza site, DLS, soil type A).

A typical example is provided in Fig. 9, where it can be seen that a selected set for the Cosenza CLS-C scenario with spectrum-compatible $\overline{Sa_{max}(T)}$, fails to satisfy Eq. (2). Apparently, satisfying spectrum compatibility with a design spectrum that is defined in terms of $Sa_{max}(T)$, does not agree with the traditional implementation of EC8-1 criteria most of the time.

4.2.3. Random Component

Using $Sa_{rnd}(T)$ as IM, the number of spectrum-compatible selections obtained was on par with the previously shown cases, with a maximum of 24 sets achieved for the Milan site, at ULS and ground type C. The percentage of these sets that also satisfy EC8-1 prescriptions is mediocre at best, with the maximum compatibility percentage being 43%, encountered at the Cosenza site for CLS and ground type C. These results are shown in Table 10. It can be said that $Sa_{rnd}(T)$ fares poorly in terms of EC8-1 compliance, in line with $Sa_{max}(T)$. This is clearly seen in Fig. 10, which provides an example for a single selection for the Cosenza CLS-A scenario, as well as a representation of how fare the means of all record selections performed for the Cosenza CLS-A and ULS-A cases.

4.2.4. RotD50

Record selections performed using this orientation-independent, yet period-dependent, IM led to numbers of compatible selections per design scenario that are very similar to the ones encountered for the other examined cases. The results of the a-posteriori verification of EC8-1 compliance are shown in Table 11. The compatibility percentages were more encouraging with respect to the ones found for $Sa_{max}(T)$ and $Sa_{rnd}(T)$, but nowhere near the one-hundred percent of $Sa_{GM}(T)$. The highest compatibility percentage of 84% was observed for the CLS, ground type C design scenario selections at the Cosenza site, while the minimum of 52% was observed for the ULS, ground type A scenario at the same site.

Examples from both of these cases are provided in Fig. 11. However, in this case these percentages only tell half the truth. In fact, Fig. 12 shows the percentage of discrete periods T_j for which Eq. (13) is not satisfied, denoted as NS (%). According to the figure, this percentage is lower than 20% for all cases but one and even for that one hovers between 20% and 30%. Therefore, non-compliance with EC8-1

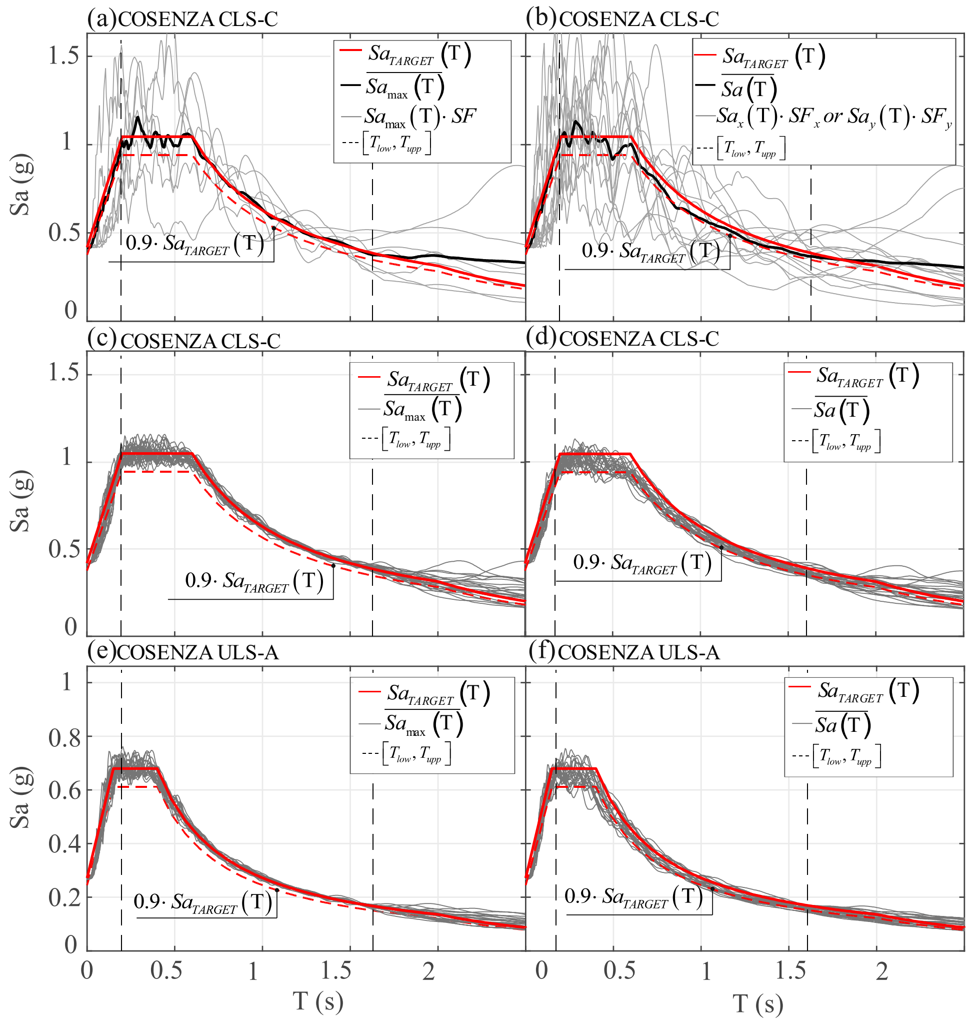

Figure 9. Results from cases where spectral acceleration ordinates are defined as $Sa_{max}(T)$. (a) Spectrum compatible record set according to Eq. (17) for the Cosenza CLS-C design scenario; (b) compatibility of the previous set with EC8-1 prescriptions; (c) mean spectra of all record sets satisfying Eq. (17) for the Cosenza CLS-C case; (d) verification of EC8-1 compatibility of the Cosenza CLS-C record sets; (e) mean spectra of all record sets satisfying Eq. (17) for the Cosenza ULS-A case; (f) verification of EC8-1 compatibility of the Cosenza ULS-A record sets.

Table 10. Number of selections in which the mean $Sa_{rnd}(T)$ spectra satisfy Eq. (17) and number of the same selections that satisfy EC8-1 prescriptions as well.

Site	Limit State	Ground types	Compatible selections	Number of selections EC8-1 compatible	EC8-1 compliance (%)
Cosenza	CLS	A	13	4	31
	CLS	C	14	6	43
	ULS	A	17	3	18
	DLS	A	21	3	14
Milan	ULS	A	24	5	21

requisites is, in most cases, an isolated incident occurring over a small spectral region. With this additional information, it can be said that RotD50 performs almost as well as $Sa_{GM}(T)$ in terms of the traditional interpretation of EC8-1 compatibility.

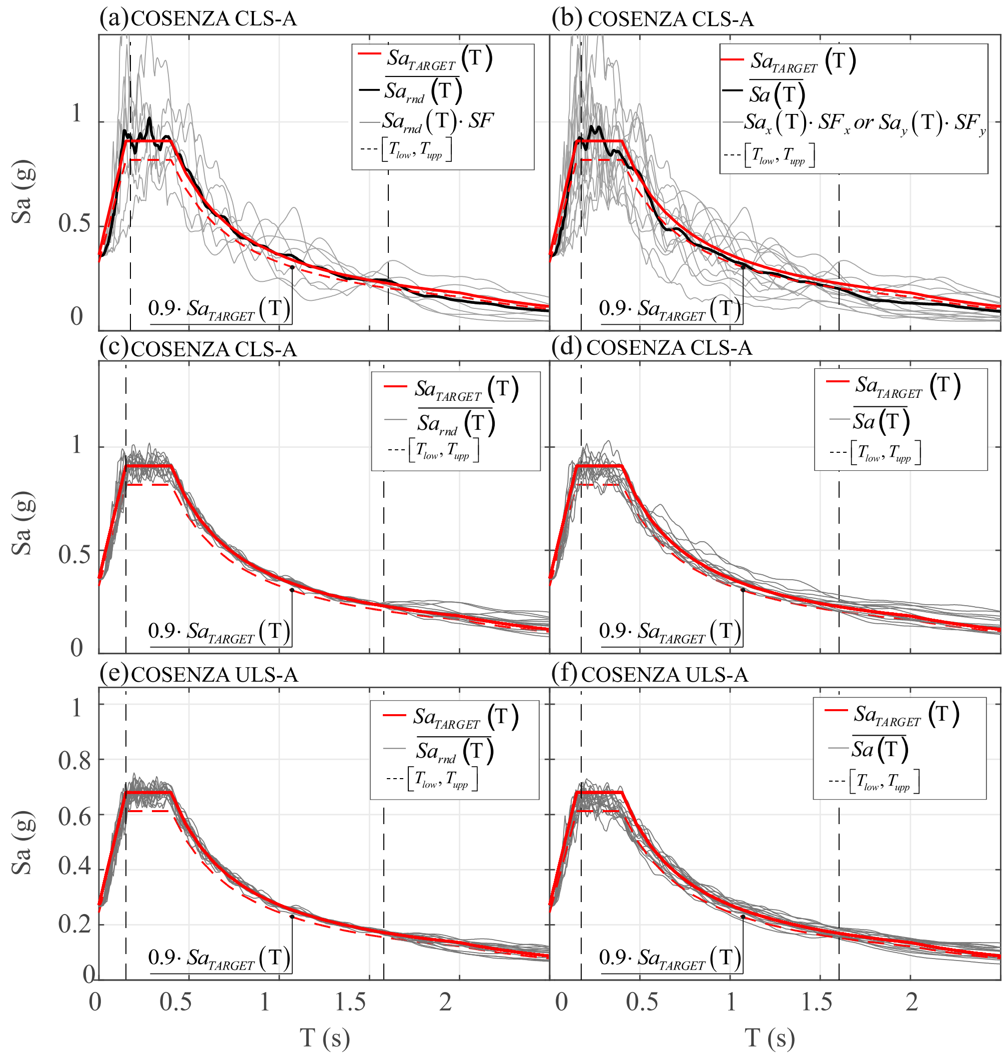

Figure 10. Results from cases where spectral acceleration ordinates are defined as $Sa_{rnd}(T)$. (a) Spectrum compatible record set according to Eq. (17) for the Cosenza CLS-C design scenario; (b) compatibility of the previous set with EC8-1 prescriptions; (c) mean spectra of all record sets satisfying Eq. (17) for the Cosenza CLS-C case; (d) verification of EC8-1 compatibility of the Cosenza CLS-C record sets; (e) mean spectra of all record sets satisfying Eq. (17) for the Cosenza ULS-A case; (f) verification of EC8-1 compatibility of the Cosenza ULS-A record sets.

Table 11. Number of selections in which the mean RotD50 spectra satisfy Eq. (17) and number of the same selections that satisfy EC8-1 prescriptions as well.

Site	Limit State	Ground types	Compatible selections	Number of selections EC8-1 compatible	EC8-1 compliance (%)
Cosenza	CLS	A	23	15	65
	CLS	C	19	16	84
	ULS	A	25	13	52
	DLS	A	21	12	57
Milan	ULS	A	27	17	63

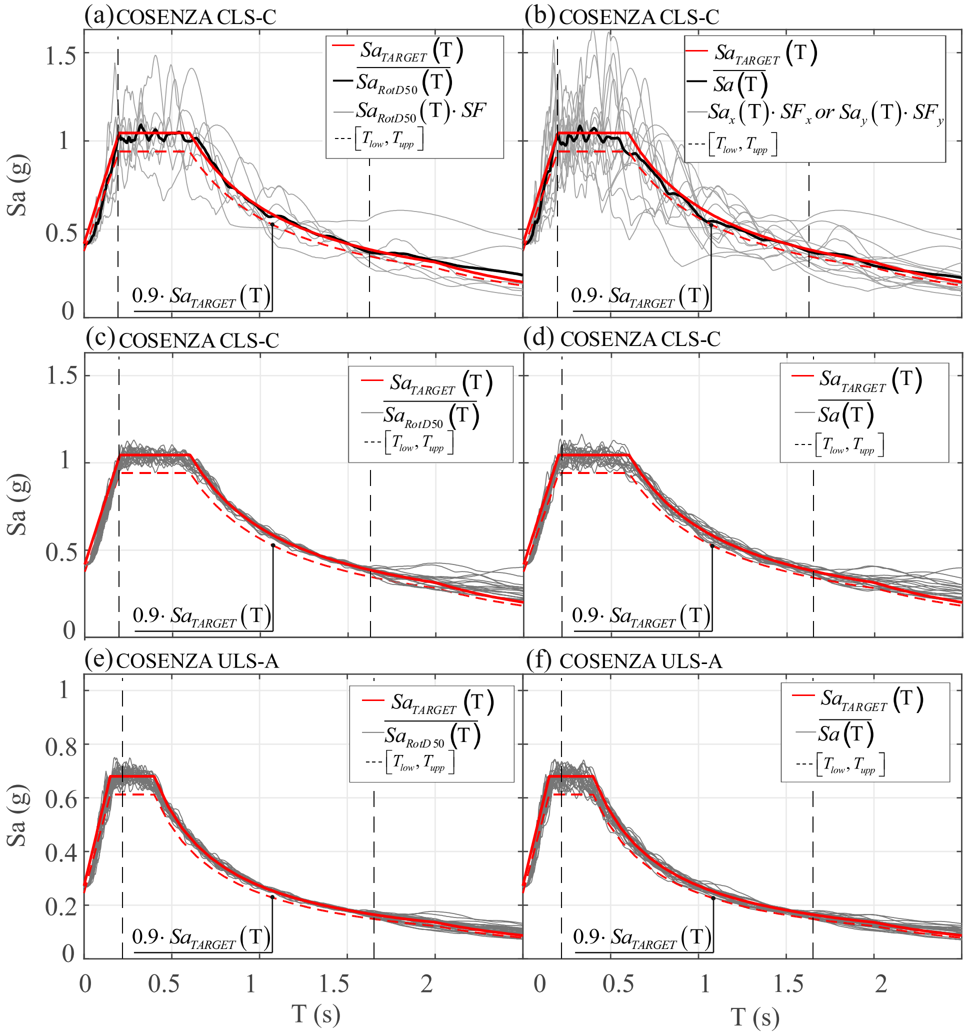

Figure 11. Results from cases where spectral acceleration ordinates are defined as $Sa_{RotD50}(T)$. (a) Spectrum compatible record set according to Eq. (17) for the Cosenza CLS-C design scenario; (b) compatibility of the previous set with EC8-1 prescriptions; (c) mean spectra of all record sets satisfying Eq. (17) for the Cosenza CLS-C case; (d) verification of EC8-1 compatibility of the Cosenza CLS-C record sets; (e) mean spectra of all record sets satisfying Eq. (17) for the Cosenza ULS-A case; (f) verification of EC8-1 compatibility of the Cosenza ULS-A record sets.

5. Conclusions

The first objective of the study presented in this article, was to revisit the apparently different record selection requirements, prescribed for the representation of seismic input via acceleration time-series, in Eurocode 8 part 1 and part 2. The focus was placed on the selection of two-horizontal-component ground motion records, while making use of recently available, large ground motion repositories to develop multiple case-study selections in this regard. Investigation of this issue was also partly motivated by the recent adoption of criteria from both families of record selection stipulations into the (Eurocode-compatible) Italian building code.

Therefore, the first question at hand was whether this difference in code provisions translates into the selection of systematically different sets. If this were indeed the case, it would imply that that different algorithms and procedures may have to be implemented when it comes to single- or

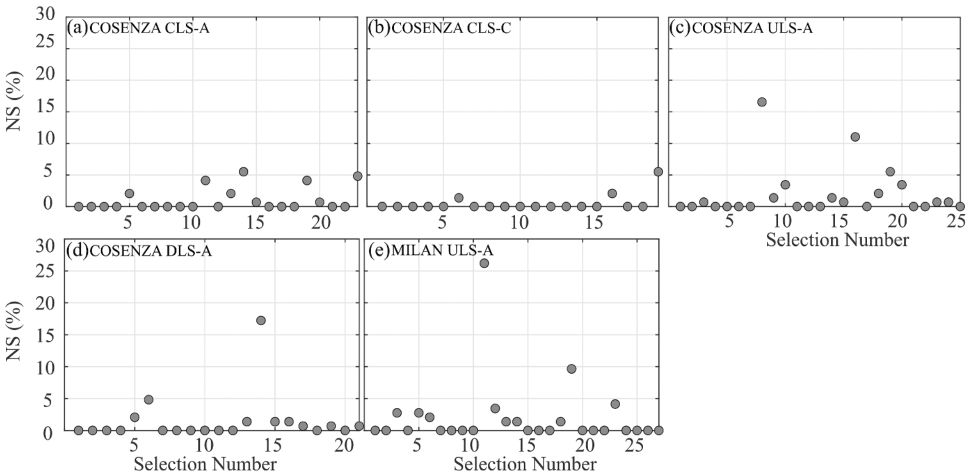

Figure 12. Percentage of the number of discrete periods from $T_{low} = 0.16s$ to $T_{upp} = 1.6s$ (out of a total of 145) where EC8-1 prescriptions are not satisfied for each case-study record selection scenario using $Sa_{RotD50}(T)$ as spectral ordinate definition: (a) Cosenza CLS-A, (b) Cosenza CLS-C, (c) Cosenza ULS-A, (d) Cosenza DLS-A, (e) Milan ULS-A.

double-horizontal-component record selection according to the Eurocodes. The results from the numerous case-study design scenarios considered, suggested that the two sets of provisions are not different after all, since adhering to one of them almost always leads to compliance also with the other, at least within the set of hypotheses that had to be made in order to render the two comparable. One of these hypotheses, was the fact that EC8-1 appears to permit different scale factors to be applied to the two horizontal components of the same record, while EC8-2 does not. It was argued in this paper that this apparent inconsistency is more formal than substantial: in fact, when different scale factors are allowed, these turn out to be quite similar regardless, due to the absence of notable directionality in far-field ground motions, especially when the horizontal ground motion components are randomly oriented. The conclusion seems to be that record selection algorithms that are based on the traditional interpretation of EC8-1 stipulations, whereupon spectral compatibility is sought against the mean of all individual ground motion components in the set pooled together, can safely continue to be used in the face of EC8-2 provisions.

The second issue that was investigated alongside the first one, using the same case-study record selection scenarios, was that of the interpretation of EC8-1 provisions, which is necessary when extending record selection criteria from the single- to the double-horizontal component case. In this context, two alternative interpretations where examined: one where spectrum compatibility was satisfied by the average spectrum of all bidirectional motion components pooled together and another where spectrum compatibility had to be satisfied in two orthogonal directions simultaneously. The investigation showed that the two interpretations can be considered equivalent, by virtue of the multitude of selected sets that were able to satisfy both alternatives.

The third issue that was tackled in this article, is the fact that most ground-motion prediction equations, commonly used in probabilistic seismic hazard analysis, introduce different intensity measure definitions, in the sense that a single scalar spectral ordinate is used to represent both of the two horizontal ground motion components. In this light, a third analysis was performed with the aim of investigating the effect that adopting alternative definitions of spectral acceleration, for the EC8 target design spectrum, would have on the selected record sets. These alternative intensity measure definitions were appropriate for bidirectional ground motion, such as geometric mean, maximum component, random component and RotD50. This part of the investigation boiled down to asking if the traditional interpretation of EC8-1 record selection criteria is consistent with spectrum-compatibility that considers a bi-directional ground motion intensity measure. The results of this series of investigations indicate that record selection performed against target design spectra expressed in terms of random or maximum component spectral acceleration, do not fare well when it comes to compatibility with the traditional interpretation of EC8-1 criteria mentioned above. On the other hand, the orientation-independent median rotated spectral acceleration RotD50, and, especially, the geometric mean of the as-recorded components behaved much better in this regard. The results showed that the spectrum-compatible record sets extracted from the database considering these two definitions of the target spectral acceleration were also compatible with EC8-1 stipulations in most cases (for RotD50) or even in all of the cases examined (for the geometric mean). The principal conclusion from this second part of the investigation, is that spectrum-compatible code-compliant record selection is not insensitive to the precise definition of the intensity measure used in probabilistic seismic hazard analysis to construct or define the target elastic design spectrum. Therefore, in cases where this information is available from hazard analysis, it should be considered when selecting records for code-mandated dynamic analysis. A secondary conclusion emerging from the examination of geometric mean spectral acceleration as an alternative intensity measure definition, is the ability of consolidated record selection algorithms, based on EC8-1 stipulations, to provide spectrum-compatible record sets for the geometric mean case.

It is believed that the results presented, and the conclusions drawn, can shed more light on the implications of code provisions for record selection and can be of practical aid for the selection of seismic input for dynamic structural analysis in the context of the Eurocodes.

Notes

1. Although seismic ground motion recorded at a single station exhibits six components, three translational and three rotational, the effect of rotational components is usually considered negligible (Kubo and Penzien 1979). The influence of the vertical component on structural response is a research topic in its own right and has been extensively discussed elsewhere (e.g., Chopra 1966; Munshi and Ghosh 1997; Papazoglou and Elnashai 1996; Vamvatsikos and Zeris 2010). However, considerations on the vertical component of ground acceleration are beyond the scope of this paper, which focuses on the two horizontal components.
2. While Part 1 of EC8 is mainly focused on buildings, it includes a series of more general provisions that also pertain to the other parts of EC8 (e.g., seismic action, performance objectives, analysis procedures, general rules). At the time of writing of the present article, a new version of EC8 is at draft stage; since a finalized version of the new EC8 is not yet available and the current EC8 is not expected to be formally superseded by the new version for a few more years, the authors chose to refrain from making explicit references to the Eurocode revision underway, apart from this note.
3. The limit states CLS, ULS, DLS considered correspond to the ones that are defined in the Italian Code (CS.LL.PP 2018) and are labelled SLC, SLV and SLD, respectively. At ULS the structure has to retain its structural integrity and a residual load bearing capacity while at DLS the performance objective is that of limiting the occurrence of damage that could provoke high repair costs and/or interruption of use. In this sense, if one were to follow the nomenclature used by the American standard for assessment of existing buildings (ASCE 2017), these would correspond to *collapse prevention, life safety* and *damage control* limit states, respectively.
4. Using the EC8 Type 1 spectrum for all cases is an intentional simplification, in the sense that disaggregation of seismic hazard for DLS at Milan hints at lower magnitudes, for which the Type 2 spectral shape could have been considered.
5. Moment magnitude.
6. In this case, this search is limited to permutations of the two orthogonal components, as they would ostensibly be found in a database. Other researchers have taken this a step further, by also rotating the components until a match could be found (Grant et al. 2008).

Acknowledgments

The work presented in this article was developed within the activities of the DPC-ReLUIS (*Rete di Laboratori Universitari di Ingegneria Sismica*) 2019-2021 research project, funded by the Department for Civil Protection (DPC) of the Italian Presidency of the Ministers' Council.

Funding

This work was supported by ReLUIS [ReLUIS-DPC 2019-2021 research program].

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